

海綿骨欠損内部の骨梁パターン形成と Scaffoldを用いた骨再生の生体力学シミュレーション

安達 泰治, 坪田 健一*, 鍋島 弘樹

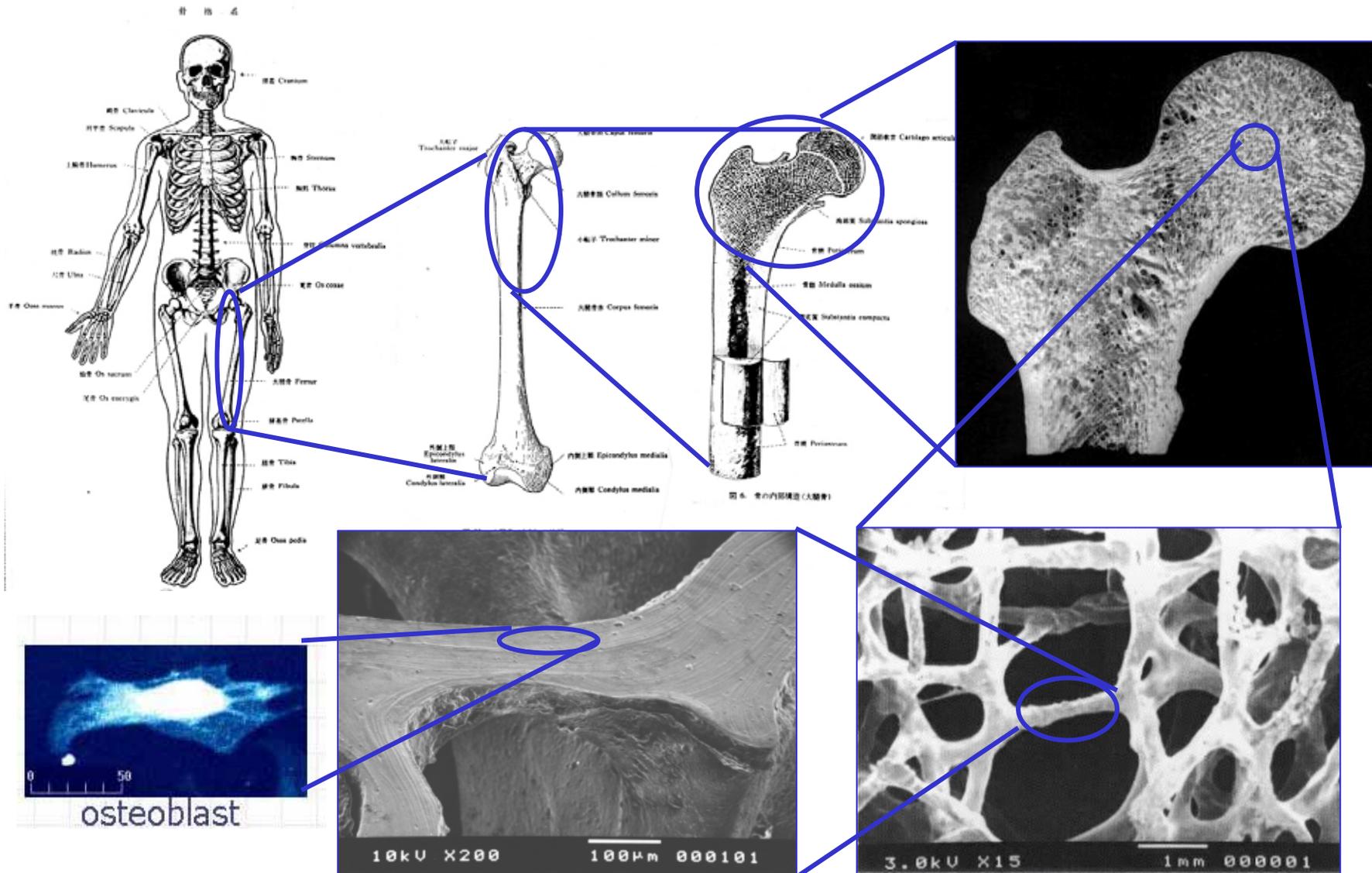
本間 義規, 富田 佳宏

神戸大学大学院自然科学研究科機械システム科学専攻
理化学研究所

