RIKEN Symposium on Computational Biomechanics, Wako, Saitama, July 31- August 1, 2002

Computational biomechanics for trabecular surface remodeling

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***Kobe University, Kobe, Japan**

Functional adaptation of bone by remodeling

Mech. environment

↓

Bone structure

Mech. stimulus

↓

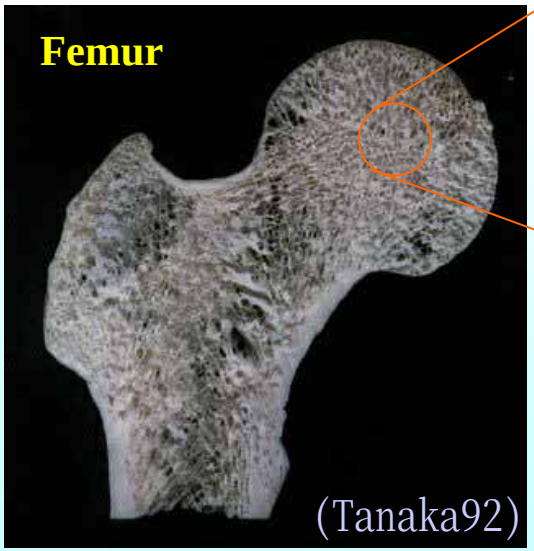
Cellular activities

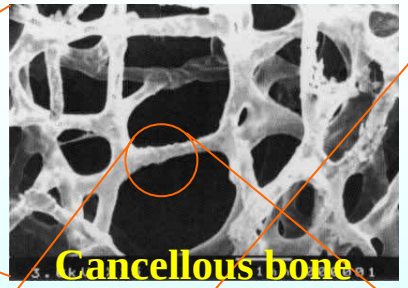
↓

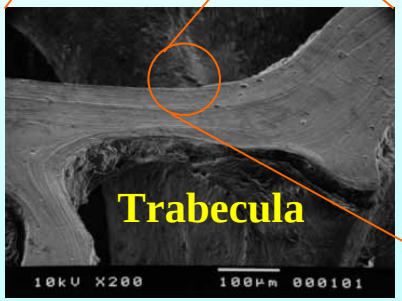
Bone form./reso.

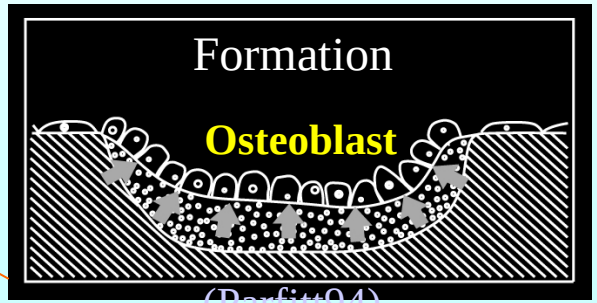
↓

Structural change



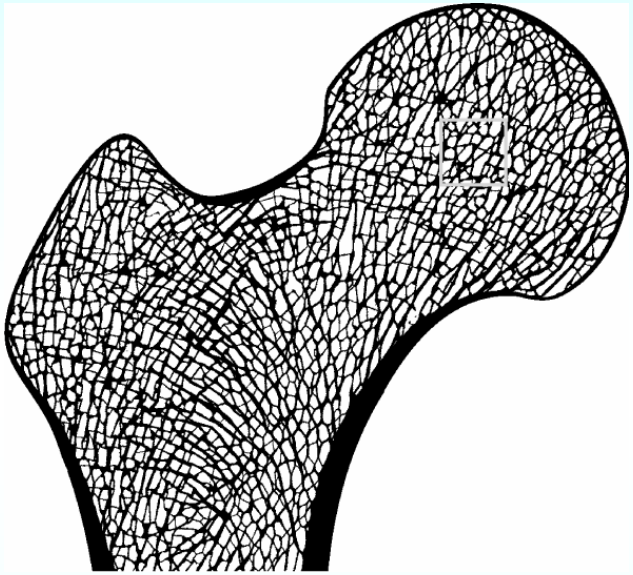






(Parfitt94)

Remodeling simulatoin for trabecular surface remodeling

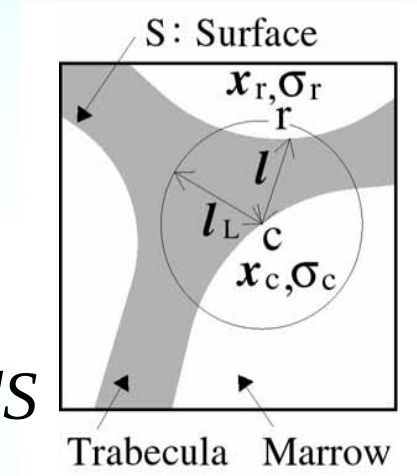


Stress nonuniformity

$$\Gamma = \ln(\sigma_c / \sigma_d)$$

Representative stress

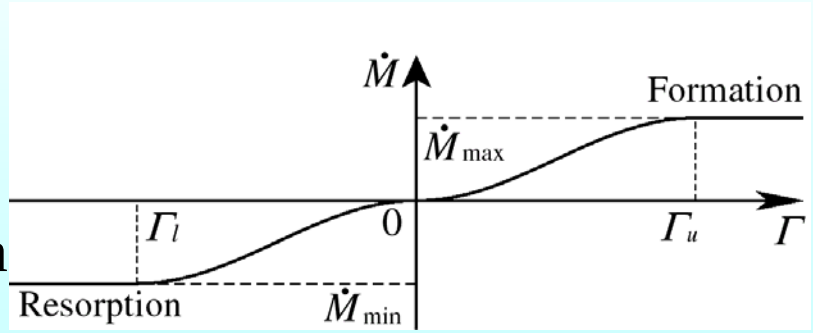
$$\sigma_d = \int_S w(l)\sigma_r dS \Big/ \int_S w(l) dS$$



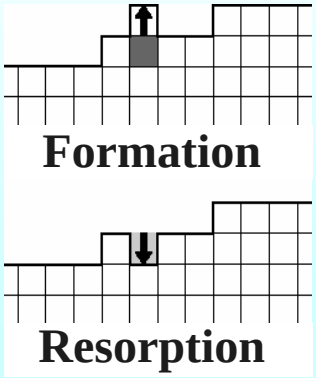
Rate equation

$$\dot{M} = F(\Gamma)$$

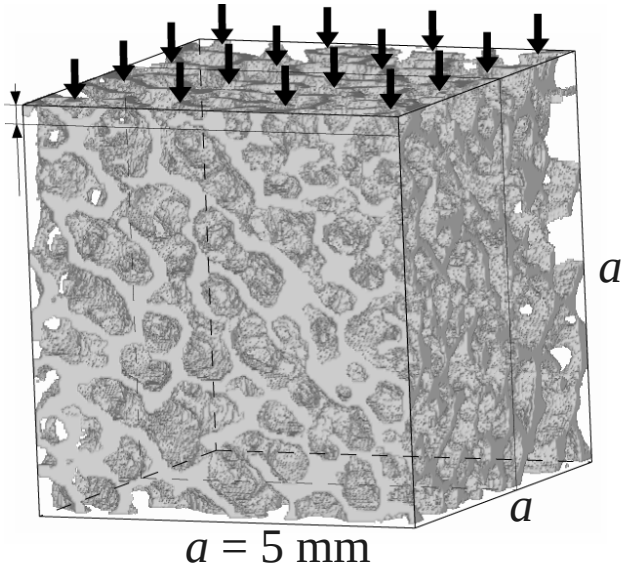
$$= \begin{cases} \Gamma > 0 : \text{Formation} \\ \Gamma < 0 : \text{Resorption} \end{cases}$$



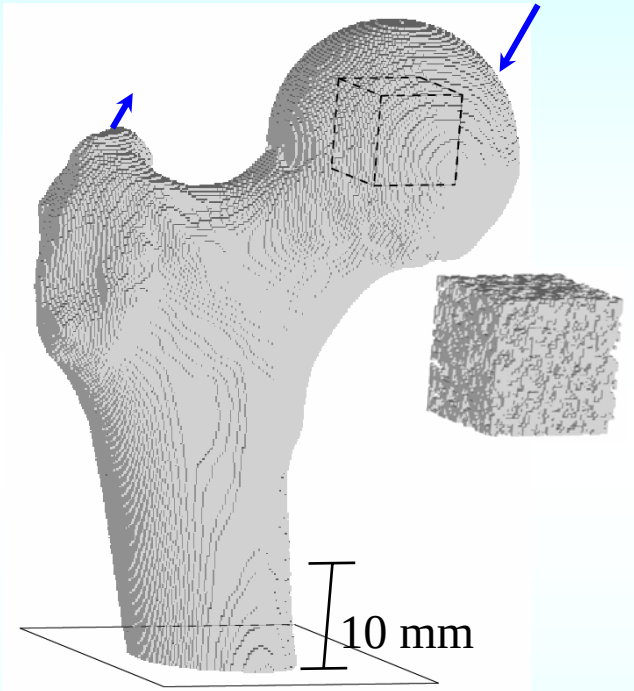
Pixel-based FEM model



Three-dimensional simulation by using image-based voxel model

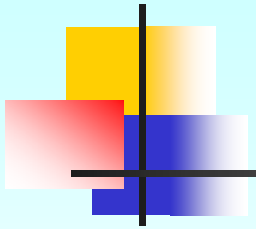


Cancellous bone cube in canine distal femur constructed from X-ray micro CT data (Bone data from ORL, U-M)**.**



Human proximal femur constructed from CT data (Bone data from Labeled visible human female CD Ver. 1.1, Research systems inc.)**.**

toward understanding of bone remodeling phenomena



Today's talk

- Application of the trabecular surface remodeling simulation using voxel-based finite element model

- Evaluation and design of a bone implant

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Trabecular remodeling simulation of a vertebral body with a fixation screw using voxel finite element models

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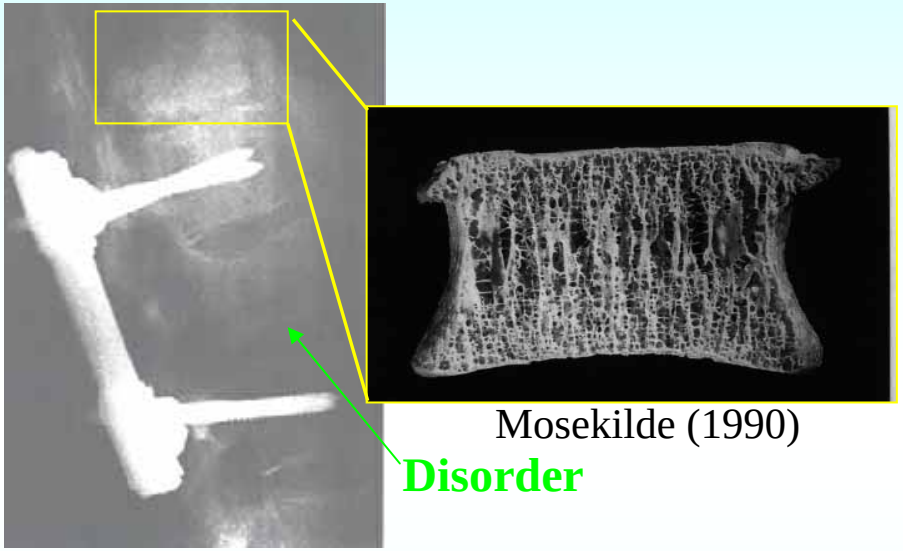
Introduction

- **Spinal reconstruction**
  for Neoplasm, Fracture, ...

