TECHNISCHE UNIVERSITÄT WIEN Vienna University of Technology

COST

INSTITUTE FOR MECHANICS OF MATERIALS AND STRUCTURES — imws

Universal patterns in bone tissues: microstructure, composition, and mechanics

C. Morin[1], P. Henits[1], R. Blanchard[1], Ch. Hellmich[1]

[1]Vienna University of Technology, Institute for Mechanics of Materials and Structures

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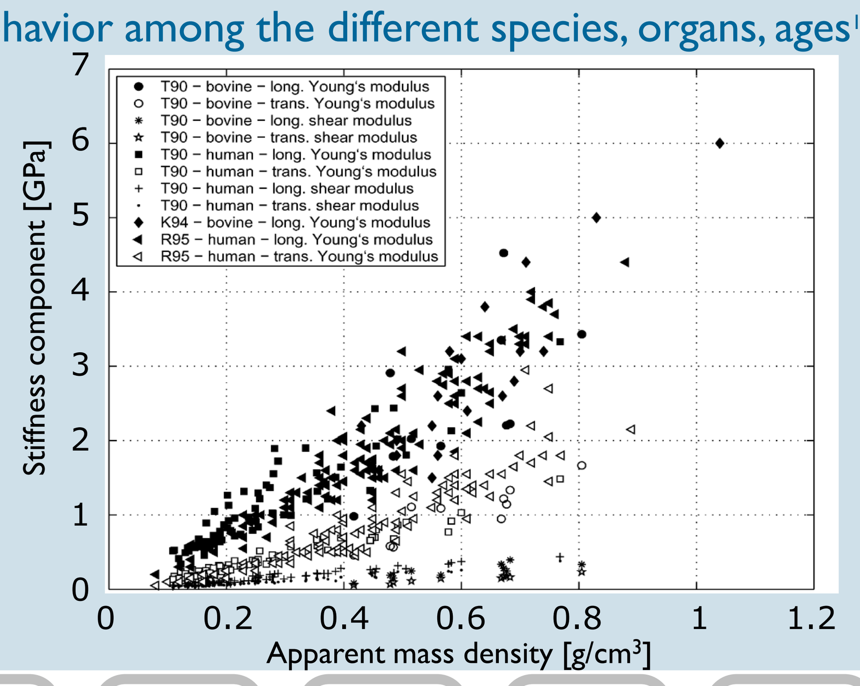
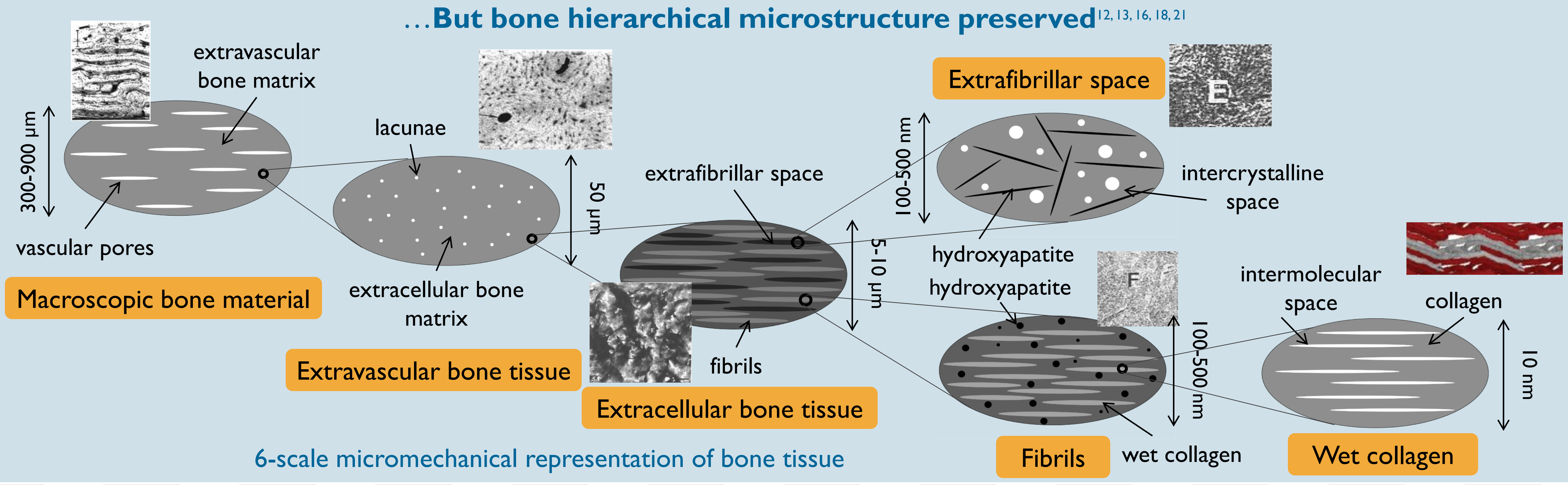
Motivation

Existence of universal patterns in bone tissues ?