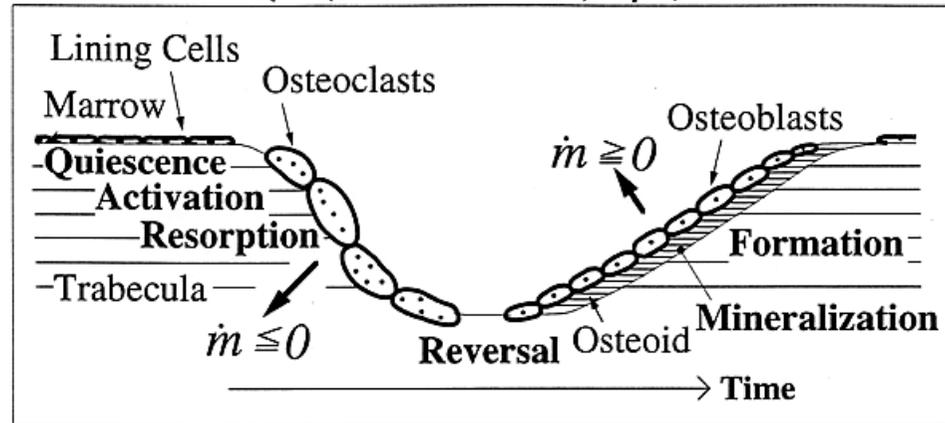
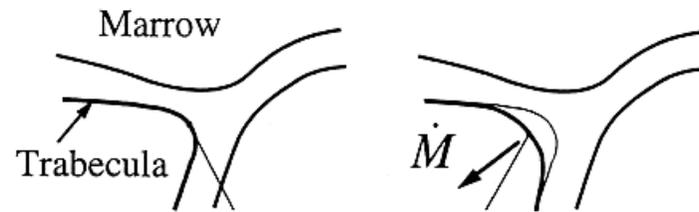
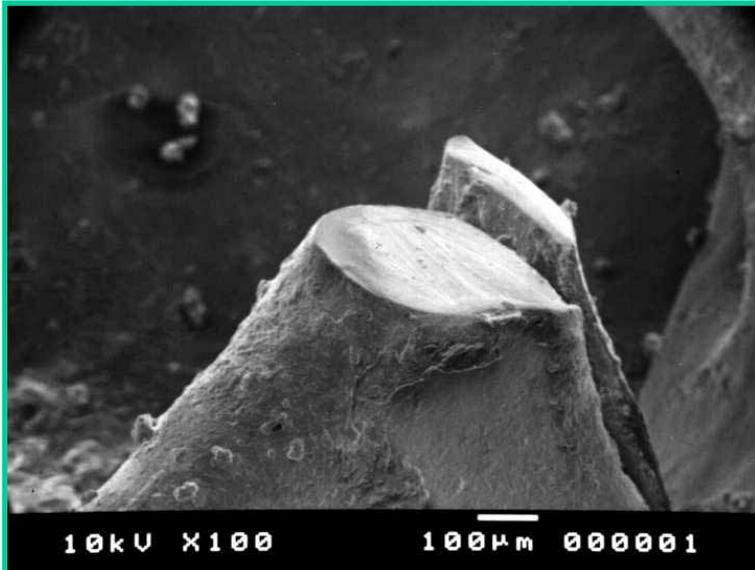
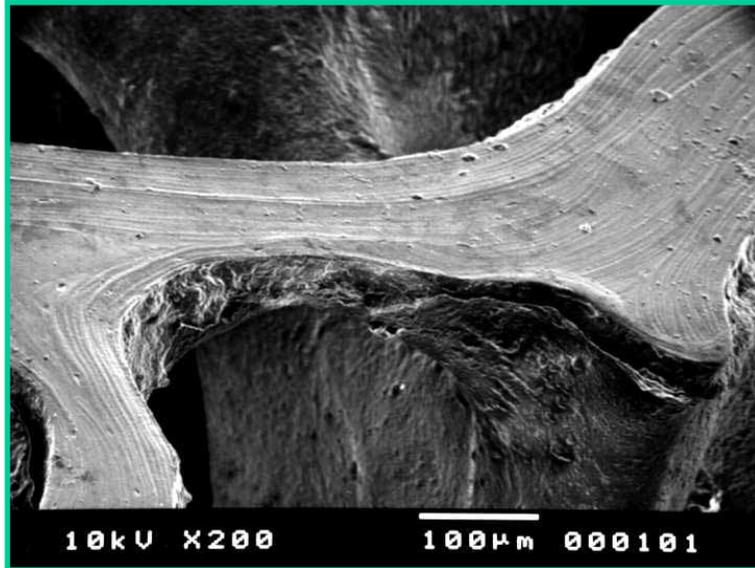
* 東北大学大学院工学研究科バイオロボティクス専攻