- **Fixation Screw**
  - Infection
  - Fatigue fracture (Bone, Screw)
  - Loosening Order of month-year



Mosekilde (1990)

Meyer & Cotler (1991)

- **Time-course change in bone structure by remodeling**

(1) Changes in mechanical environment of bone

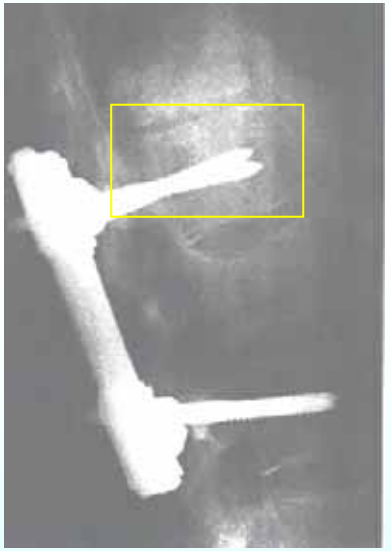
(2) Adaptive bone remodeling

(3) Changes of bone morphology

↳ **Important for proper fixation**

Introduction (cont.)

- Trabecular structural changes around fixation screw in vertebral body

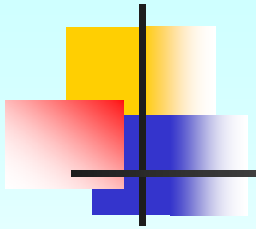


Meyer & Cotler (1991)

- Difficulty in
  1. Observing structural change *in vivo*
  2. Simulating the structural changes

Purpose

- Effects of a fixation screw on the three-dimensional trabecular structural change in a vertebral body



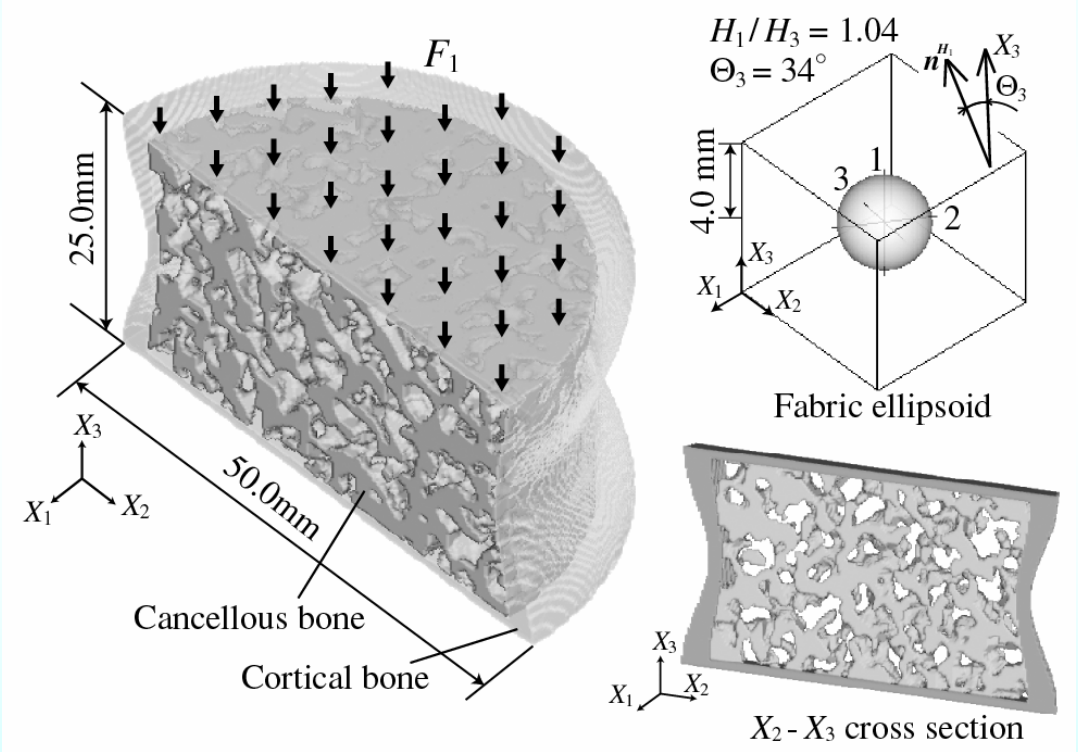
Methods

- Voxel-based finite element models of trabecular surface remodeling

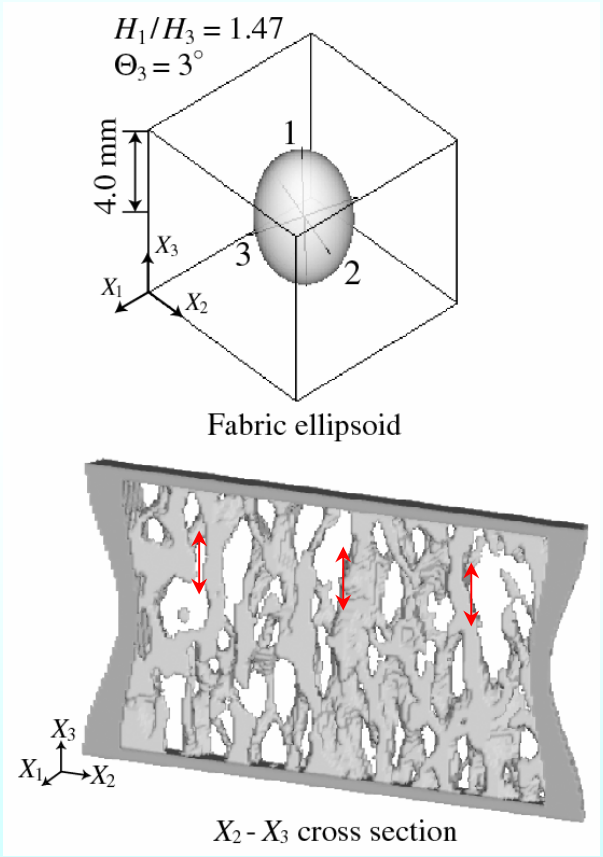
- Two structural scales:
  (1) Entire vertebral body
  (2) Bone-screw interface

Trabecular remodeling simulation for entire vertebral body (normal case)

- Voxel model for normal vertebral body

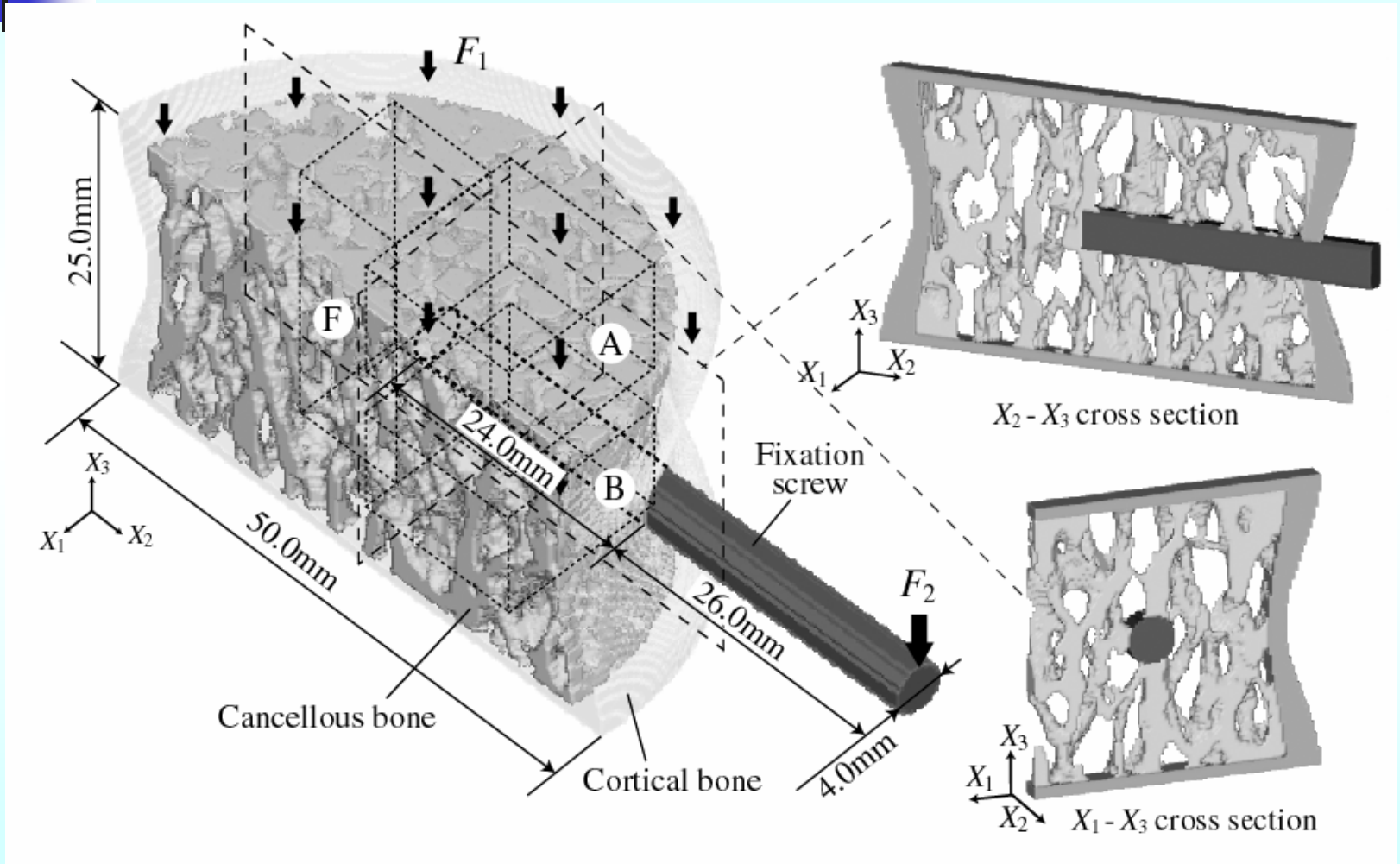


- Simulation result



- Voxel size: 250 μm
- Model parameter: $l_L = 2.5\,\mathrm{mm}$, $\Gamma_l = -1.25$, $\Gamma_u = 1.0$
- Isotropic elastic material: E = 20 GPa, ν = 0.3