Great diversity and variability of bone composition and mechanical behavior among the different species, organs, ages[16], …



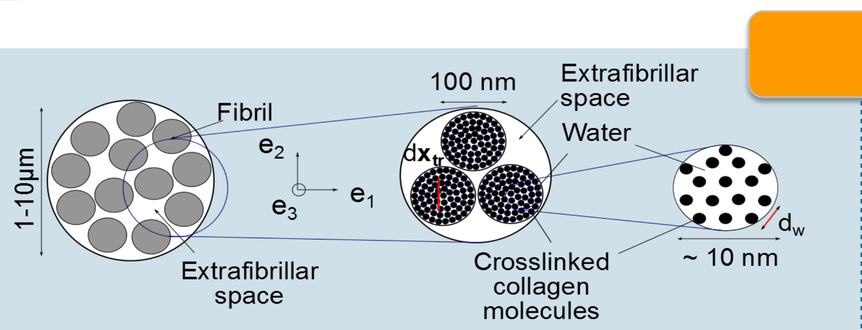
…But bone hierarchical microstructure preserved[12,13,16,18,21]



6-scale micromechanical representation of bone tissue

Structure of collagenous tissues

Proportional swelling of fibrillar and extrafibrillar spaces[39]



Upon hydration, the extrafibrillar space growth evolves proportionally to the swelling of the fibrils.

$$V_{ef} = \beta\,(V_{fib} - V_{dry})$$

As soon as the fibrils are fully hydrated, only the extrafibrillar volume continues to grow.

The swelling rule is checked through…

mass-volume relation

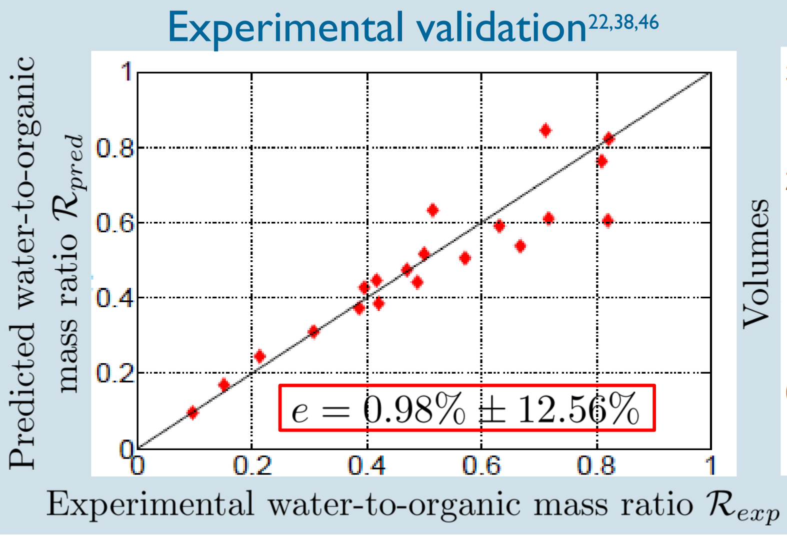
$$\frac{V_{tissue}}{V_{dry}} = 0.88\,\frac{\mathcal{R}\rho_{col} + \rho_{H_2O}}{\rho_{H_2O}}$$

