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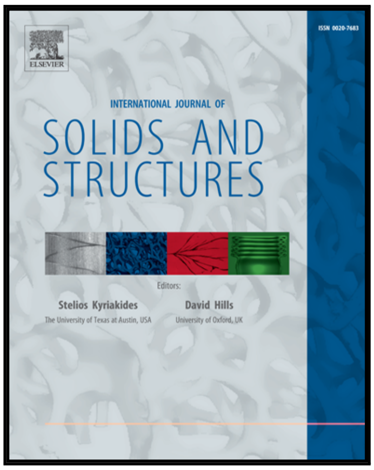

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A computational framework for modelling damage-induced softening in fibre-reinforced materials – Application to balloon angioplasty

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Abstract

A computational framework for modelling damage-induced softening in fibre-reinforced materials is presented. The main aspect of this framework is the proposed non-local gradient-enhanced continuum damage formulation. At the material level, the elastic constitutive behavior is defined by a hyperelastic functional including a volumetric and an isochoric contribution. The isochoric contribution is subdivided into three contributions associated to three different phases $i = 0, 1, 2$. Phase 0 is represented by an incompressible neo-Hookean material, whereas phases 1 and 2 are represented by an exponential format that accounts for the stretching along two preferred anisotropy directions, i.e. two fibre families. Furthermore, a $1 - d^i$–type damage function, is introduced to reproduce the loss of stiffness in each phase i. Following the ideas discussed in Dimitrijević and Hackl (2008); Waffenschmidt et al. (2014), and references cited therein, the model is built around the enhancement of the local free energy function by means of terms that contain the referential gradients of the non-local damage variables ϕ^i. The inclusion of these terms ensures an implicit regularisation of the finite element implementation. A finite element implementation of the non-local gradient-enhanced continuum damage model is presented. To this end we develop an 8-noded Q1Q1P0 hexahedral element following a variational approach, in order to efficiently model the quasi-incompressible behaviour of the hyperelastic material. This element is implemented in Abaqus by means of a user subroutine UEL. Three boundary value problems are studied: an anisotropic plate with a hole, a balloon angioplasty and a full-3D artery-like tube. These computational experiments serve to illustrate the main capabilities of the proposed model.

Keywords: balloon angioplasty, gradient-enhanced damage, finite deformations, finite element method, anisotropic biological tissues, coupled problem, Abaqus UEL

1. Introduction

The physical modelling and numerical simulation of complete surgical interventional procedures has increasingly drawn much attention during the last decade. In this regard, balloon angioplasty is certainly one of the most important surgical intervention techniques used to extend or reopen narrowed blood vessels in order to restore the continuous blood flow in, for instance, atherosclerotic arteries. A balloon, typically made of a highly flexible rubber-like plastic sheet, is inserted within the blocked artery and inflated by means of high pressure using magnitudes between p = 600-2000 [kPa]. The balloon contacts the inside of the artery and slightly overstretches the arterial tissue beyond the physiological pressure level. Inelastic, i.e. predominantly damage-related and elastoplastic processes are induced during its inflation which result in an irreversible deformation within the artery upon this supraphysiological loading. As a beneficial consequence, provided that the inelastic deformations do not exceed a specific limit, higher deformations, respectively diameters of the blood vessels, can be obtained at the same pressure level and a continuous blood flow can be guaranteed.

Several studies on the modelling and simulation of the mechanics of balloon angioplasty exist in the literature. As a common feature amongst these works, they all regard the arterial tissue as a composite material made of an isotropic ground substrate of elastin fibres and a highly anisotropic network of collagen fibres, principally following the paper Gasser et al. (2006). In the aforementioned work the authors develop a hyperelastic constitutive model for blood vessels, where the isotropic ground substance is modelled as an incompressible neo-Hookean material, and the collagen fibres are modelled as two fibre-reinforcements helically oriented along the circumferential direction of the artery.

In Holzapfel et al. (2004), the mechanics of balloon angioplasty are investigated from a computational point of view by performing a finite element study on the identified atherosclerotic arterial geometry by means of an inelastic anisotropic constitutive model. In a later work, Gasser and Holzapfel (2007), the authors study the mechanics of balloon angioplasty by considering the balloon-induced overstretch of remnant non-diseased tissues in atherosclerotic arteries, specifically a stenotic residually stressed artery composed of adventitia, me-

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