

A GRADIENT-ENHANCED CONTINUUM DAMAGE MODEL WITH APPLICATION TO FIBRE-REINFORCED TISSUES AT FINITE STRAINS

C. Polindara^{1,*}, T. Waffenschmidt¹, A. Menzel^{1,2}, S. Blanco³ and J. Goicolea³

¹ Institute of Mechanics, Department of Mechanical Engineering, TU Dortmund,
Leonhard-Euler-Str. 5, D-44227 Dortmund, Germany

² Division of Solid Mechanics, Lund University, P.O. Box 118, SE-22100 Lund, Sweden

³ Department of Mechanics and Structures, School of Civil Engineering, Technical University
of Madrid, C/ Profesor Aranguren S/N, 28040 Madrid, Spain

* Corresponding author: cesar.polindara@udo.edu

Key words: *Gradient-enhanced damage, Large deformations, Finite element method, Anisotropic biological tissues*

A non-local gradient-based damage formulation within a geometrically non-linear setting is presented. The hyperelastic constitutive response at local material point level is governed by a strain energy function which is additively composed by an isotropic neo-Hookean matrix and by an anisotropic fibre-reinforced material based on the model proposed by [3]. The neo-Hookean matrix is assumed to behave elastically while only the anisotropic contribution is affected by the damage, which is governed by a scalar $[1-d]$ -type damage formulation. Following the concepts in [2] and [1], the local free energy function is enhanced by a gradient-term of the non-local damage variable which, itself, is introduced as an additional independent variable. In order to link the local and non-local damage field variables, κ and ϕ respectively, a penalisation term is also incorporated within the free energy function, which reads

$$\Psi = \Psi^{\text{iso}} + f_d(\kappa) \Psi^{\text{ani}} + \frac{c_d}{2} \nabla_{\mathbf{x}} \phi \cdot \mathbf{C}^{-1} \cdot \nabla_{\mathbf{x}} \phi + \frac{\beta_d}{2} [\phi - \kappa]^2 \quad (1)$$

Based on the principle of minimum total potential energy, a coupled system of Euler-Lagrange equations, i.e. the balance of linear momentum and the balance of the non-local damage field, is obtained and solved in weak form. Two different three-dimensional finite element discretisations are implemented, i.e. Q1Q1 and Q2Q1 hexahedral elements. Following this framework a finite element simulation of a two-layered fibre-reinforced artery-like tube subjected to internal pressure is performed. This idealised setting is commonly used to assess basic capabilities of particular constitutive models for arteries,

see e.g. [4] and references cited therein. The results show that the proposed gradient-enhanced damage model is able to reproduce the loss of stiffness due to fibre-degradation in an artery when the blood pressure reaches values far beyond the physiological range. These results are of great importance within biomechanical applications provided they can serve as a basis for planning of medical interventions such as angioplasty.

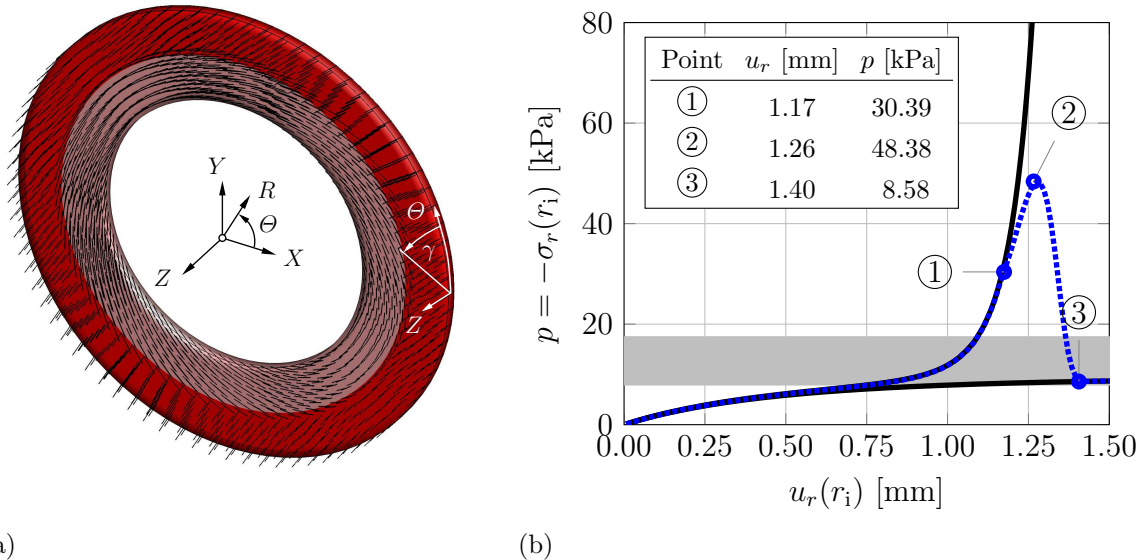


Figure 1: Two-layered fibre-reinforced artery-like tube subjected to internal pressure. (a) Finite element mesh with fiber orientations. Media (inner layer) and adventitia (outer layer) are highlighted in different colors. (b) Load-displacement response for the inflated tube: pressure p versus radial displacement $u_r(r_i)$ at the inner radius of the tube. The lower and upper solid black curves represent the purely elastic response of the neo-Hookean ground substance and the fibre-reinforced material, respectively. The blue curve shows the mechanical response captured by the gradient-enhanced damage model. The gray-shaded region represents the physiological range for blood pressure.

REFERENCES

- [1] T. Waffenschmidt, C. Polindara, A. Menzel and S. Blanco. A gradient-enhanced large-deformation continuum damage model for fibre-reinforced materials. *Computer Methods in Applied Mechanics and Engineering*, 268: 801-842, 2014.
- [2] B. J. Dimitrijević and K. Hackl. A method for gradient enhancement of continuum damage models. *Technische Mechanik*, 28(1):43-52, 2008.
- [3] T. Gasser, R. Ogden, and G. Holzapfel. Hyperelastic modelling of arterial layers with distributed collagen fibre orientations. *Journal of the Royal Society Interface*, 3:15-35, 2006.
- [4] V. Alastrué, M. Martínez, M. Doblaré and A. Menzel, Anisotropic micro-sphere-based finite elasticity applied to blood vessel modelling. *Journal of the Mechanics and Physics of Solids*, 57:178-203, 2009.