X-ray diffraction & continuum mechanics

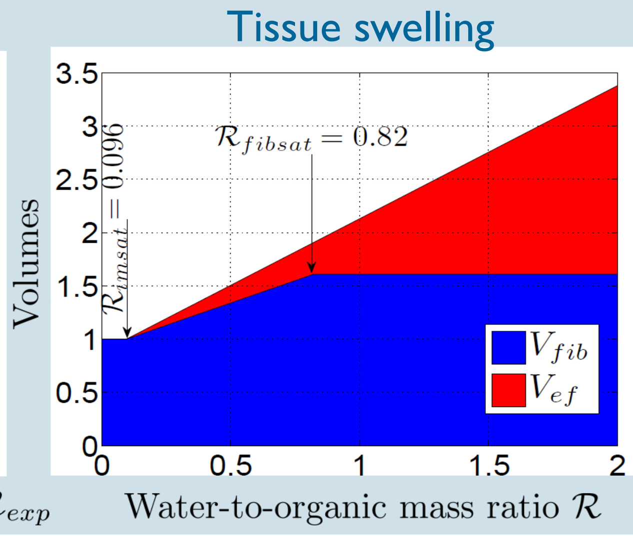
$$\frac{V_{fib}}{V_{dry}} = \left(\frac{d_w}{d_{dry}}\right)^2$$

$$\frac{V_{tissue}}{V_{dry}} = \beta\left(\frac{V_{fib}}{V_{dry}} - 1\right) + \frac{V_{fib}}{V_{dry}}$$

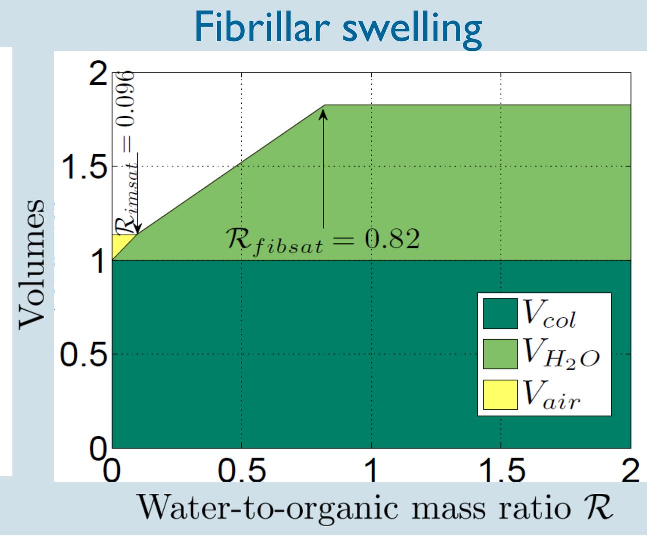
Experimental validation[22,38,46]



Tissue swelling

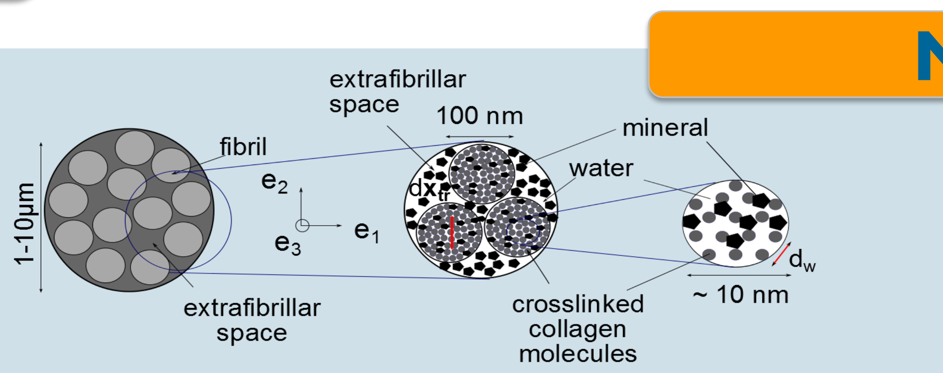


Fibrillar swelling



Mineralization of collagenous tissues

Mineralization occurs in closed thermodynamic systems[40]



Mineralizing bone tissue acts as a closed thermodynamic system, where crystals precipitate from an ionic solution:

$$\dot{m}^{fib}_{fl} = -\dot{m}^{fib}_{HA} \text{ and } \dot{m}^{ef}_{fl} = -\dot{m}^{ef}_{HA}$$

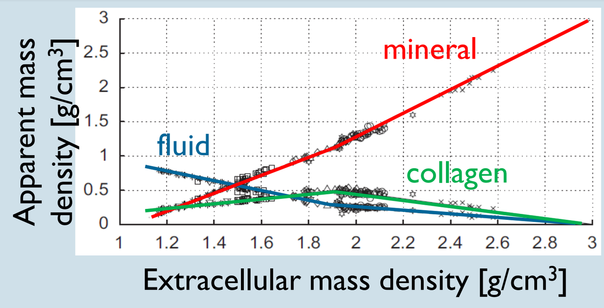
while the fibrillar and extrafibrillar masses are preserved:

