Modified pseudo-elastic approach for modelling cyclic response of biological heart valves

A. Avanzini[1], D. Battini[1], M. Berardi[1], G. Donzella[1]
[1] *Department of Industrial and Mechanical Engineering, University of Brescia - Health&Wealth, Italy,*
e-mail: andrea.avanzini@unibs.it

***Abstract*—A modified pseudo-elastic approach is proposed to model cyclic response on biological heart valves. The model takes into account hysteretic effects, in combination with hyperelastic anisotropic behaviour of valve leaflets, allowing reproduction of different loading and unloading paths. FEM implementation considered a biological heart valve during the closure phase.**

***Keywords*— Pseudo-elasticity, Biological Heart Valve, Finite element simulation.**

I. INTRODUCTION

BIOLOGICAL heart valves (BHV) exhibit excellent hemodynamic function but their long term durability is still a concern, with an average life of about 12-15 years before the need of a replacement surgery [1]. Failure of BHV may occur as a consequence of complex and interacting processes and mechanical loading has been recognized as an important factor. While in literature several examples of static or dynamic stress analyses were reported, only a few studies concerning long-term fatigue damage of aortic valves [2,3] can be found. Modelling the cyclic response of valve leaflets may provide useful information for the development of such type of predictive models. To this aim, we implemented a valve model which included hysteresis cycle to which biological soft tissues of the leaflets may be subjected.

II. METHODS

A. Constitutive Modelling approach

A classical pseudo-elastic approach was modified and implemented into the framework of hyperelastic theories for anisotropic soft materials. In particular an Holzapfel-Gasser-Ogden (HGO) type of strain energy function W was chosen for leaflet tissue, since it is really useful for the representation of different kind of biological tissues [4]. W is expressed as per eq. (1):

$$W = W_{iso} + W_{aniso} = c_{10}(I_1 - 3) + \frac{k_1}{2k_2}\left(e^{k_2(I_4-1)^2} - 1\right) \quad (1)$$

I_1 is the first invariant of right Cauchy-Green deformation tensor and I_4 is a pseudo-invariant associated with stretch in the fibre direction whereas c_{10}, k_1 and k_2 are material parameters.

In order to change the response of the material in the unloading phase, the pseudo-elastic theory [5] was applied. Two scaling parameters (η_1, η_2) were considered, associated respectively with the isotropic and anisotropic components of the strain energy function, to account for very different softening behaviour of the ground matrix and the embedded fibres, as shown in eq. (2):

$$W = \eta_1 W_{iso}(I_1) + \eta_2 W_{aniso}(I_4) + \phi(\eta_1,\eta_2) \quad (2)$$

$\phi(\eta_1,\eta_2)$ is a dissipation function that can be seen as a measure of the energy dissipated during the cycle.

B. BHV Model

The geometrical model of the valve was taken from a previous work [6] and consists of two parts (stent and leaflets). Valve diameter (D) is 18.6 mm, whereas valve height (H) is 10.42 mm, as schematically represented in Fig. 1. In the starting configuration it is almost closed, with leaflets mounted externally on the stent and in a curved configuration but not yet touching.

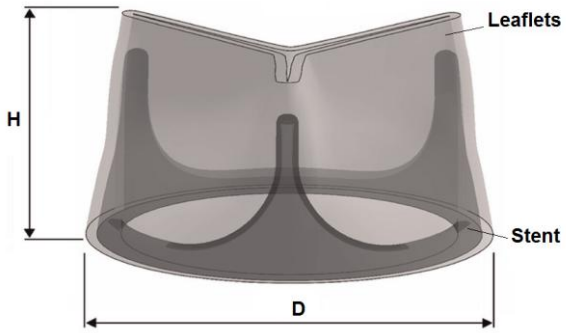

Fig.1.Biological Heart Valve model

A dynamic analysis was carried out considering the closure phase of the cardiac cycle, during which leaflets experience highest stress levels. A uniform pressure was applied on leaflets surface up to 100 mmHg and then released.

For the strain energy function definition, one family of fibres with a circumferential orientation was considered. Material parameters were estimated by fitting data reported in literature for bovine pericardium [7] with HGO model (eq.1).

Ideally any given cyclic applications modelled would require a precise description of the unloading path. Unfortunately precise information on the unloading path relative to bovine pericardium tissue could not be found in literature. For the present investigation the coefficients needed for the implementation of pseudo-elastic model were therefore assumed to have representative values typical of biological tissues.

III. RESULTS

To verify the model efficiency and the mathematical

procedures for its implementation and fitting of material parameters, representative data taken from literature [8,9] were first reproduced, simulating different loading and unloading paths. As shown in Fig.2 the model is actually capable to correctly reproduce different types of loading and unloading paths for different directions.

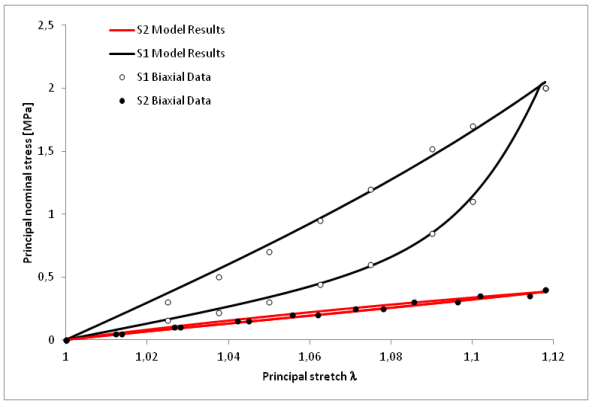

Fig.2.Verification of modelling approach for loading and unloading paths

It is important to point out that this model is suitable for the description of the behaviour of the material after the operation of preconditioning and thus with the loading-unloading cycle already stabilized.

