Phase-field modelling of damage evolution in cortical bone

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Abstract

With ageing, bone becomes stiffer and more brittle, leading to an increased risk of fracture. The changes in properties can be attributed to changes in bone composition and microstructure. Computational models can be used to elucidate the links between fracture behaviour and microstructure. Moreover, computational models are useful because experimental determination of mechanical properties of the different tissues in the bone microstructure is difficult. With computational models, it is possible to investigate the fracture behaviour of normal and ageing bone, as well as the role of the microstructure in the fracture process. Models relying on cohesive criteria e.g. the cohesive zone method and the extended finite element method have been used extensively in this regard. More recently, phase-field models have been introduced for this purpose. However, as no validation studies have been published, it remains unclear to what extent classical phase-field methods accurately represent bone. In this contribution, we evaluate the predictive performance of a classical phase-field finite element model in comparison with experiments performed by Gustafsson et al. (2024).
A phase-field finite element model of bovine cortical bone with a resolved osteonal microstructure consisting of osteons, matrix and cement line was used. A set of material parameters was estimated using a design-of-experiments approach in which all six parameters (three moduli and three critical energy release rates) were varied according to a Box-Behnken design to create response surfaces for peak force, tortuosity and toughness. From the response surfaces, the parameter set that minimised the error with respect to experimental results from single-edge notched bending (SENB) of bovine bone and subsequent imaging of the crack path (Gustafsson et al., 2024) was identified as the best fit.

The model was then validated using new specimen geometries in comparison with data from corresponding SENB experiments (Gustafsson et al., 2024). It was found that phase-field models in their classical form predict peak load, toughness and final crack path with reasonable accuracy. However, the force versus crack mouth opening displacement (CMOD) response was not well captured. Being based on linear-elastic fracture mechanics, the phase field models predicted brittle failure. On the other hand, SENB experiments performed on bovine cortical bone showed both an initial, gradual damage evolution, resulting in a non-linear response, and a ductile post-peak behaviour with increasing toughness as the crack length increases.

The observations imply that the material locally undergoes non-elastic deformation and

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that the size of this plastic or bridging zone (i.e. the characteristic length) is significant compared to other dimensions of the specimen. The cohesive-zone phase-field formulation of Wu and Nguyen (2018) implemented by Navidtehrani et al. (2021) accurately predicts failure of both notched and unnotched specimens also when the characteristic length is non-negligible. When the cohesive-zone phase-field model was implemented in the bovine cortical bone geometries, considerably better agreement was obtained between the experimental and predicted force vs. CMOD curves. The present contribution investigates the predicted damage development and crack path in comparison to post-fracture CT scans of the experimental cortical bone specimens. As the findings indicate that fracture in healthy bone is ductile or quasi-brittle, care should be taken when applying classical, brittle phase-field methods to bone.

References:

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