NANOSCALE COMPRESSIVE DEFORMATION MECHANISMS AND YIELD PROPERTIES OF HYDRATED BONE EXTRACELLULAR MATRIX

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Bone features a hierarchical architecture combining antagonistic properties like toughness and strength. In order to better understand the mechanisms leading to this advantageous combination of properties, its postyield and failure behavior was analyzed on the length scale of a single lamella.
Micropillars were compressed to large strains in saline solution to measure their anisotropic yield and post-yield behavior under near-physiological conditions. An increase in strength compared to the macroscale by a factor of 1.55 was observed in line with theory for size effects in quasi-brittle materials. Furthermore, a clear influence of hydration with a reduction by 60% compared to *in vacuo* results was found. This is well in line with literature nanoindentation data and the known change in properties of the organic phase upon hydration.
Post-compression transmission electron microscopic analysis revealed anisotropic deformation mechanisms. In axial pillars, where fibrils were oriented parallel to the loading axis, bands of localized shear deformation similar to kink bands known from composite mechanics were observed. Furthermore, shear cracks emerged at the interface of ordered and disordered regions.

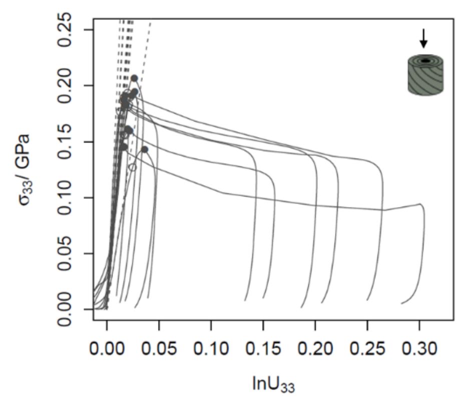

Figure 1 – Stress-strain curves of axial hydrated bone micropillars

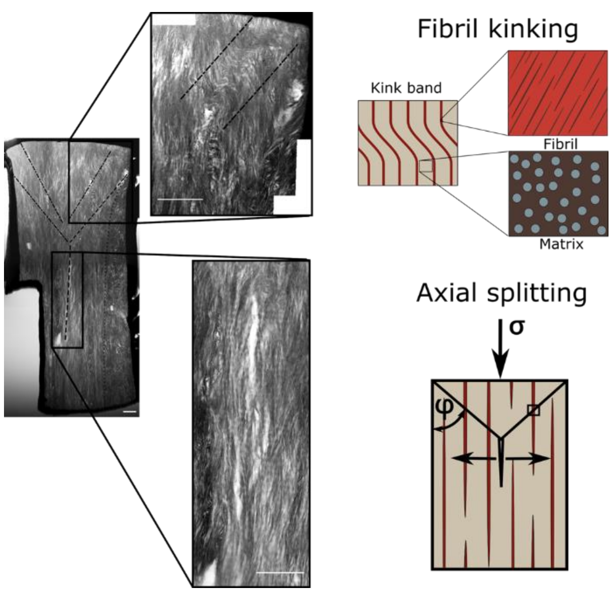

Figure 2 – Observed deformation mechanisms in axial micropillars and mechanical modeling. Scale bars represent 500nm

Micromechanical analysis of fibril kinking allowed to make an estimate of the extrafibrillar mineral matrix shear strength: 110±20 MPa. It was observed that when two opposing shear planes met a wedge was formed, splitting the micropillar axially in a mode 1 crack. Making use of an analytical solution for winglet cracks starting from oblique flaws, the mode 1 fracture toughness of bone extracellular matrix for splitting along the fibril direction was estimated to be 0.07 MPa√m. This is one to two orders of magnitude smaller than what has been measured on the macroscale, which may be rationalized by the absence of extrinsic toughening when testing small homogeneous volumes of bone with a primarily uniaxial fibril orientation. In transverse pillars, where fibrils were oriented perpendicular to the loading axis, cracks formed in regions where fibrils were primarily oriented parallel to the shear plane thereby reducing the local fracture resistance. This study underlines the importance of bone's hierarchical structure for its macroscopic strength and fracture resistance and the need to study structure-property relationships and failure mechanisms under hydrated conditions on all length scales.