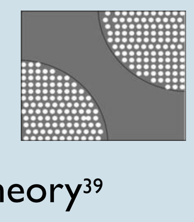
$$m^0_{fib} = m^t_{fib} = m^\infty_{fib} \text{ and } m^0_{ef} = m^t_{ef} = m^\infty_{ef}$$

Translation of mass conservation to mass density-diffraction spacing relation by means of:

1. Bilinear laws for the composition of mineralized tissues[1,3,14,15,26,27,31,34,48]
2. Uniform extracollagenous mineral concentration[19]
3. Continuum deformation theory[39]

$$\frac{V^\infty_{fib}}{V^0_{fib}} = \left(\frac{d^\infty_w}{d^0_w}\right)^2$$

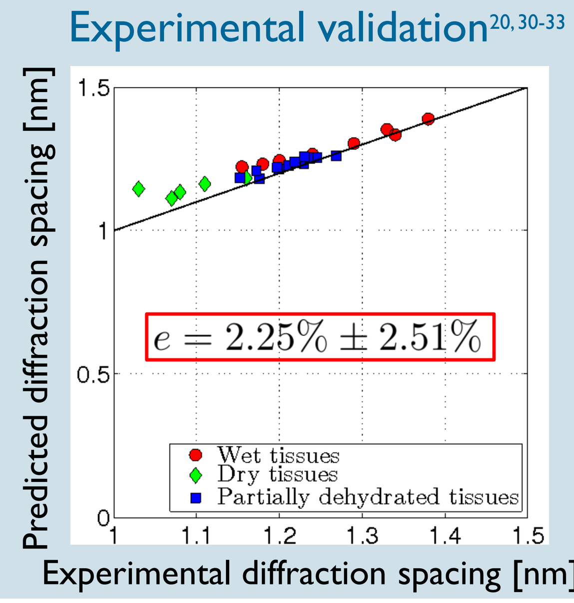




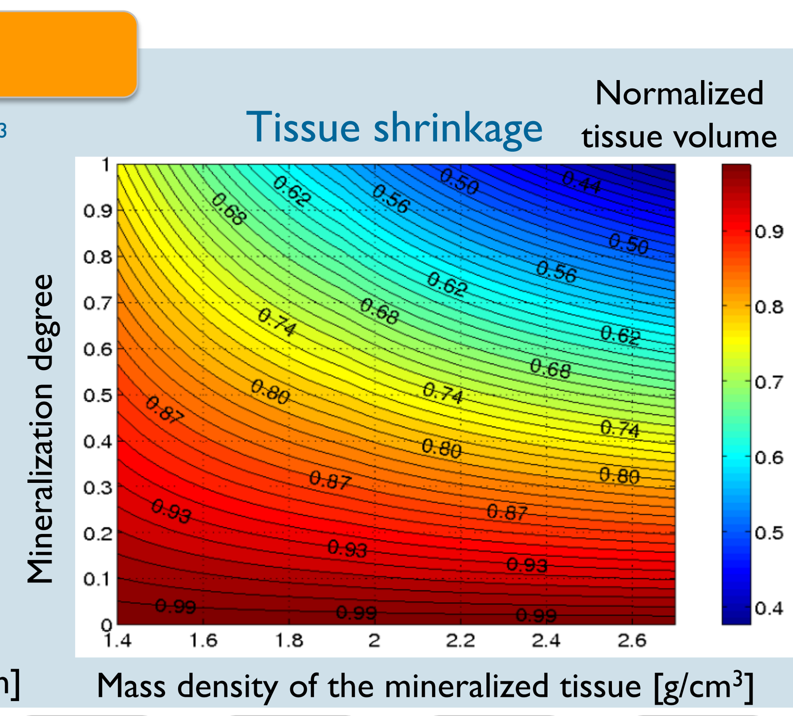
Check through the prediction of the diffraction spacing:

$$d^\infty_w = d^0_w \sqrt{\frac{1 - f^0_{ef}\left[1 - \left(\frac{\rho_{HA}}{\rho_{fl}} - 1\right) f^\infty_{HA} \frac{f_{col}}{\rho_{HA} f^\infty_{HA}/\rho_{fl} + f^\infty_{fl}}\right]}{\left(1 - f^0_{ef}\right)\left[1 + \left(\rho_{HA}/\rho_{fl} - 1\right) f^\infty_{HA}\right]}}$$

