PAPER REF: 3887

TARGETING THE RESPONSE OF BIOLOGICAL TISSUE VIA FINITE-VOLUME MICROMECHANICS

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ABSTRACT

The finite-volume direct averaging micromechanics (FVDAM) theory is employed in conjunction with the Particle Swarm Optimization algorithm to target the response of three types of heart-valve chordae tendineae with different stiffening characteristics due to different crimp periods. The thickness of the wavy layer at fixed amplitude-to-wavelength ratio that mimics the crimped collagen microstructure is shown to be an important design parameter together with the surrounding soft matrix material.

Keywords: micromechanics, homogenization, finite-volume method, biological tissue, bioengineered materials.

INTRODUCTION

The stiffening response of heart-valve chordae tendineae is due to the crimped pattern of collaged fibers arranged in planar bundles. The knee of the stress-stretch curve of this biological tissue is controlled by the amplitude-to-wavelength ratio of the planar collagen bundles which produce stiffening upon full extension. Three characteristic ratios have been identified in marginal, basal and strut chordae tendineae which lead to stiffening at increasingly higher stretches.

Herein, we employ the finite-volume direct averaging micromechanics (FVDAM) theory with finite-deformation modeling capability (Khatam and Pindera, 2012) to target the stiffening response of the three chordae types using wavy multilayer microstructures comprised of continuous layers representing planar bundles of collagen fibers embedded in much softer matrix. The objective is to identify combinations material and geometric parameters at fixed amplitude-to-wavelength ratio of the crimped collagen fiber pattern obtained from experiment that best fit the response of marginal, basal and strut chordae tendineae. Towards this end the FVDAM theory is incorporated into the Particle Swarm Optimization algorithm and the ensuing optimum microstructural designs compared with extensive parametric studies.

RESULTS AND CONCLUSIONS

Both the stiff collagen-like layers and the soft matrix are modelled using the compressible Mooney-Rivlin model with the strain energy given by

$$W = c_1(I_1 / I_3^{1/3} - 3) + c_2(I_2 / I_3^{2/3} - 3) + K/2(J-1)^2$$

where I_1, I_2, I_3 are the right Cauchy-Green deformation tensor invariants, K is the bulk modulus, $J = \det\mathbf{F}$ and the initial shear modulus is given by $\mu = 2(c_1 + c_2)$. The material parameters used in the simulations are given in the table.

Table 1 - Material parameters for stiff and soft wavy layers based on the compressible Mooney-Rivlin material.

Layer	*E* (MP)	*ν*	*k* (MPa)	*μ* (MPa)	c_1 (MPa)	c_2 (MPa)
Stiff	125.0	0.3	104.167	48.076	24.038	0.0
Soft	0.1	0.3	0.083	0.038	0.019	0.0

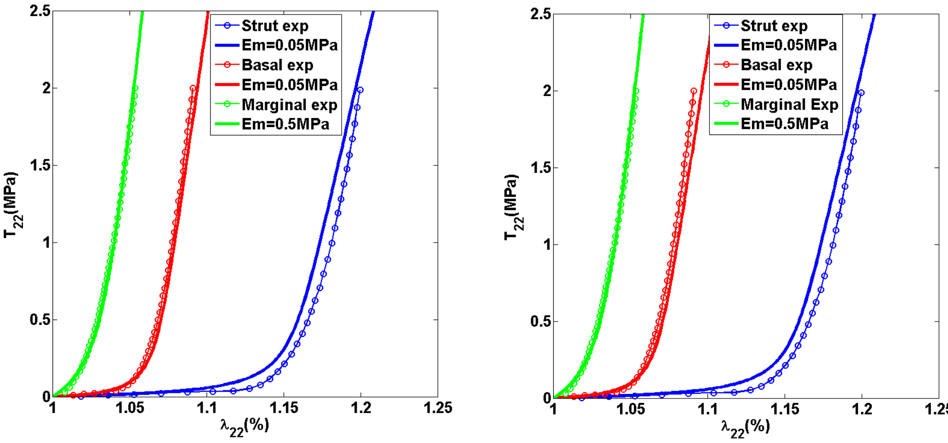

Fig. 1 - Comparison of experimental and targeted stress-stretch response of three types of chordae endineae with different stiffening response due to differences in the wavy collagen fiber bundle crimp period. Results based on parametric sensitivity study using 8 stiff layers (left) versus results obtained from the FVDAM-implemented Particle Swarm Optimization yielding 8, 3 and 8 layers for strut, basal and marginal chordae tendineae (right)

The objective function minimizes the differences between the experimental and predicted response of chordae tendineae obtained by varying the thickness of stiff layers that mimic the planar bundles of collagen fibrils at fixed volume fraction and amplitude-to-wavelength ratio, and the Young's modulus of the matrix. The layer thickness was varied by subdividing the initial single stiff layer into two, four and eight thinner layers while keeping the overall unit cell dimensions fixed.

The results shown in the figure obtained from the optimization studies exhibit excellent correlation with experimental data for the three chordae tendineae types. They are further supported by the results from the parametric sensitivity studies wherein the best design parameters were identified from three-dimensional carpet plots of the objective function variation with the design variables. These plots possess cross-sections with discontinuous objective function derivatives with respect to the design variables, justifying the use of the employed non-gradient optimization algorithm. These results also indicate that multiple designs with comparable optimal targeted performance that mimics the chordae tendineae response are possible if no additional constraints are imposed on the optimization problem.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the NSF Nano and Bio Mechanics Program Grant Award # CMMI-1030673.

REFERENCES

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