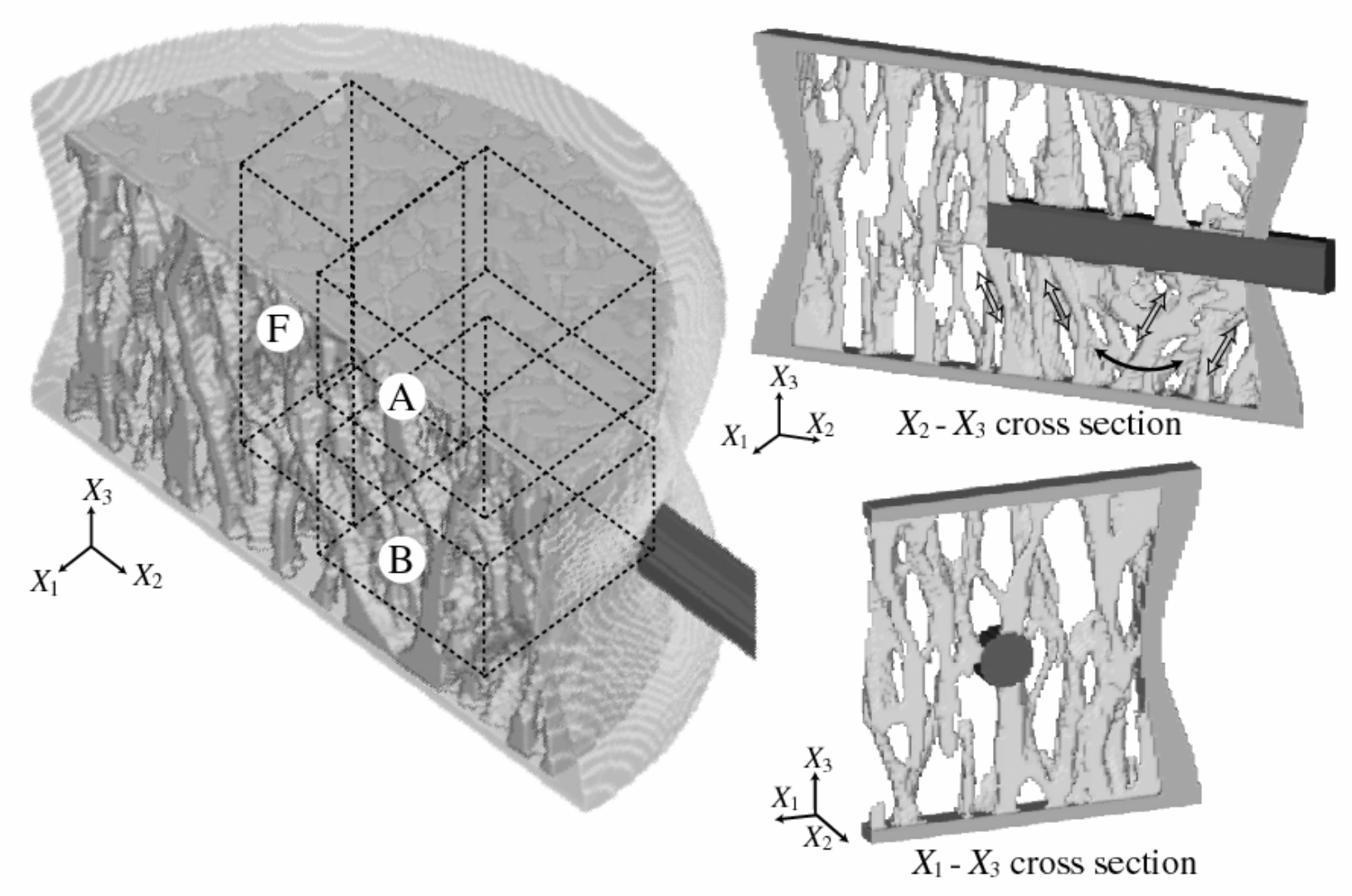
Voxel model of a vertebral body with a fixation screw



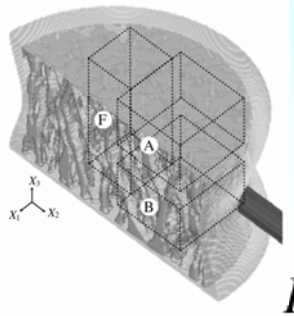
* Isotropic elastic material:

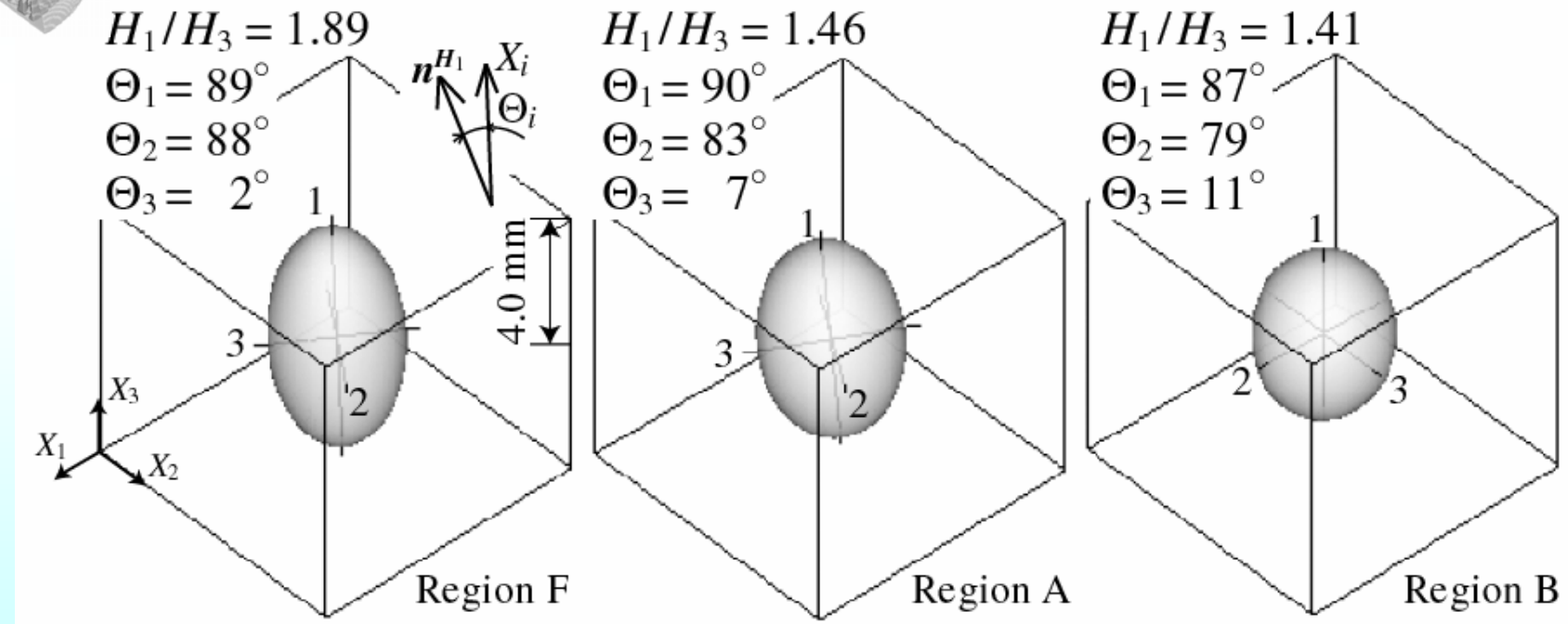
Bone (E_b = 20 GPa, ν_b = 0.3), Screw(E_s = 200 GPa, ν_s = 0.29)

