11th World Congress on Computational Mechanics (WCCM XI)
5th European Conference on Computational Mechanics (ECCM V)
6th European Conference on Computational Fluid Dynamics (ECFD VI)
July 20 - 25, 2014, Barcelona, Spain

MULTISCALE MODELLING OF DAMAGE AND FAILURE IN A BIOLOGICAL HIERARCHICAL MATERIAL

Ingo Scheider[1*], Swantje Bargmann[1,2], Tao Xiao[1], Ezgi Yilmaz[3] Gerold Schneider[3] and Norbert Huber[1]

[1] Helmholtz-Zentrum Geesthacht, Institute of Materials Research, Geesthacht, Germany
[2] Technical University Hamburg-Harburg, Institute of Continuum Mechanics, Hamburg, Germany
[3] Technical University Hamburg-Harburg, Institute of Advanced Ceramics, Hamburg, Germany

Key Words: *biomechanics, hierarchical microstructure, representative unit cell, fibre reinforced material.*

The microstructure of many biological materials consists of various constituents and different characteristic length scales that were optimized by evolution with respect to geometry and material properties. The main ingredient for achieving these optimal properties, e.g. stiffness, strength and damage tolerance, is a hierarchical microstructure, which spans many scales including characteristic lengths ranging from a few nanometres up to one millimetre.

This contribution is concerned with the modelling and computation of the mechanical behaviour, in particular with the failure, of the enamel of a bovine tooth [1, 2]. Dental enamel is the outermost layer of a tooth crown consisting of a hierarchical and graded structure. Approximately 90 vol% of enamel consist of the hydroxyapatite mineral, the rest being protein and water. For the underlying model description on the very basic microstructural level, which is the nanometer scale, we resort to a non-linear Neo-Hookean model for the fibrous mineral and to the Arruda-Boyce model for the protein, in combination with a cohesive zone approach for modelling the various failure mechanisms. The model accounts for non-linear, large-deformation kinematics and softening at the first level hierarchy and it is validated against experimental data.

The numerical implementation is carried out with the help of the finite element method. A representative microstructural unit consisting of a few fibres on the smallest scale is simulated, with the above mentioned models for deformation and a three-dimensional cohesive zone model which maps cracking of the mineral fibres as well as debonding between the mineral fibre and the protein, see [3] and also [4]. The next hierarchical level, which spans the characteristic length of a few microns, is formed by fibres consisting of the composite material from the nano level and a thin protein layer in between. The fibre volume fraction is similar to that from the lower scale such that the microstructure can be assumed to be self-similar. For the modelling of the second level numerical homogenization of the hyperelastic behaviour and the damage has been conducted.
Orthotropic elastic properties are derived from the hyperelastic response of the RVE, whereas the failure behaviour is extracted as a traction-separation law based on the softening behaviour of the cell.
Numerical results of the representative unit cells and the complete microstructure agree very well with the features of the microstructural behaviour seen in experiments.

REFERENCES

[1] Bechtle S, Özcoban H, Lilleodden ET, Huber N, Schreyer A, Swain MV, et al. Hierarchical flexural strength of enamel: transition from brittle to damage-tolerant behaviour. Journal of the Royal Society Interface. 2012;9:1265-74.
[2] Yilmaz ED, Bechtle S, Özcoban H, Schreyer A, Schneider GA. Fracture behavior of hydroxyapatite nanofibers in dental enamel under micropillar compression. Scripta Materialia. 2012;68:404-7.
[3] Bargmann S, Scheider I, Xiao T, Yilmaz ED, Schneider GA, Huber N. Towards bio-inspired engineering materials: Modeling and simulation of the mechanical behavior of hierarchical bovine dental structure. Computational Materials Science. 2013;79:390-401.
[4] Scheider I, Chen Y, Hinz A, Huber N, Mosler J. Size effects in short fibre reinforced composites. Engineering Fracture Mechanics. 2013;100:17-27.