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Research Paper

Evaluating the macroscopic yield behaviour of trabecular bone using a nonlinear homogenisation approach

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ABSTRACT

Computational homogenisation approaches using high resolution images and finite element (FE) modelling have been extensively employed to evaluate the anisotropic elastic properties of trabecular bone. The aim of this study was to extend its application to characterise the macroscopic yield behaviour of trabecular bone. Twenty trabecular bone samples were scanned using a micro-computed tomography device, converted to voxelised FE meshes and subjected to 160 load cases each (to define a homogenised multiaxial yield surface which represents several possible strain combinations). Simulations were carried out using a parallel code developed in-house. The nonlinear algorithms included both geometrical and material nonlinearities. The study found that for tension-tension and compression-compression regimes in normal strain space, the yield strains have an isotropic behaviour. However, in the tension-compression quadrants, pure shear and combined normal-shear planes, the macroscopic strain norms at yield have a relatively large variation. Also, our treatment of clockwise and counter-clockwise shears as separate loading cases showed that the differences in these two directions cannot be ignored. A quadric yield surface, used to evaluate the goodness of fit, showed that an isotropic criterion adequately represents yield in strain space though errors with orthotropic and anisotropic criteria are slightly smaller. Consequently, although the isotropic yield surface presents itself as the most suitable assumption, it may not work well for all load cases. This work provides a comprehensive assessment of material symmetries of trabecular bone at the macroscale and describes in detail its macroscopic yield and its underlying microscopic mechanics.

Abbreviations: (FE), Finite element; (CT), Computed tomography; (MIL), Mean interceptlength; (RVE), Representative volume element; (MPI), Message passing interface

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1. Introduction

Exponential growth of older population implies that problems associated with deteriorated mechanical capabilities of bone need urgent attention. Computational modelling to examine the mechanical response of musculoskeletal systems requires the mechanical behaviour of bone to be defined satisfactorily (Pankaj, 2013). A continuum description of bone that can be related to its microstructure and includes its anisotropy and its yield behaviour will go a long way in predicting failure of bone and bone-implant systems.

The macroscopic elastic behaviour of bone has been mostly modelled using isotropic linear elasticity. Often, bone macroscopic properties are assumed to be homogeneous with separate elastic properties being assigned to cortical and trabecular bone (Completo et al., 2009; Conlisk et al., 2015). Sometimes, subject specific macroscopic elastic properties are assigned using computed tomography (CT) scans, which permit inhomogeneity in the material properties on the basis of CT attenuations (Helgason et al., 2008; Schileo et al., 2008; Tassani et al., 2011). That said, since CT attenuations can only provide scalar values, assumption of isotropy needs to be made. However, it is well recognised that the macroscopic behaviour of bone is not isotropic. For trabecular bone, which resembles open cell foams, the anisotropy is largely a consequence of its anisotropic microarchitecture (Odgaard et al., 1997; Turner et al., 1990). An ultrasonic approach proposed by van Buskirk et al. (1981) was shown to provide a good approximation of nine orthotropic elastic constants if a heterogeneity correction were included. In general, experimental mechanical techniques are unable to provide the complete stiffness tensor at the resolution required for modelling (Odgaard et al., 1989).

Image based computational approaches have been successfully applied for the evaluation of the macroscopic stiffness tensors (Donaldson et al., 2011; van Rietbergen et al., 1995). In these, micro-CT (or micro-magnetic resonance imaging) scans of bone are converted into high resolution 3D finite element (FE) meshes, with a detailed geometry of its microstructure. The solid phase (or bone tissue) is assigned isotropic elastic properties and the volume element (VE) is then computationally subjected to six strain/stress states (three normal and three shear). The response enables evaluation of the full macroscopic elastic stiffness tensor using the standard mechanics methodology (van Rietbergen et al., 1996). Previous studies have extensively employed these homogenisation approaches, and relationships between stiffness and microarchitectural indices (volume fraction and fabric tensor) have also been established (Cowin, 1986; Turner and Cowin, 1987; Turner et al., 1990; Zysset and Curnier, 1995).

While modelling bone as an elastic material may be adequate for a few applications, a significant proportion of applications requires evaluation of post-elastic response, e.g. to evaluate implant loosening resulting in its failure. Many studies still continue to employ elastic analyses to predict arbitrarily post-elastic behaviour (Falcinelli et al., 2014).

Both stress- and strain-based criteria have been used to describe the macroscopic yield surface of bone (Keaveny et al., 1994; Keller, 1994; Kopperdahl and Keaveny, 1998). In recent years a consensus appears to be emerging that strain-based criteria are easier to apply as trabecular bone behaviour in this space is “more isotropic” and density independent than in stress space (Bayraktar et al., 2004; Chang et al., 1999; Pankaj and Donaldson, 2013). There is also now some evidence to suggest that failure of bone is strain-controlled rather than stress-controlled (Nalla et al., 2003). However, there is little consensus on the yield criterion that may be suitable for this cellular material.

Homogenisation techniques, using micro-CT images and FE analyses, that have been successful in the elastic domain, require huge computational resources in the plastic regime for a number of reasons: nonlinear homogenisation requires a large number of load cases (unlike the linear elastic regime which only requires six); nonlinear simulations require considerably more computational effort; and to capture nonlinear phenomena FE meshes need to be finer. As a consequence, nonlinear homogenisation to obtain the macroscopic yield criterion of bone requires high performance computing and has been attempted only by a few previous studies (Bayraktar et al., 2004; Sanyal et al., 2015; Wolfram et al., 2012). All these studies used a simple bilinear criterion to represent the solid phase of bone. Wolfram et al. (2012) used a limited number of load cases which can lead to loss of information on physiologically possible complex load cases, while both Sanyal et al. (2015) and Wolfram et al. (2012) made a priori assumptions with regard to macroscopic yield surface symmetries; the former assumed it to be transverse isotropic and the latter orthotropic.

Nanoindentation experiments on bone suggest that the solid phase of bone has a pressure-dependent yield surface (i.e. its yielding depends on hydrostatic stress), which arises because of bone's cohesive-frictional behaviour (Tai et al., 2006). Due to this reason, bone tissue (or the solid phase) can be modelled using classical criteria, such as Mohr-Coulomb or Drucker-Prager (Carnelli et al., 2010; Tai et al., 2006).

On the macroscale, high density bone is prone to tissue yielding, while low density bone is likely to fail via a mixture of large deformation failure mechanisms and tissue yielding (Bevill et al., 2006; Morgan et al., 2004; Stolken and Kinney, 2003). At the microscale, total strains can be large and a small strain approximation may be invalid. It is important to note that local yielding or buckling may not imply simultaneous yielding of the homogenised structure; the latter results from a significantly compromised stress carrying capacity.

The aim of this study is to characterise the macroscopic yield surface of trabecular bone by using a numerical homogenisation approach, derived from multiscale theory (de Souza Neto et al., 2015; Kruch and Chaboche, 2011; McDowell, 2010): using high resolution FE meshes obtained from micro-CT images; applying a range of load cases which adequately describes the multiaxial behaviour of bone at the macroscale (including complex normal and shear load combinations); incorporating both geometrical and material nonlinearities; and with a validated pressure sensitive yield criterion for the solid phase. We consider a range of trabecular bone densities and also examine the efficacy of quadric surfaces as representatives for its macroscopic yield surface.