Trabecular structural changes around the fixation screw

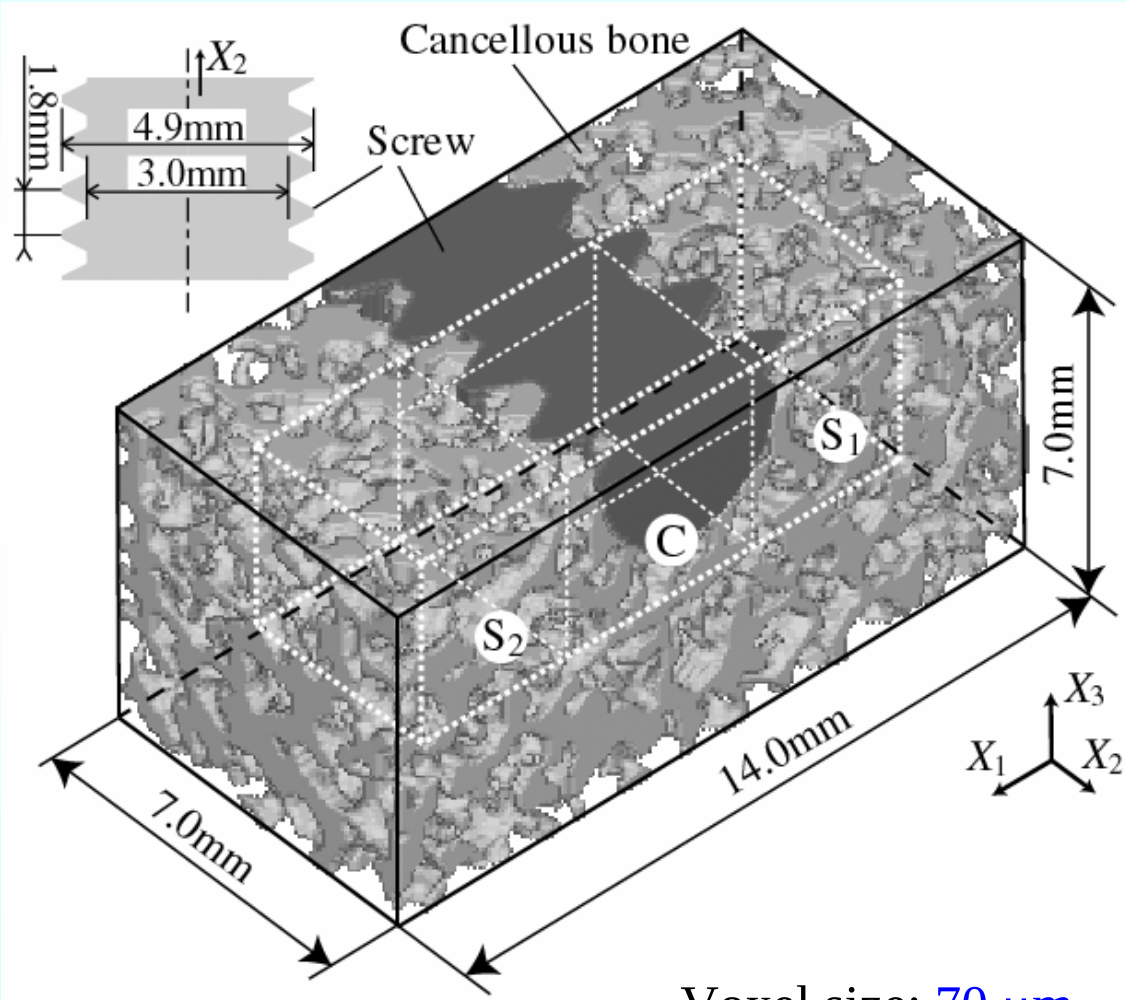


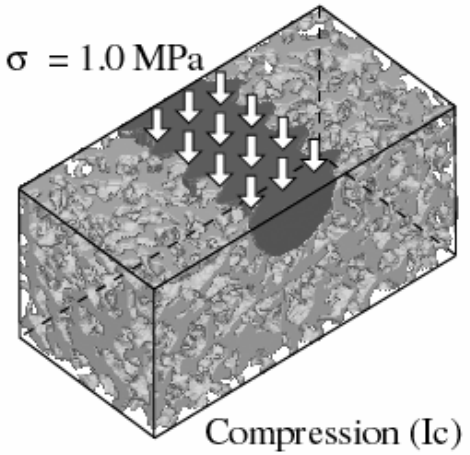
Fabric ellipsoid in each region

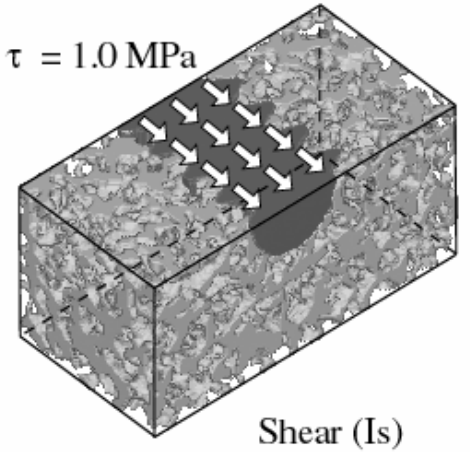




Trabecular remodeling simulation for bone-screw interface

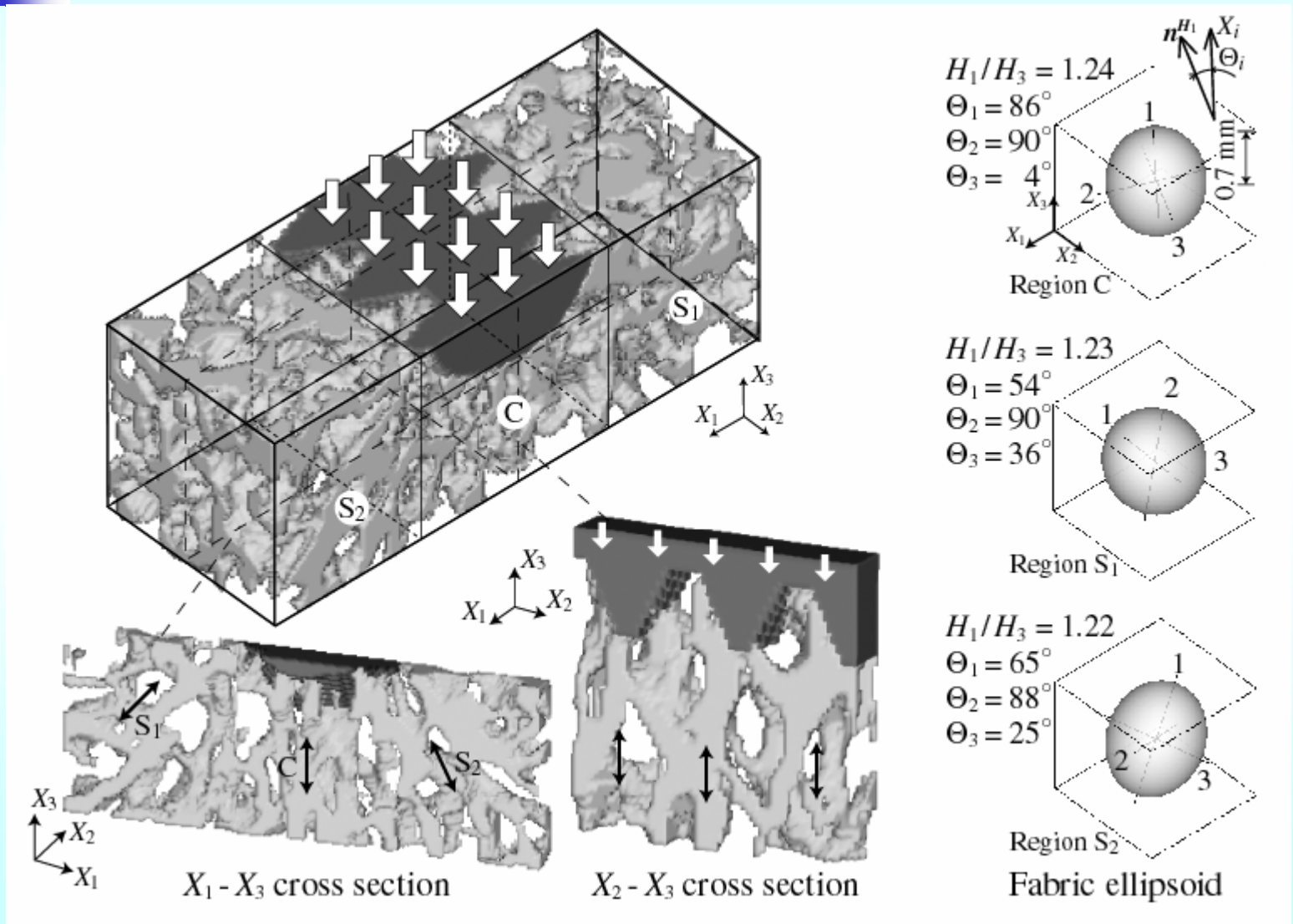




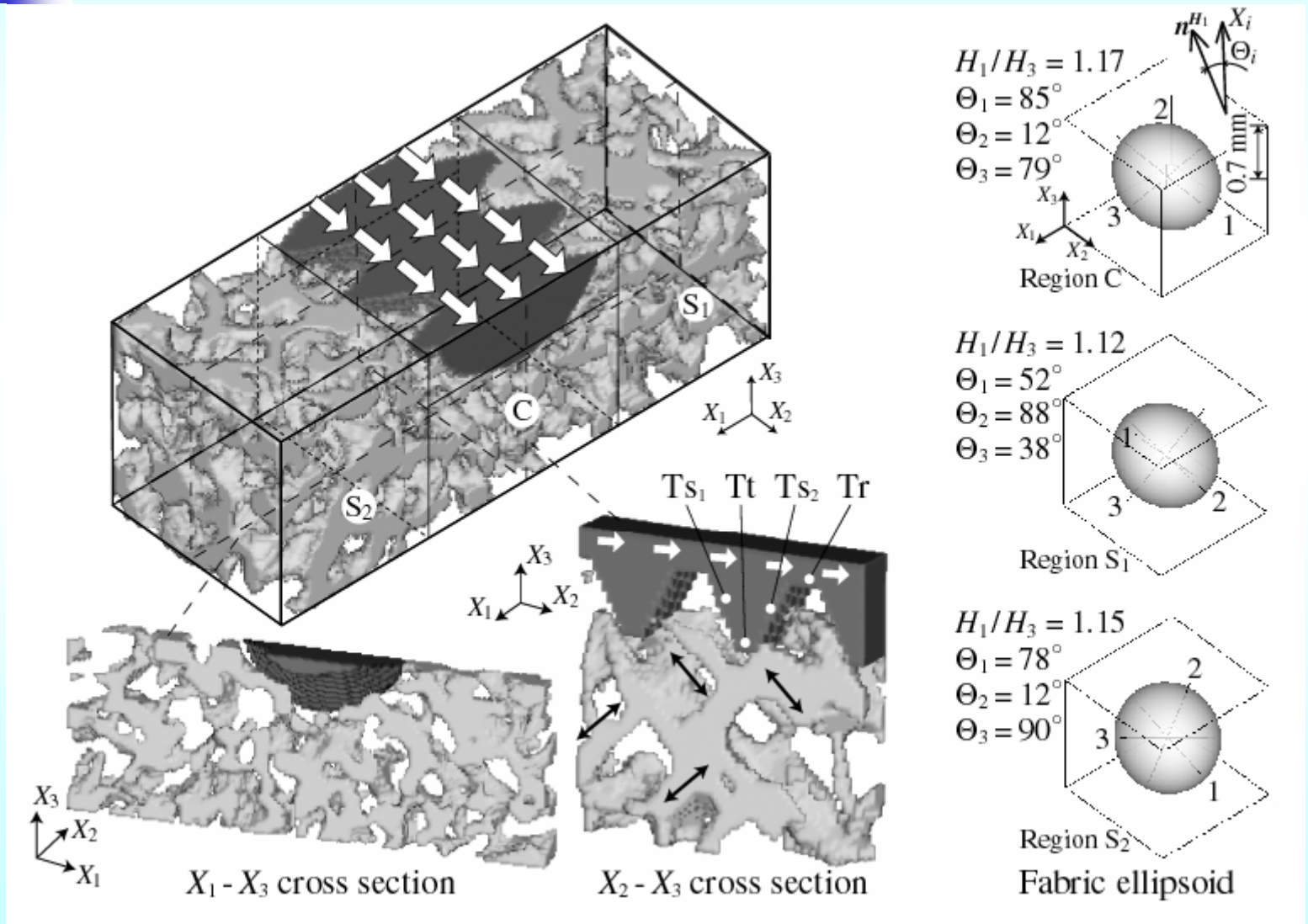


- Voxel size: 70 μm
- Model parameter: $l_L = 700\,\mu\text{m}$, $\Gamma_l = -1.88$, $\Gamma_u = 1.5$

Trabecular structural changes for compressive loading case (Ic)

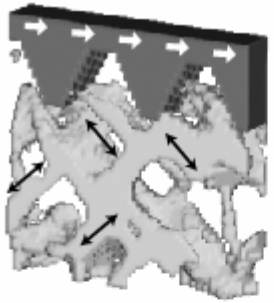


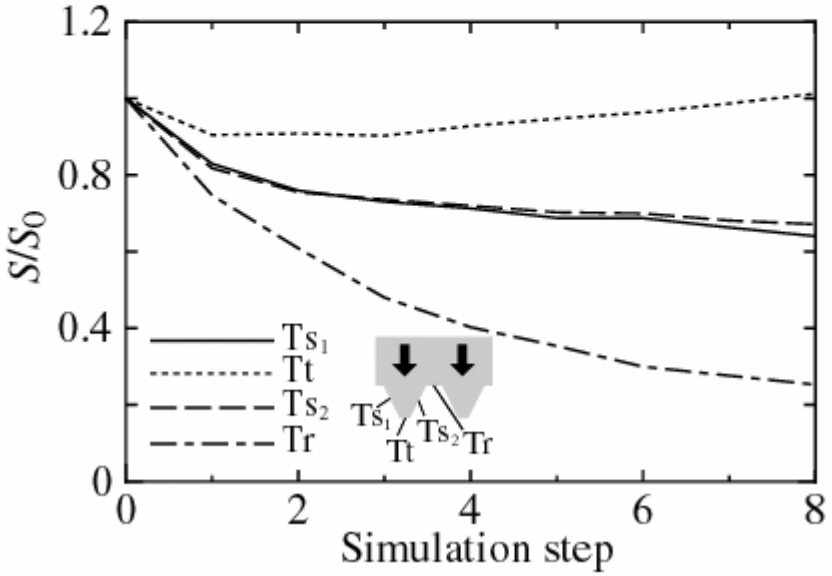
Trabecular structural changes for shear loading case (Is)