Experimental validation[20,30-33]



Tissue shrinkage

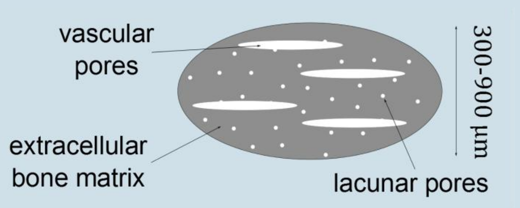


Multiscale mechanical behavior of bone

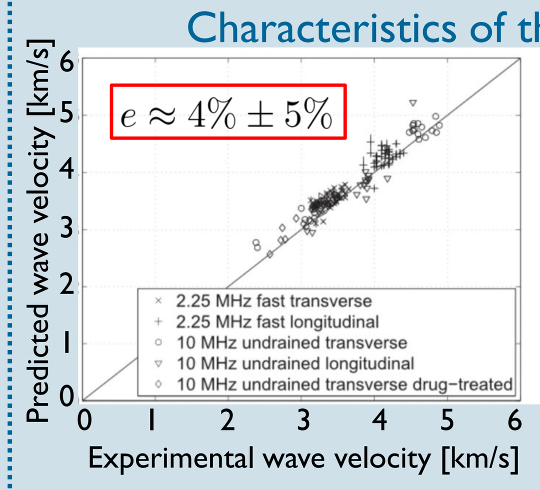
Wave propagation in bone tissues[17,20,41]

The characteristics of the longitudinal waves traveling in bone tissues are predicted by means of a poro-micro-mechanical approach[17,20,48].

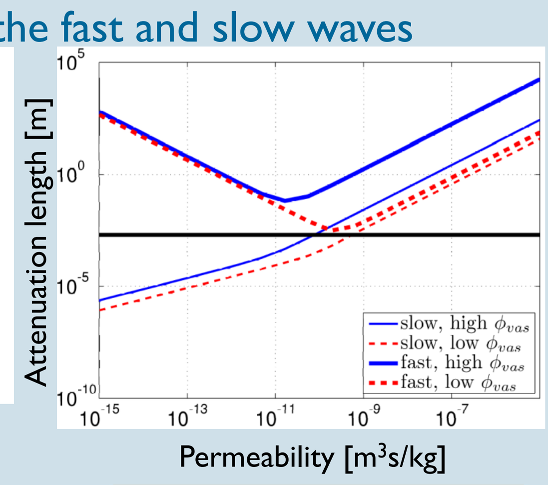
The micromechanical representation of the macroscopic bone tissue comprises two pore spaces (the *vascular pores*, allowing fluid flow and undrained *lacunar pores*), embedded in the *extracellular bone matrix*.



Characteristics of the fast and slow waves



Experimental validation[25,28-32,36]



Only fast waves transmit low-porosity bone tissue

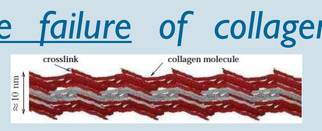
Strength of bone tissues[11,42]

Bone failure can be explained by

- *mutual ductile sliding of mineral crystals along layered-water films*, modeled by an elastic-perfectly plastic law for hydrated mineral crystals

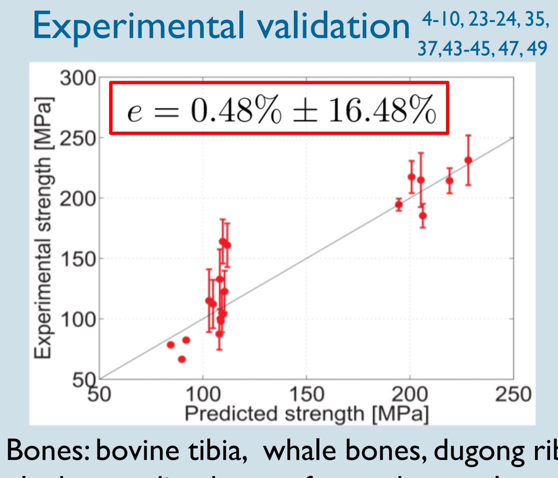
$$\mathcal{F}(\boldsymbol{\sigma}) = k \max_i \sigma^i_{\theta,\phi} - \min_i \sigma^i_{\theta,\phi} - \sigma^{ult}_{HA} \leq 0$$

