Finite element study of Poisson's ratio for soft tissues with helical fibre structure

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1. Introduction

Most of soft tissues such as arteries, tendons and intervertebral discs are composed of extracellular fibres which are considered to be crimped and surrounded by matrix called ground substance. In Gatt et al. (2015) the authors proposed that this crimped fibre structure may be the reason of the negative Poisson's ratio ($\nu < 0$) they observed for tendons under uniaxial tests. Besides, negative Poisson's ratio have also been discovered in skin tissue (Veronda and Westmann 1970), carotid arteries (Timmins et al. 2010) and annulus fibrosus tissue (Baldit et al. 2014; Derrouiche et al. 2019; Dusfour et al. 2020). In addition, soft tissues were also well reported to have large ($\nu > 0.5$) Poisson's ratio (Vergari et al. 2011; Swedberg et al. 2014). In Xiao et al. (2020) the authors studied the tendon Poisson's ratio by considering the fibre corrugation as a 2D sinusoidal structure, but no negative value was found in their study. Many soft tissues such as aortic wall (Niestrawska et al. 2016) and tendon (Verzár 1964; Evans and Barbenel 1975; Thompson et al. 2010) are found to possess a helix-shape fibre 3D micro-structure. In Khani et al. (2016) the authors studied the mechanical properties of composites reinforced by helical fibres, but the effective Poisson's ratio of the composite was not determined.

Present study is aimed at investigating the correlation between soft tissue Poisson's ratio and fiber structure. To do so, the considered soft tissues are assumed to be composite materials reinforced by helical fibres and matrix is supposed to be perfectly bounded with the fibres. We further consider a periodic arrangement of the helical fibres, with or without cross-links in the aim to investigate their respective implication on the overall composite Poisson's ratio.

2. Methods

An homogenization procedure, based on double scale asymptotic expansions which is well documented by Papanicolau et al. (1978), is used to estimate the effective rigidity tensor. A finite element model is developed to numerically study the mechanical properties of the composite reinforced by Fig.1 (a) uni-helix fibres and Fig.1 (d) helix with cross-linked fibres. The Poisson's coefficients are calculated from the effective rigidity tensor of the composite. The stress-strain curve for soft tissue is usually J-shaped, and the proposed model only focuses on small initial strain which is considered as quasi-linear behavior. The elastic modulus of fibres is set to 100 MPa based on measurements (Dutov et al. 2016) and the elastic modulus of the matrix is set to 10 kPa (Cortes and Elliot 2012). The Poisson's ratio of both the fibres and the matrix is set to 0.3 (Reese et al. 2010). We define the representative elementary volume (REV) associated to periodic boundary conditions. The geometric design is built by using Solidworks and FreeCAD, the mesh is generated by Gmsh, the finite element analysis is calculated by Cast3m and the data analysis is done by Python programming.

2.1 Representative elementary volume

The REV of the composite reinforced by uni-helix fibres is shown in Fig. 1(a-c) and the composite reinforced by helix with cross-linked helix fibres is shown in Fig. 1(d-f), respectively. The helix lead direction is set parallel to the z-axis and the cross-links are set perpendicular to the z-axis and are connected to the nearest helix fibre at the furthest point. The helix angle is set to 28° for both of the considered REV whereas the fibres occupy a fraction of the overall volume varying from 2% to 24%.

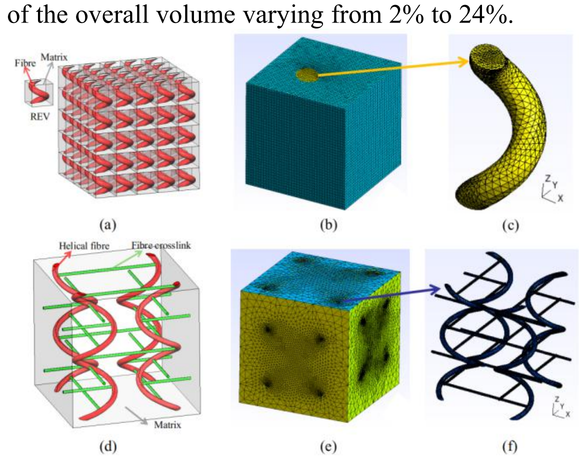

Figure 1. (a) REV of the helical fibre reinforced composite. (b) Finite element mesh of (a). (c) Mesh of the fibre in (b). (d) REV of the composite reinforced by helix with cross-linked fibres. (e) Finite element mesh of (d). (f) Mesh of the fibre in (e).

2.2 Boundary conditions

To obtain macroscopic elastic properties, periodic boundary condition is applied to the REV. The periodicity requires that the opposite surfaces of the REV have the same deformation for a linear displacement field in the REV. To impose the periodic boundary condition, the finite element mesh of the REV is set as shown in fig. 1(b) and (e), where the meshes on the opposite boundary surfaces are identical.

3. Results and discussion

The Poisson’s ratios of composites reinforced by uni-helix fibres are shown in Fig. 2 (a). The term ν_{ij} is defined as Poisson’s ratio that characterize the strain in the j direction produced by the loading in the i direction. No negative effective Poisson's ratio was found for volume fractions ranging from 2% to 24%. ν_{yz} and ν_{xz} decrease with the increase of the fibre volume fraction and ν_{xy} and ν_{yx} are larger than 0.3 when fibre volume fraction is ranging from 3% to 20%. Fig. 2 (b) shows that Poisson’s ratios of composite reinforced by cross-linked fibres ν_{yz}, ν_{xz}, ν_{zy} and ν_{zx} are negative, ν_{xy}, ν_{yx}, ν_{zy} and ν_{zx} decrease and stabilize with the increase of the fibre volume fraction ranging from 2% to 24%.

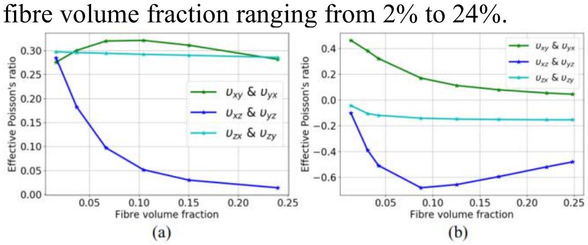

Figure 2. The Poisson’s ratio versus fibre volume fractions. (a) Composite reinforced by uni-helix fibres. (b) Composite reinforced by cross-linked fibres.

4. Conclusions

The Poisson’s ratio of both fibre and matrix are set to 0.3 but the effective ratio of the composite varies with the fiber structure. No negative effective Poisson's ratio was found for composite reinforced by uni-helix fibres but negative effective Poisson's ratio are found in composite reinforced by cross-linked fibres. The effect of cross-link position on Poisson’s ratio will be further studied and we consider that cross-link might also lead to large poisson's ratio. In conclusion, we think that considering cross-links associated to specific and more realistic structural arrangement of fibres may be crucial for further soft tissue models.

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