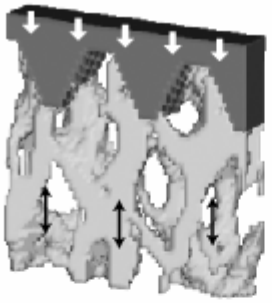
Changes in contact area between bone and screw threads

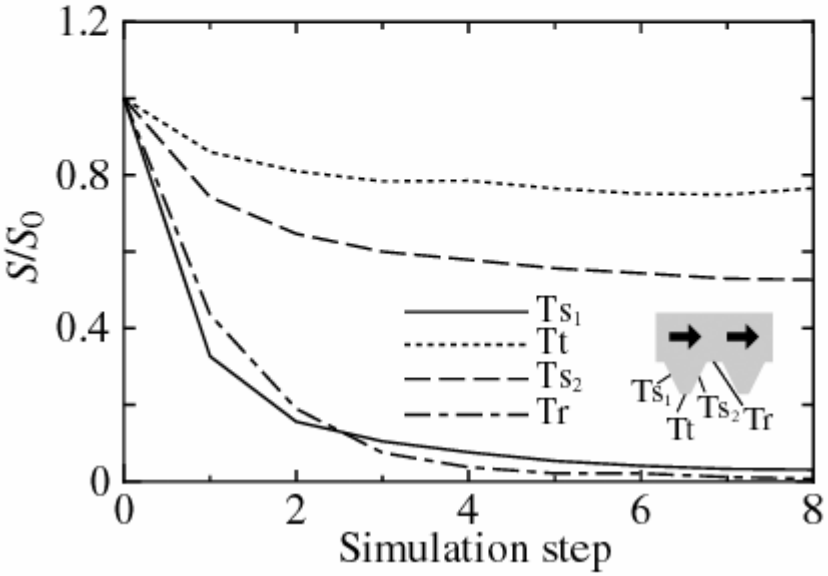
- Compressive loading

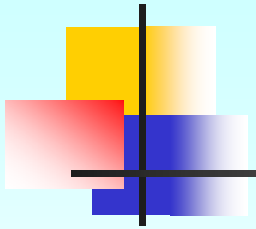




- Shear loading





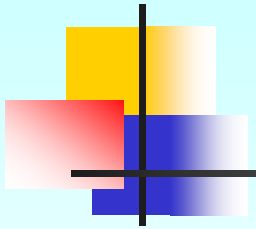


Conclusions

- Trabecular surface remodeling simulation for a vertebral body with a fixation screw using voxel-based finite element models

- Effects of the fixation screw on the trabecular structural changes in entire cancellous region of the vertebral body

- Trabecular structural changes depending on the loads applied to the screw



Future works

- Comparison to experimental observation

- 3D digital image-based model

- Application to shape design of screw

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Femoral stem shape design of artificial hip joint using a voxel based finite element method

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*** Computer and Information Division, The Institute of Physical and Chemical Research (RIKEN), Wako, Japan**

Introduction

Femoral Stem (Total Hip Arthroplasty)

- **Cement**
- **Cementless type**

For long-term fixation of stem

→ **Stress at bone-stem interface** plays a key role in

Loosening (mechanically & biologically)

- **Stress shielding**
- **Stress concentration**
- **Remodeling**
- **Fracture, *etc*….**

→ **Uniform stress at bone-stem interface**

Purpose

Application of

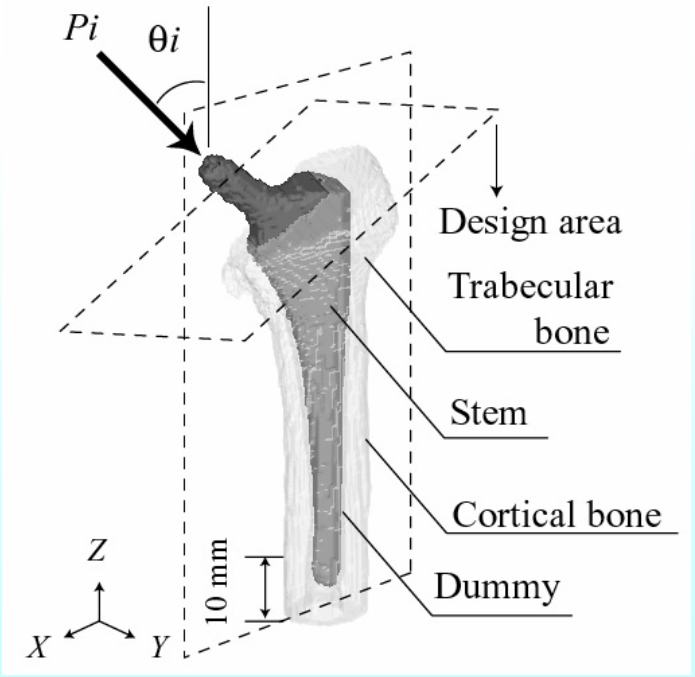
trabecular surface remodeling simulation method

to shape design of femoral stem

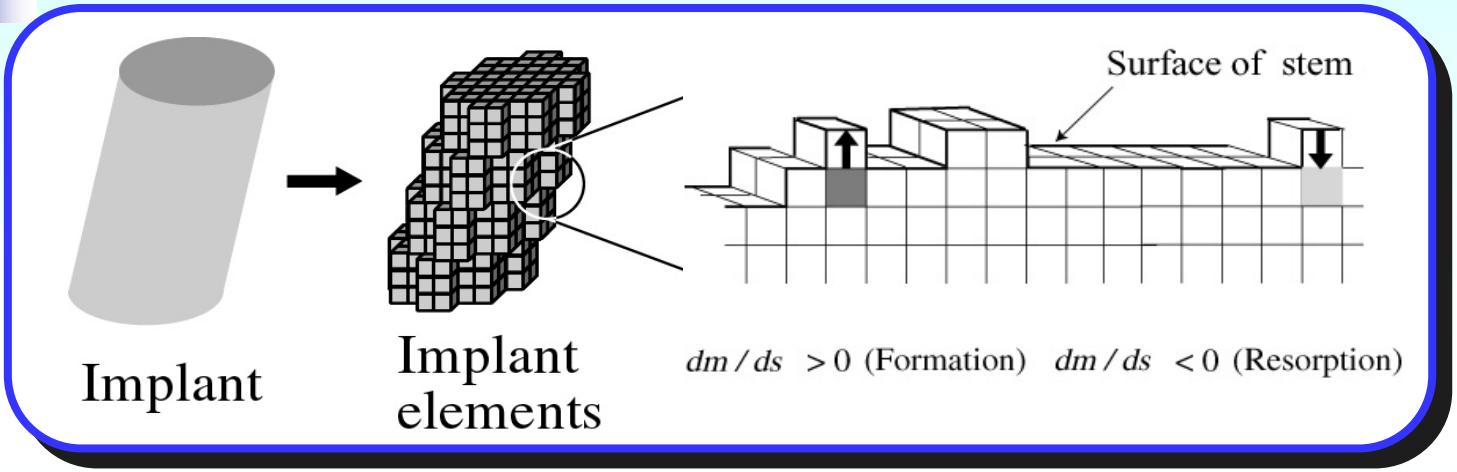
based on stress uniformity at bone-stem interface

Investigate the effects of

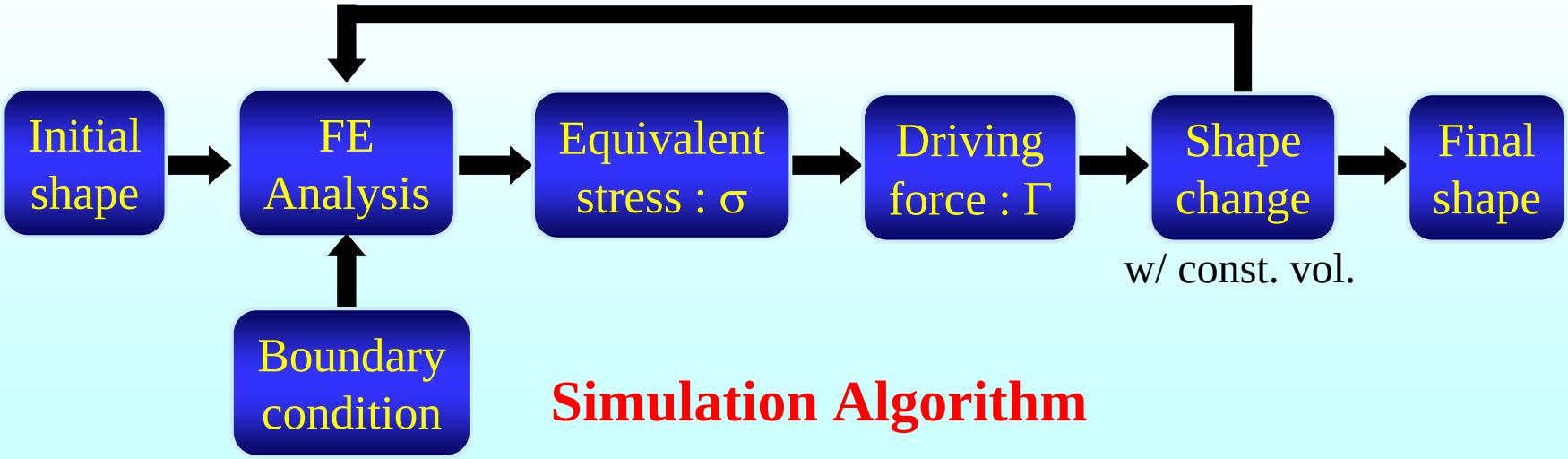
- Loading condition
- Bone shape
- Initial stem shape
- Design region
- Condition at bone-stem interface
- …..