- *followed by brittle failure of collagen crosslinks*

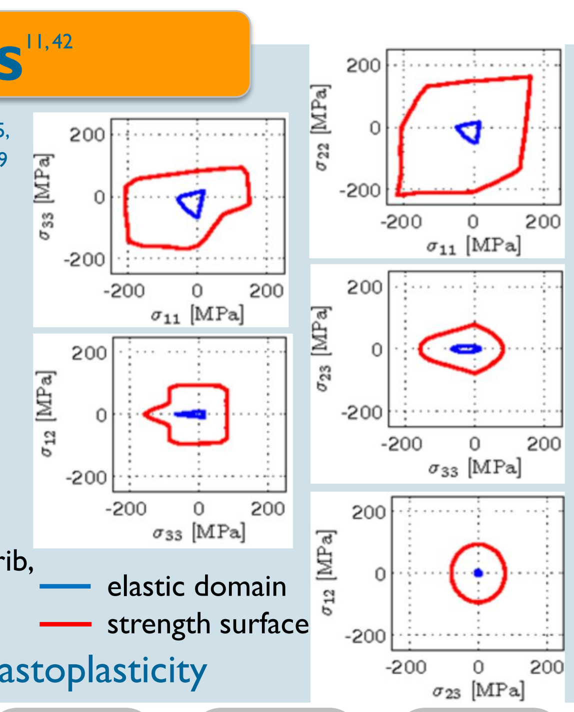


$$\mathcal{F}_{col}(\boldsymbol{\sigma}_{col}) = |\max_i \sigma_{col,i}| - \sigma^{ult}_{col} \leq 0$$

Experimental validation[4-10,23-24,35,37,43-45,47,49]



Bones: bovine tibia, whale bones, dugong rib, elephant radius, human femur, deer antler

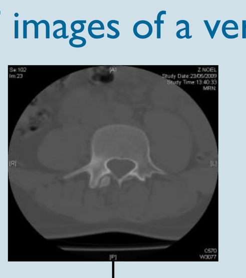


Multiscale, multisurface elastoplasticity

Conclusion

Failure-risk analysis of a vertebra

CT images of a vertebra

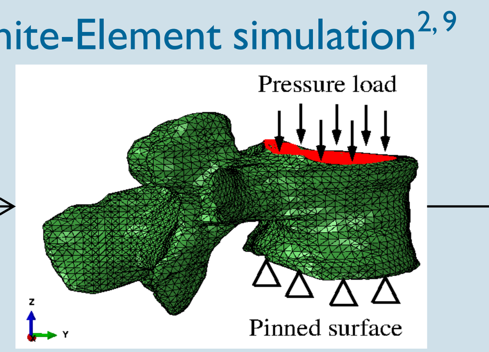


Micromechanical model

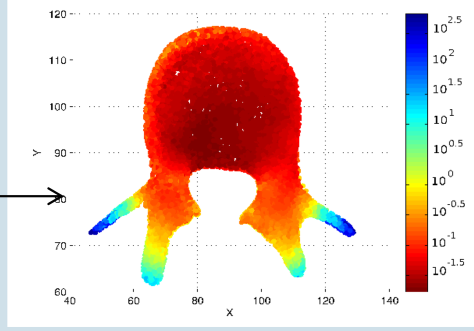
Elastic properties

Point-dependent vascular porosity

Finite-Element simulation[2,9]



Post-treatment: distance to the yield surface



Nomenclature and references

Nomenclature

d	equatorial diffraction spacing
f	volume fraction
$\mathcal{F}$	yield function
k	parameter of the Mohr-Coulomb criterion
m	mass
$\mathcal{R}$	water-to-organic mass ratio
V	volume
β	proportionality constant
ρ	mass density
$\boldsymbol{\sigma}$	stress field
σ^i	i-th principal stress
σ^{ult}	ultimate stress
Superscripts	
ef	in the extrafibrillar space
fib	in the fibrillar space
∞	at the end of the mineralization process
0	before the start of the mineralization process
Indices	
air	of air
col	of collagen
dry	in dried tissues
ef	of extrafibrillar space
fib	of fibrillar space
$fibsat$	at fibrillar saturation point
fl, H_2O	of fluid
HA	of hydroxyapatite
$imsat$	at intermolecular pore saturation point
$tissue$	of collagenous tissue
w	in wet tissues
θ,ϕ	orientation angles of the hydroxyapatite needle in a spherical coordinate system

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