Upon successful completion of such preliminary investigation the model was applied to the more complex geometry of a biological valve. A contour map of von Mises stress is reported in Fig. 3.

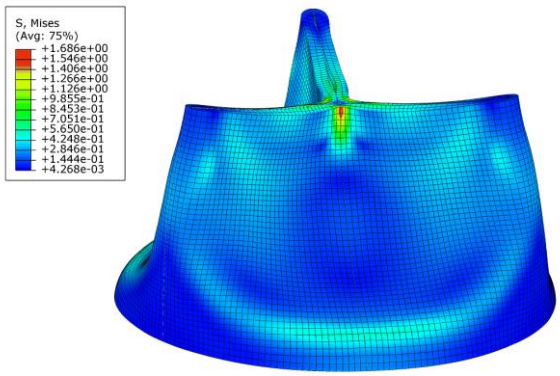

Fig.3.Contour maps of von Mises stress

Overall the stress levels were comparable with those reported in [6], in which case a Fung type constitutive law was adopted, and more in general with findings reported in literature. Peak stress in the range 1-2 MPa could be observed near the tips of the stent and in central regions, near the base of the valve.

The additional capability to predict unloading path and compute hysteresis cycle is demonstrated in Fig. 4. (values refer to the most stressed node).

From a computational point of view the model and related subroutines proved to be remarkably stable and efficient.

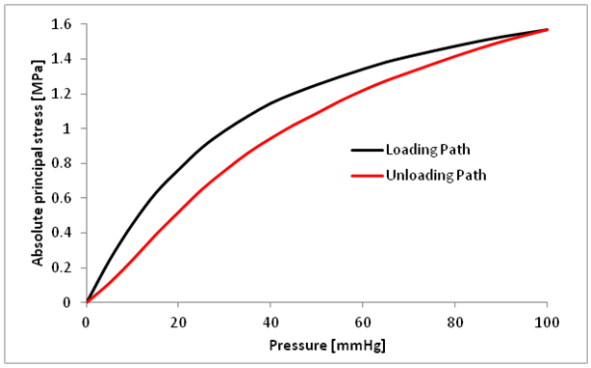

Fig.4. Loading/unloading paths

IV. Conclusion

There are few works on fatigue of biological tissues in general and even less works on experimental fatigue test on biological aortic valves. By analysing the hysteresis cycle, it could be possible to get useful information regarding the fatigue behaviour development of damage in the valves.

The same formulation can also be used to represent tissues damage; in this interpretation the scaling parameters are actually damage indexes and at the end of the unloading path they maintain their values. Notably a similar approach was recently applied by Pierce et al. [10] on human thoracic and abdominal aortic aneurismal tissue.

References

[1] H. Mohammadi and K. Mequanint, "Prosthetic aortic heart valves: Modeling and design", *Medical Engineering and Physics*, vol.33(2), pp.1331-147, 2001.

[2] C. Martin and W. Sun, "Modeling of long-term fatigue damage of soft tissue with stress softening and permanent set effects", *Biomechanics and Modeling in Mechanobiology*, vol.12(4), pp. 645-655, 2013.

[3] C. Martin and W. Sun, "Simulation of long-term fatigue damage in bioprosthetic heart valves: effects of leaflet and stent elastic properties", *Biomechanics and Modeling in Mechanobiology*, vol.13(4), pp. 759-770, 2014.

[4] T.C. Gasser, R.W. Ogden and G.A. Holzapfel, "Hyperelastic modelling of arterial layers with distributed collagen fibre orientations," *Journal of the Royal Society Interface*, vol.3(6), pp. 15-35, 2006.

[5] R.W. Ogden and D.G. Roxburgh, "A pseudo-elastic model for the Mullins effect in filled rubber," *Proceedings of the Royal Society a-Mathematical Physical and Engineering Sciences*, vol.455(1988), pp. 2861-2877, 1999.

[6] A. Avanzini, A. and D. Battini, "Structural analysis of a stented pericardial heart valve with leaflets mounted externally" *Proceedings of the Institution of Mechanical Engineers Part H-Journal of Engineering in Medicine*, vol.228(10), pp. 985-995, 2014.

[7] K. Li and W. Sun, "Simulated thin pericardial bioprosthetic valve leaflet deformation under static pressure-only loading conditions: implications for percutaneous valves", *Ann Biomed Eng*, vol.38(8), pp. 2690-2701, 2010

[8] A. Dorfmann, B.A. Trimmer and W.A.Jr. Woods, "A constitutive model for muscle properties in a soft-bodied arthropod", *Journal of the Royal Society Interface*, vol. 4(13), pp. 257-269, 2007.

[9] E. Pena, B. Calvo, M.A. Martinez and M. Doblare, "On finite-strain damage of viscoelastic-fibred materials. Application to soft biological tissues," *International Journal for Numerical Methods in Engineering*, vol. 74(7), pp. 1198-1218, 2008.

[10] D.M. Pierce, F. Maier,H. Weisbecker, C. Viertler, P. Verbrugghe, N. Famaey, I. Fourneau, P. Herijgers and G.A. Holzapfel, "Human thoracic and abdominal aortic aneurysmal tissues: damage experiments, statistical analysis and constitutive modeling," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 41, pp. 92-107, 2015