Method

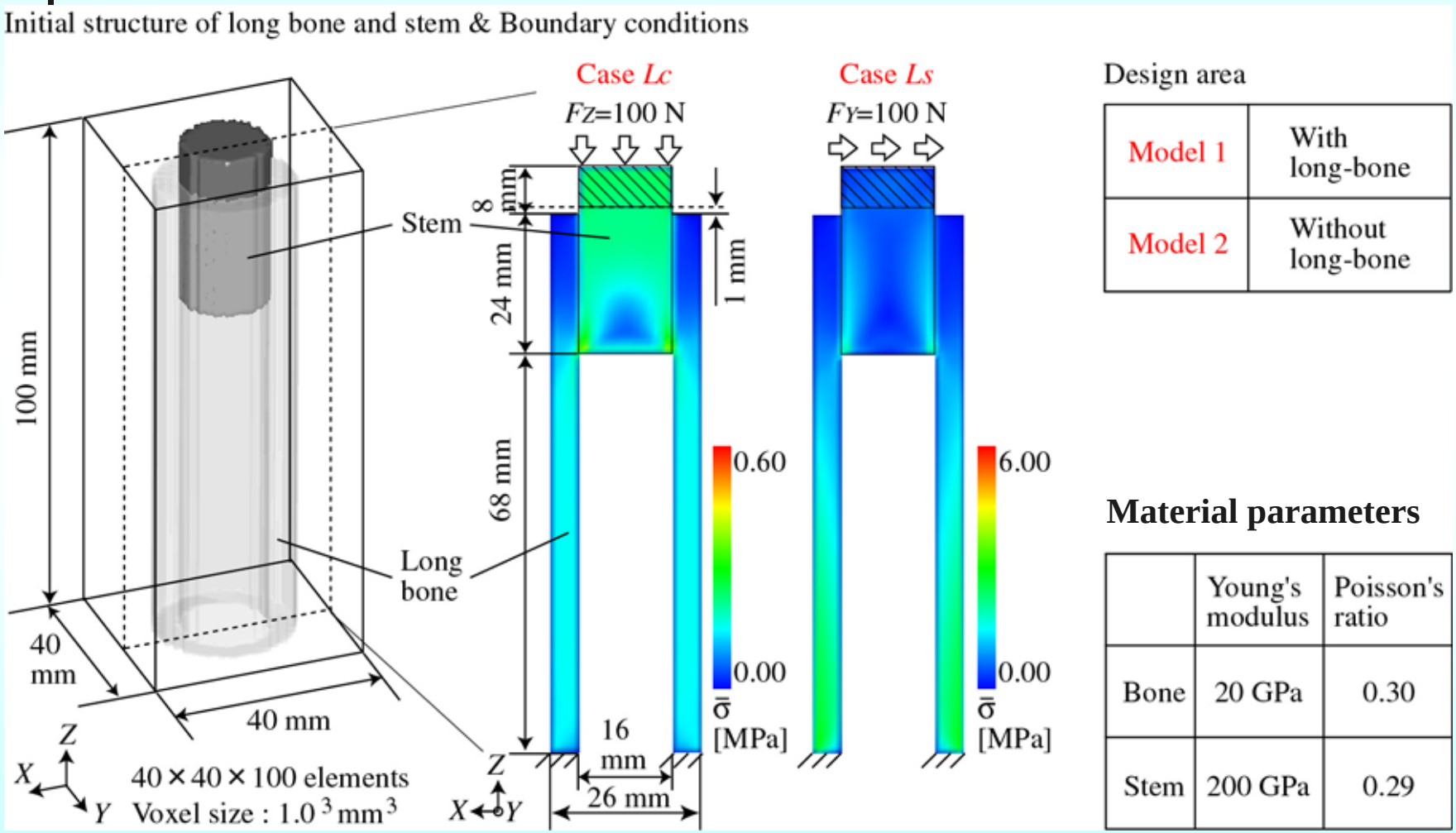


Modeling by Voxel Finite Elements



Simulation Algorithm

Simple model study



Design area

Model 1	With long-bone
Model 2	Without long-bone

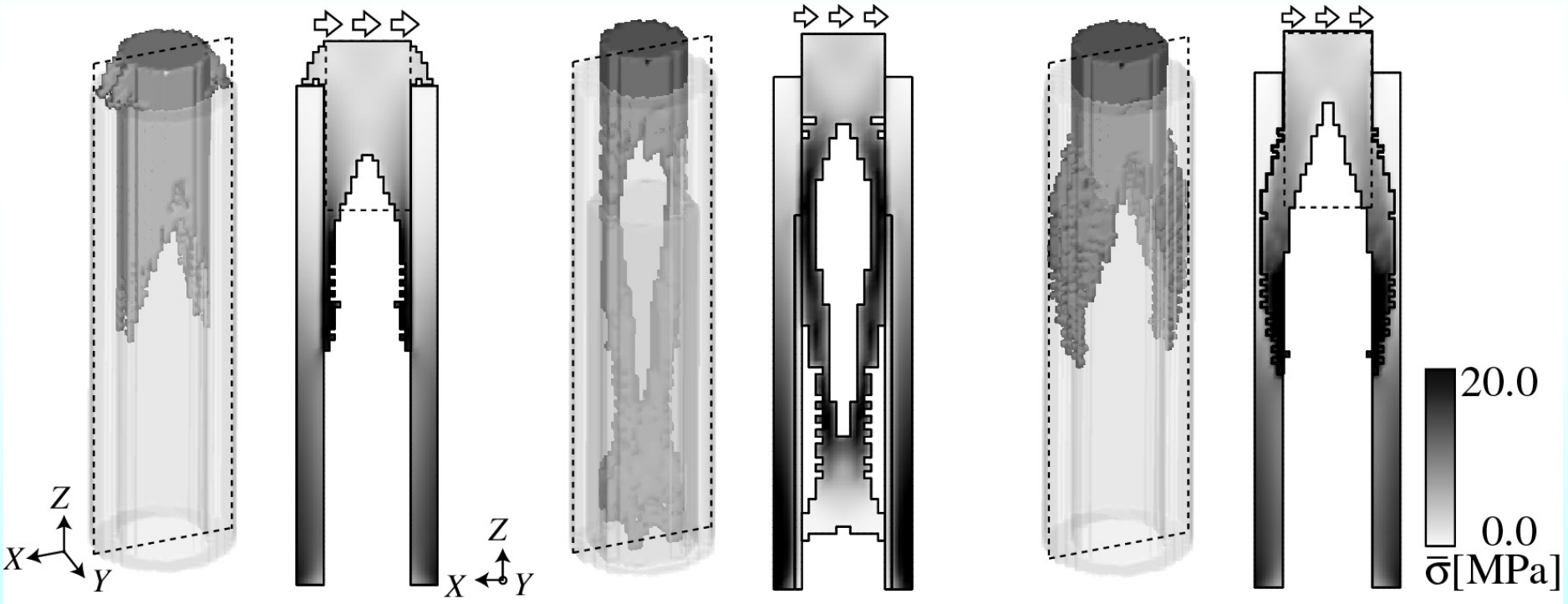
Material parameters

	Young's modulus	Poisson's ratio
Bone	20 GPa	0.30
Stem	200 GPa	0.29

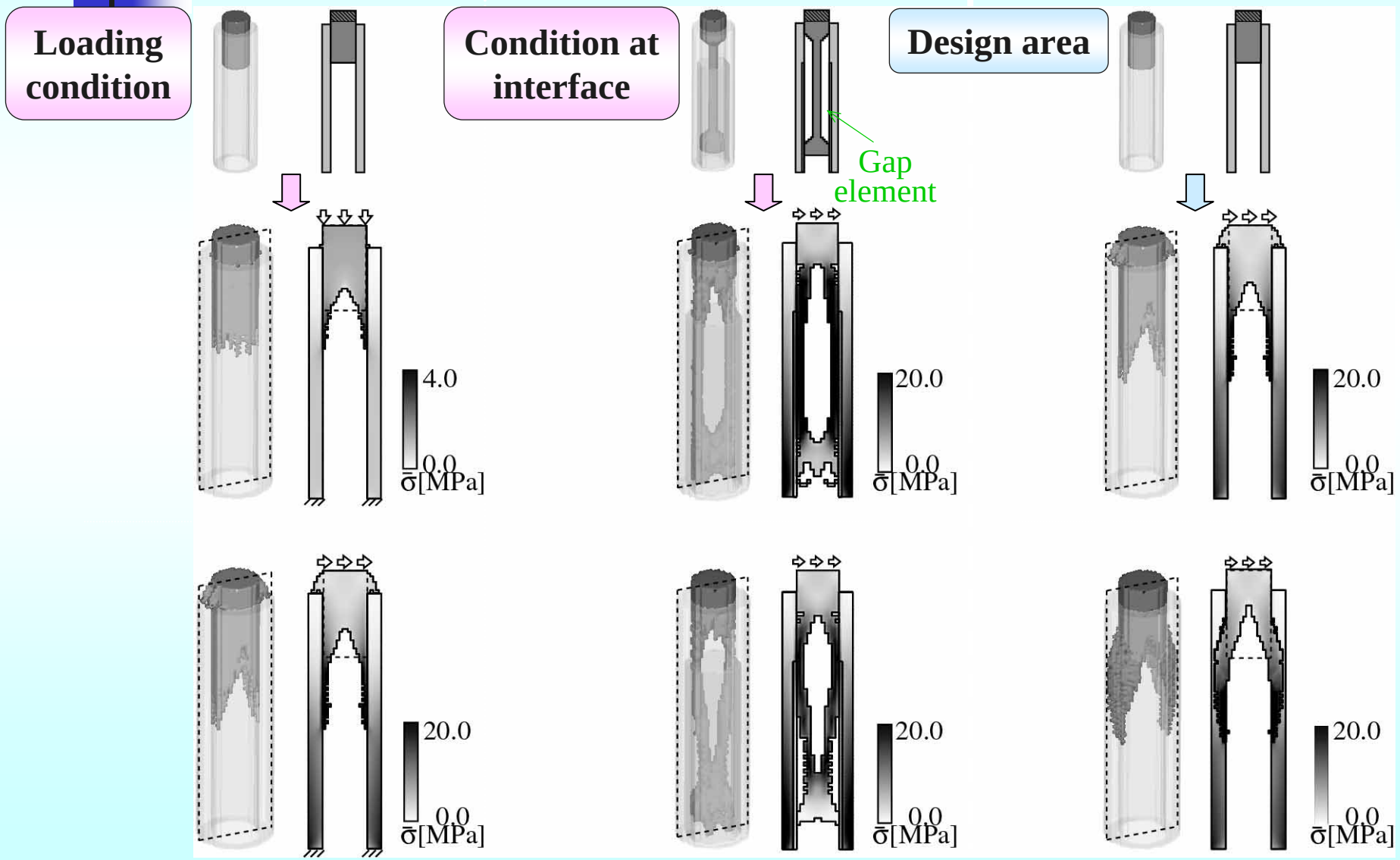
Computational model of long bone and stem