骨の階層構造

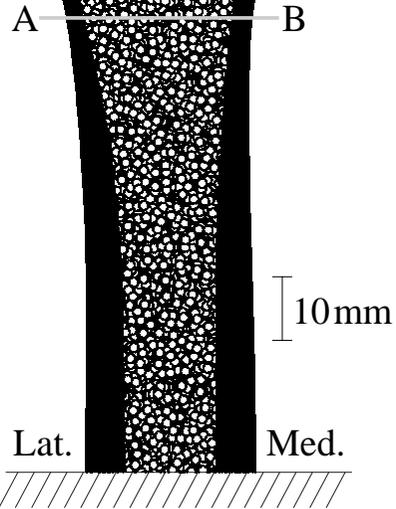
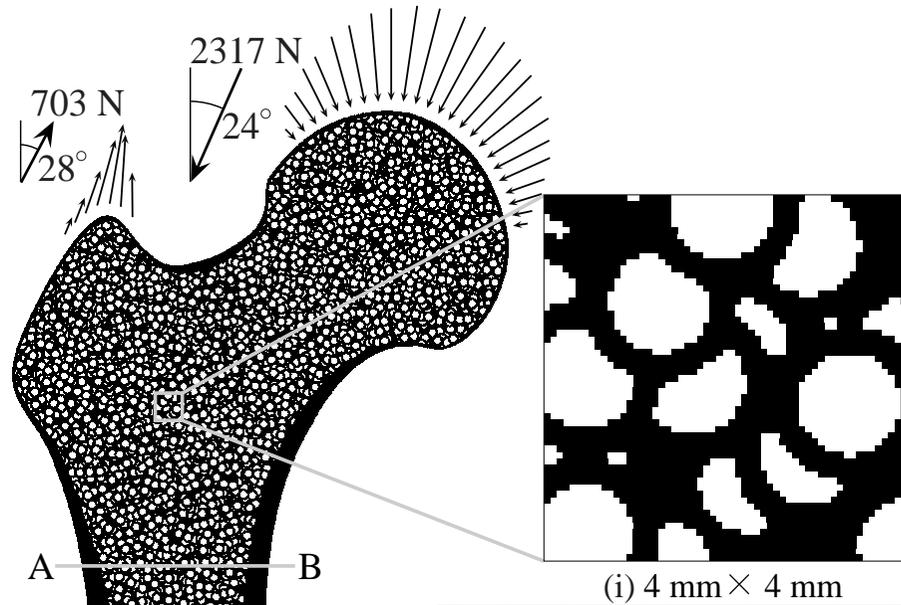


骨梁表面の再構築サイクル

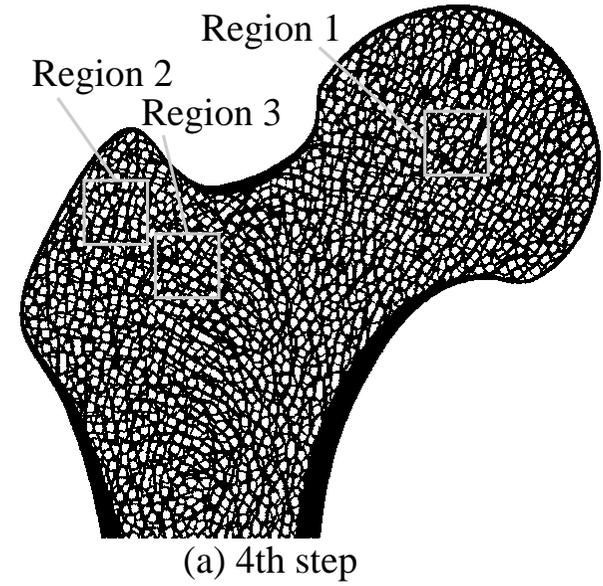
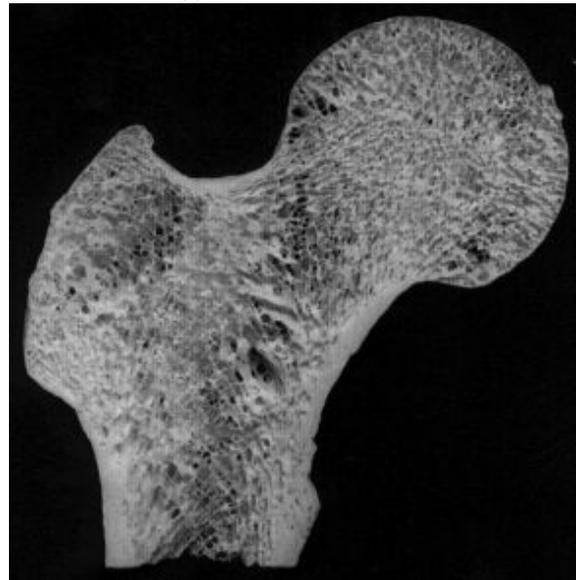


