

Hierarchical biomaterials mechanics

Problem

Biomimetics deals with the application of nature-made “design solutions” to the realm of engineering. In this context, mimicking biological materials with fine-tuned mechanical properties has been on the agenda of engineering research and development for many years. The premise of biomimetics is that it is possible to reduce diversity and complexity of biological materials to a number of ‘universal’ functioning principles. This requires foremost a deep understanding of the hierarchical structure of biological materials. It now appears that multi-scale mechanics may hold the key to such an understanding of “building plans” inherent to entire classes of material.

Approach

Based on various physical-chemical and mechanical experiments, our focus is the development of multi-scale mechanical models. These models mathematically and computationally quantify how basic building blocks of biological materials (such as hydroxyapatite minerals, collagen, and water in all bones found throughout the vertebrate kingdom) govern the materials’ mechanical properties at different length scales, from a few nanometers to macroscopic scales. Thereby, multi-scale homogenization theory allows us, at each scale, to identify material representations that are as simple as possible; but as complex as necessary for reliable computational predictions of key material properties, such as poro-elasticity, creep, and strength. This can be seen as “reverse” biomimetics engineering: (civil) engineering methods are used to understand biological systems.

Recent Findings

One of our key findings is that bone’s mechanical properties are governed by porous polycrystals which

Core Competencies

- **Multiscale continuum micromechanics: elasticity, strength, and creep of bone, wood, concrete, and bioreplacement materials.**
- **Ultrasonic and poro-mechanical testing**
- **Applications in image-based biomedical diagnosis, implant design, and in civil engineering structures (e.g. tunnels)**



Christian Hellmich

the minerals build up as structural complement to the collagen fibrils found in all connective tissues (also in tendon, cartilage, skin). These polycrystals are not only central to the magnitude of elastic anisotropy of bone materials; but also to their tensile-to-compressive strength ratio

that results from universal failure characteristics of differently oriented submicron-sized mineral platelets. The perspective thus offered by micro-mechanics has opened, for the first time, a theoretical understanding of bone mechanics, which is consistent with all major experimental observations.

The developed tools have also driven forward our understanding of hierarchical materials with deep roots in Civil Engineering: wood and concrete. Indeed, there are interesting similarities between the failure of extrafibrillar minerals and that of cement hydration products.

Impact

Experimentally validated multi-scale models for hierarchical materials emerge as central design tools for tailoring material composition and morphology that fulfill functional requirements (e.g. minimization of failure risk). This is true for classical civil engineering problems (e.g. shotcrete tunneling); but even more so for the rapidly growing field of regenerative medicine, where biomimetic tissue engineering scaffolds are implanted for tissue regeneration. At the same time, such models open new avenues for the interpretation of state-of-the-art imaging techniques such as (Micro) Computer Tomography.

Current Research Team Members:

- Dr. Bernhard Pichler (Ph.D. 2003)
- Dr. Andreas Fritsch (Ph.D. 2009)
- Christoph Kohlhauser (Ph.D. Candidate)
- Shafi Ullah (Ph.D. Candidate)
- Fabien Perus (S.M. Candidate, on leave from Ecole Polytechnique)

Recent Graduates:

- Dr. Stefan Scheiner (Ph.D. 2009), leaving for University of Western Australia, Perth

Current Research Collaborations:

- Multiscale strength project: Prof. Luc Dormieux, Paris Tech (Ecole des Ponts), France.
- Micromechanics-driven CT data exploitation: Prof. Cornelia Kober, Hamburg University of Applied Sciences, Germany ; Prof. Franco Rustichelli, Universita Politecnica delle Marche, Ancona, Italy ; Dr. Vladimir Komlev, Russian Academy of Sciences, Moscow

Selected Publications

1. Fritsch A., Hellmich Ch., Dormieux L., and Sanahuja J., "Mechanical behavior of hydroxyapatite biomaterials: an experimentally validated micromechanical model for elasticity and strength", *J. Biomed. Mater. Res.* 88A, 149-161, 2009.
2. Hellmich Ch., Kober C., Erdmann B., "Micromechanics-based conversion of CT data into anisotropic elasticity tensors, applied to FE simulations of a human mandible", *Ann. Biomed. Eng.* 36(1), 108-122, 2008.
3. Scheiner S., Hellmich Ch., "Continuum microviscoelasticity model for aging basic creep of early-age concrete", *J. Eng. Mech.* 135(4), 307-323, 2009.
4. Scheiner S., Sinibaldi, R., Pichler, B., Komlev V., Renghini, C., Vitale-Brovarone, C., Rustichelli F., Hellmich C., "Micromechanics of bone tissue engineering scaffolds, based on resolution error-cleared computer tomography", *Biomaterials* 30, 2411-2419, 2009.