Effect of …

Loading condition	Condition at interface	Design region



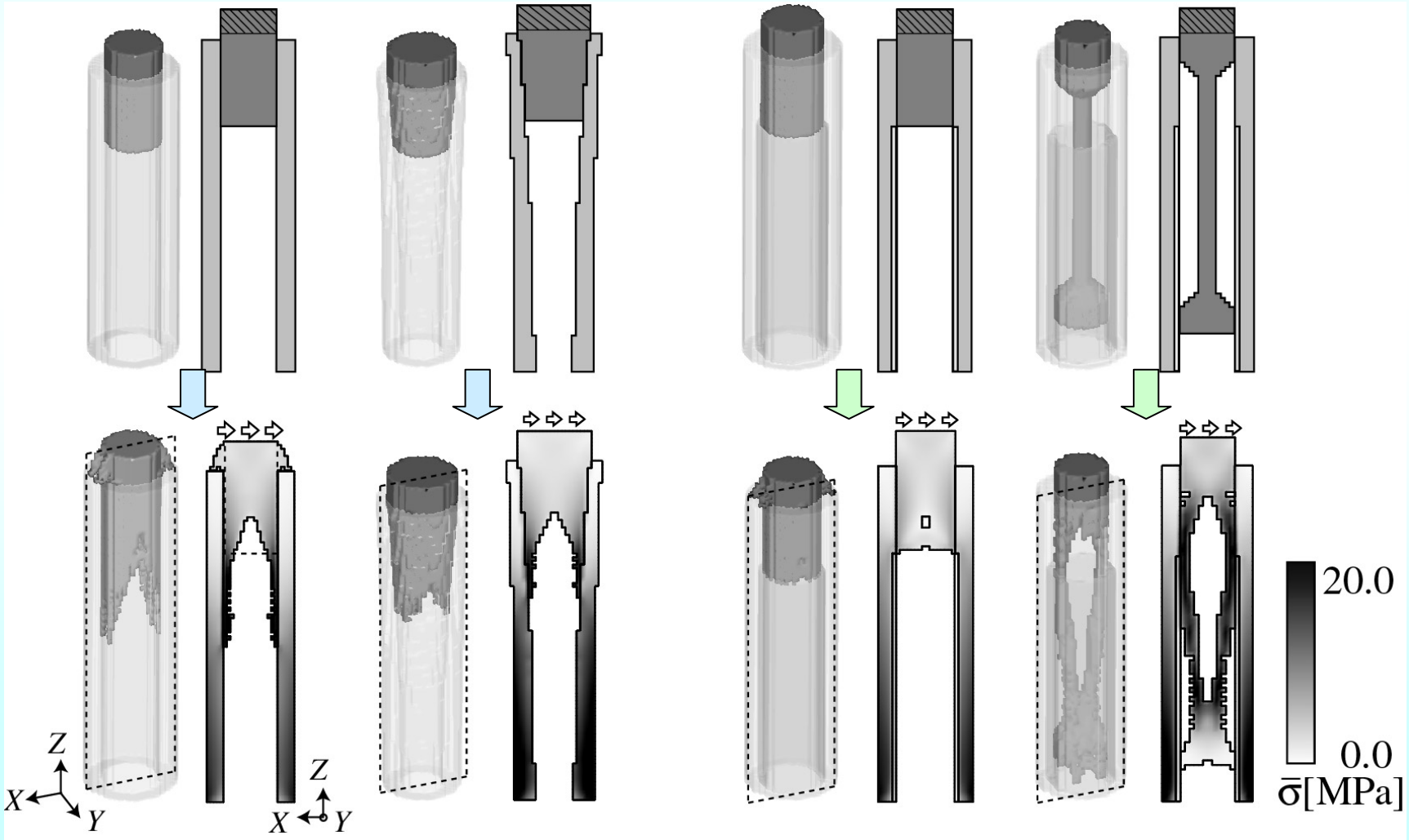
Effects of boundary condition & design region



Effects of bone shape & initial stem shape

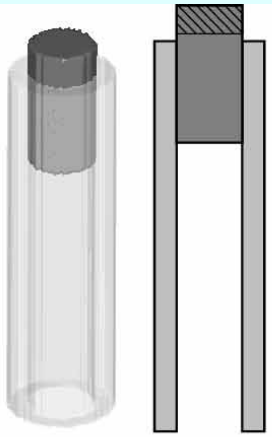
Bone shape

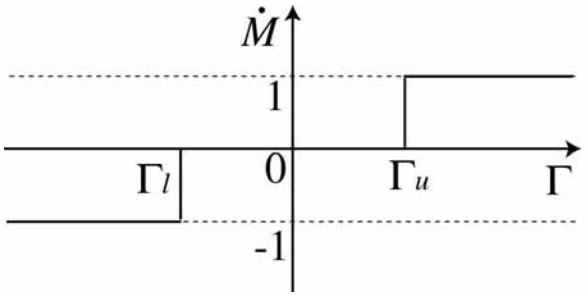
Initial stem shape



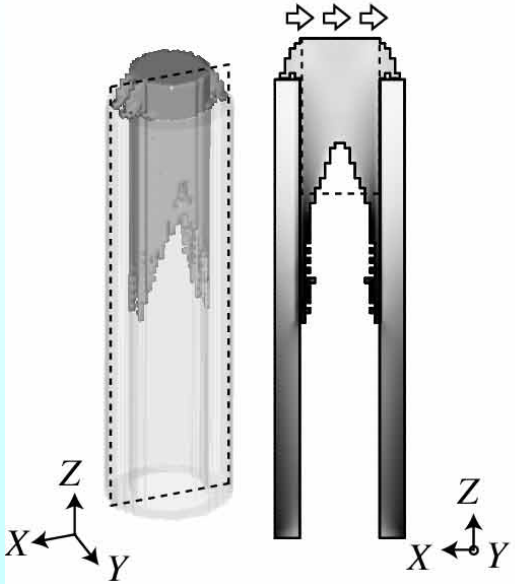
Effects of rate equation to modify stem shape

$\Gamma = \ln(\sigma_c / \sigma_d)$

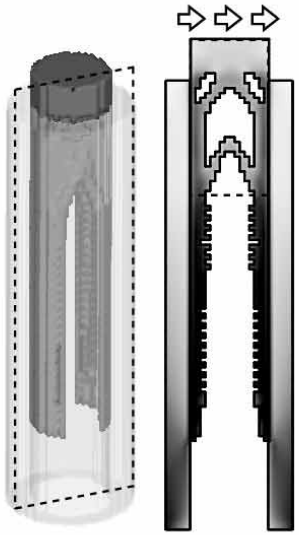




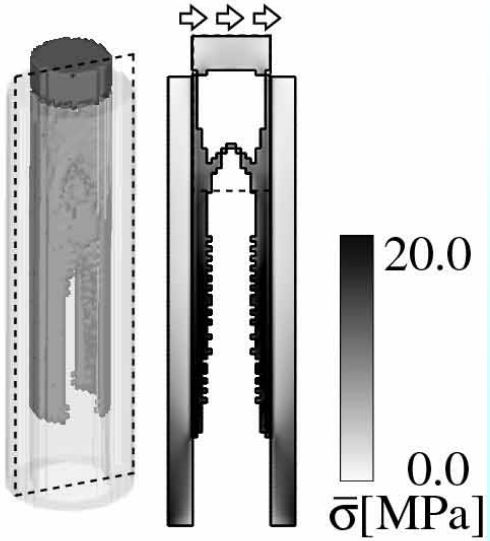
$\sigma_d = \int_S w(l)\sigma dS / \int_S w(l) dS$



$\sigma_d = (\sigma_{\max} + \sigma_{\min}) / 2$



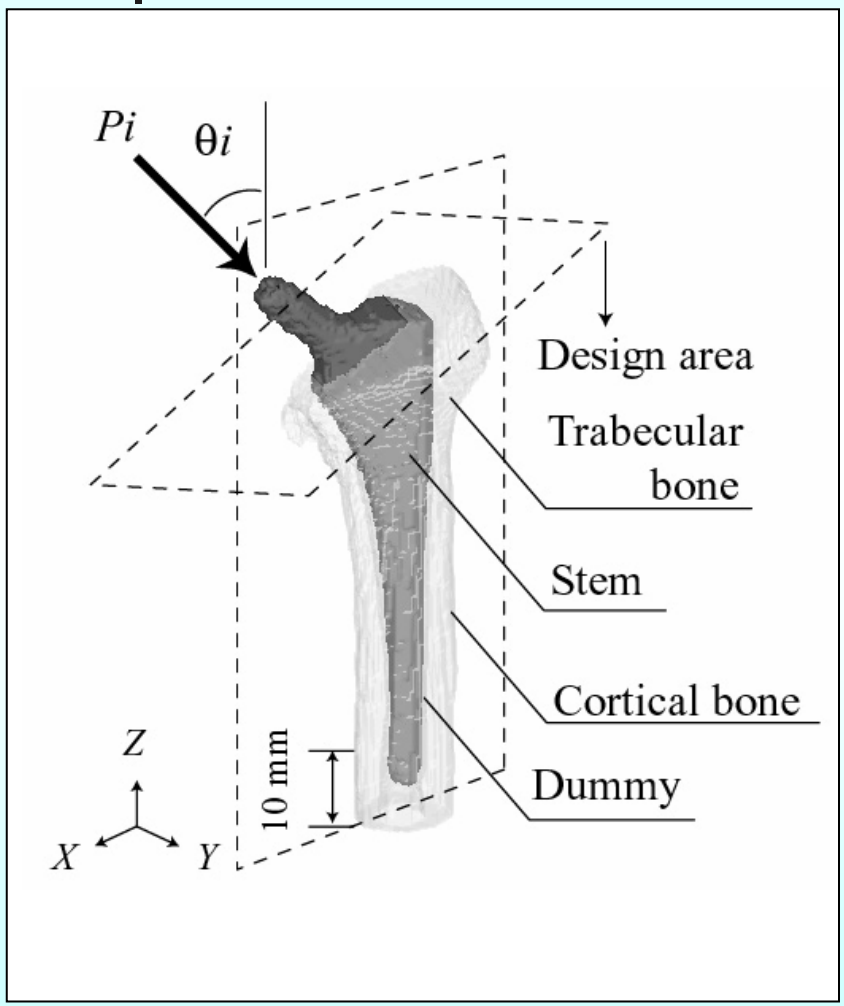
$\sigma_d = \sigma_{mean}$

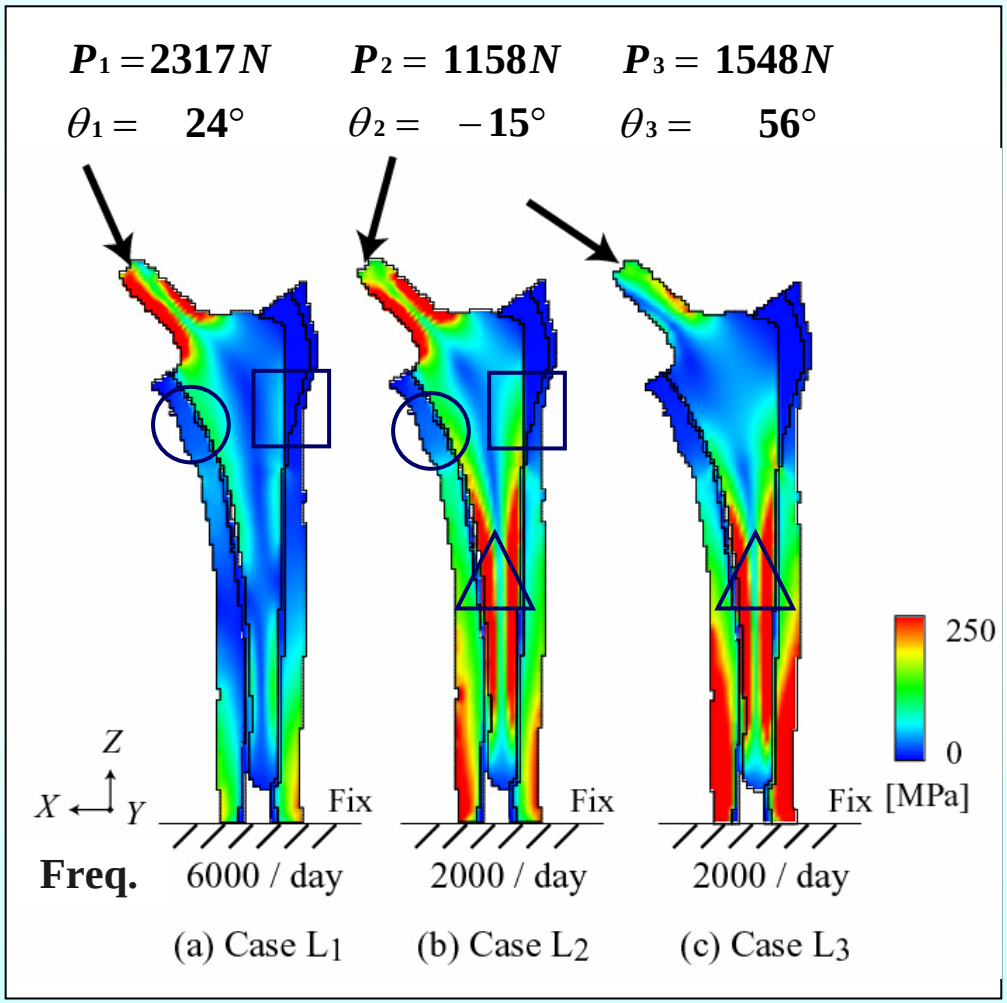


Effects of …

- **Boundary Conditions**
  - **Loading conditions**
  - **Bone-stem interface (fixed / not fixed)**
    → Cement & Cementless w/ porous coated
- **Design Region**
  - **Medullary cavity / Cortical region**
    → Occupied / Rasping volume
  - **Bone shape**
    → Personalization
- **Initial stem shape**
- **Rate equation to modify stem shape**
- **…**

Digital image-based bone-stem model



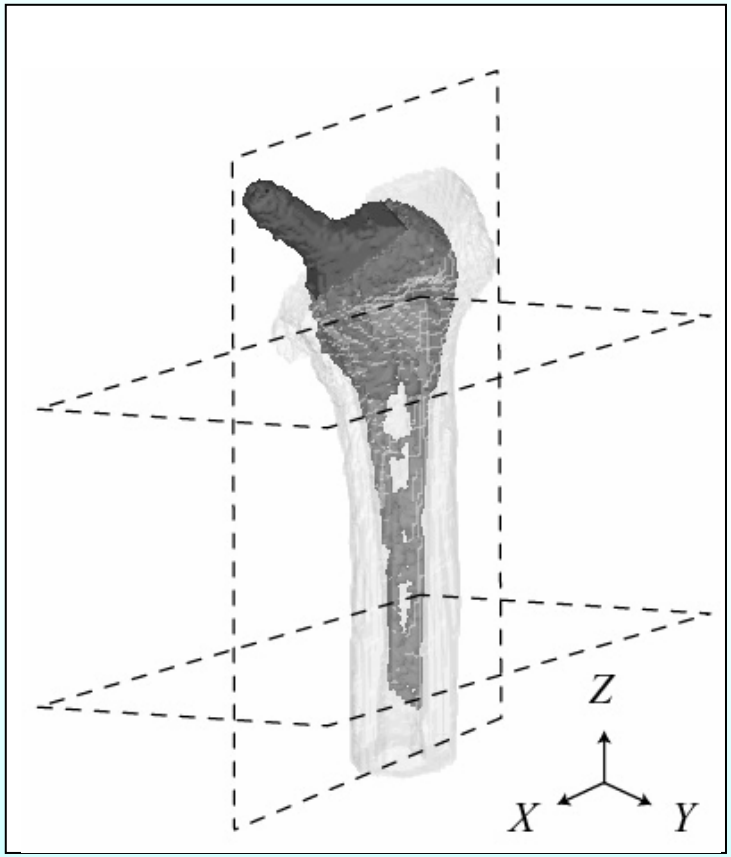


Initial Shape

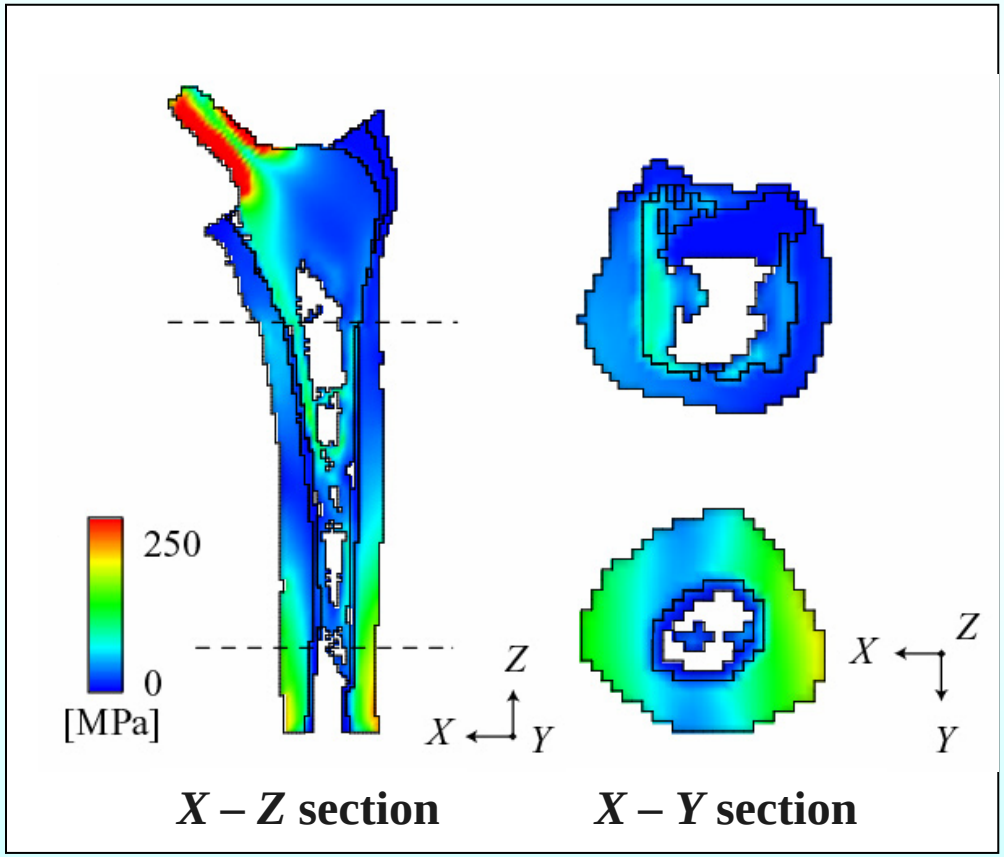
Equivalent stress on X – Z section

Change in stem shape and equiv. stress

Case L1 : L2 : L3 = 3 : 1 : 1

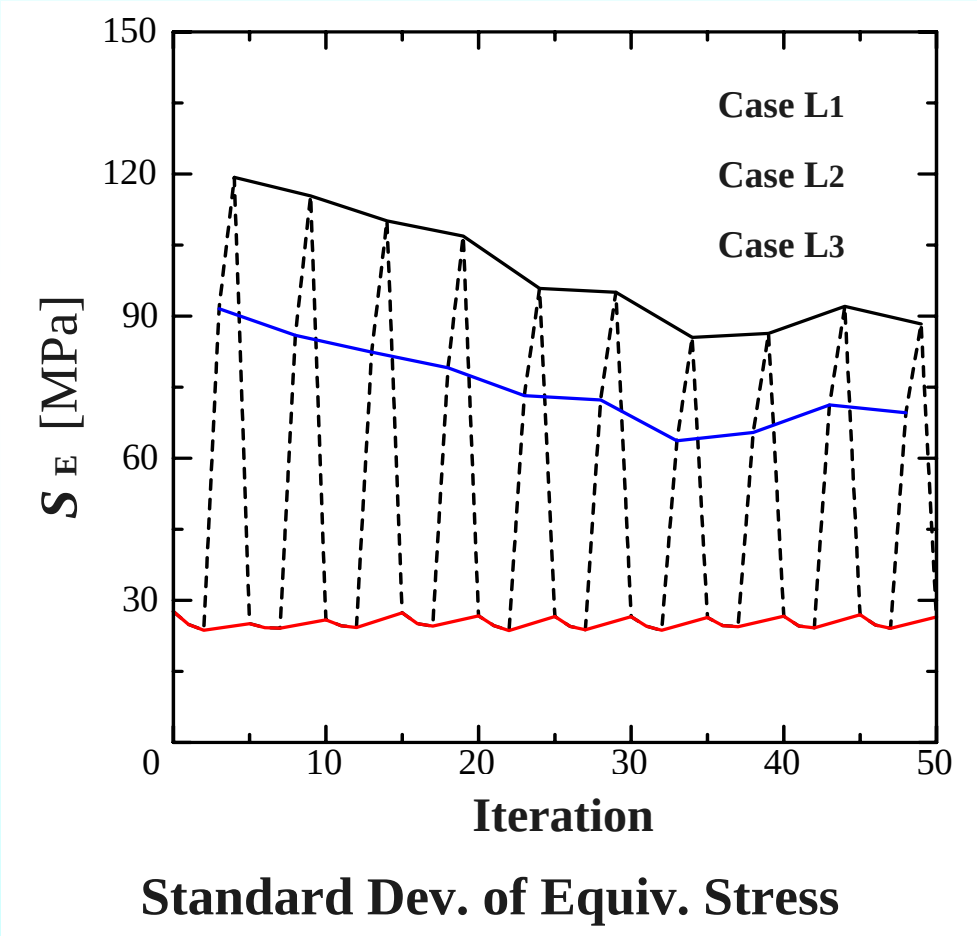


Stem Shape



Equivalent Stress

Change in stress distribution (non uniformity)



Standard Dev. of Equiv. Stress

Case L_1 →

Case L_2, L_3 ↘

Conclusions

Trabecular remodeling simulation was applied to design stem shape based on uniform stress criterion

- **Simple model studies**
- **Digital Image-based model study**

Future application

- Global / local analysis

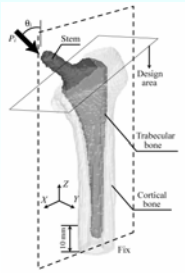
- Stem shape design considering remodeling at bone-stem interface

- Optimal porous area, …

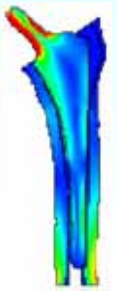
Computational design system for bone implant

Individual modeling of bone and implant

Medical image, 3D CAD data



Evaluation of implant



Design of stem shape

Choice of the implant type

Manufacturing directly from image-based model

* IPA: Information-technology Promotion Agency, Japan