Trabecular surface remodeling
(Parfitt A. M. 1994)

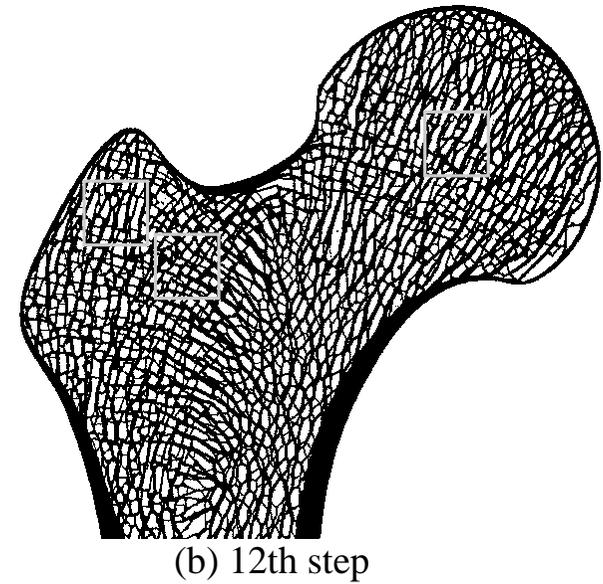
大腿骨骨頭部骨梁分布



(a) Boundary Condition

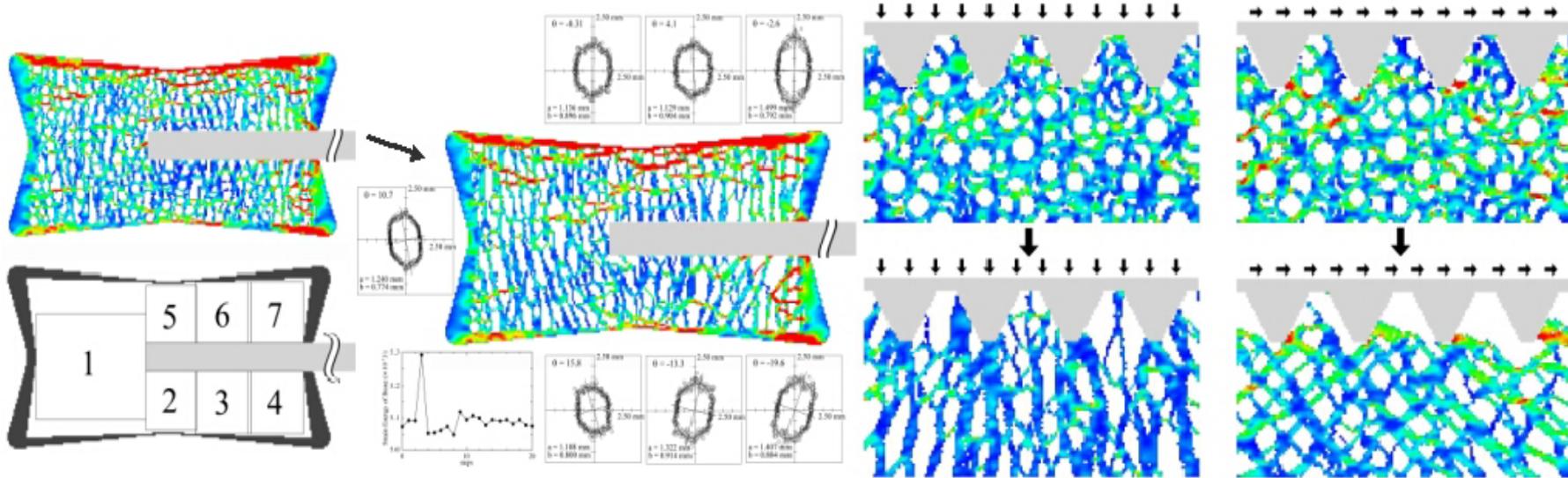
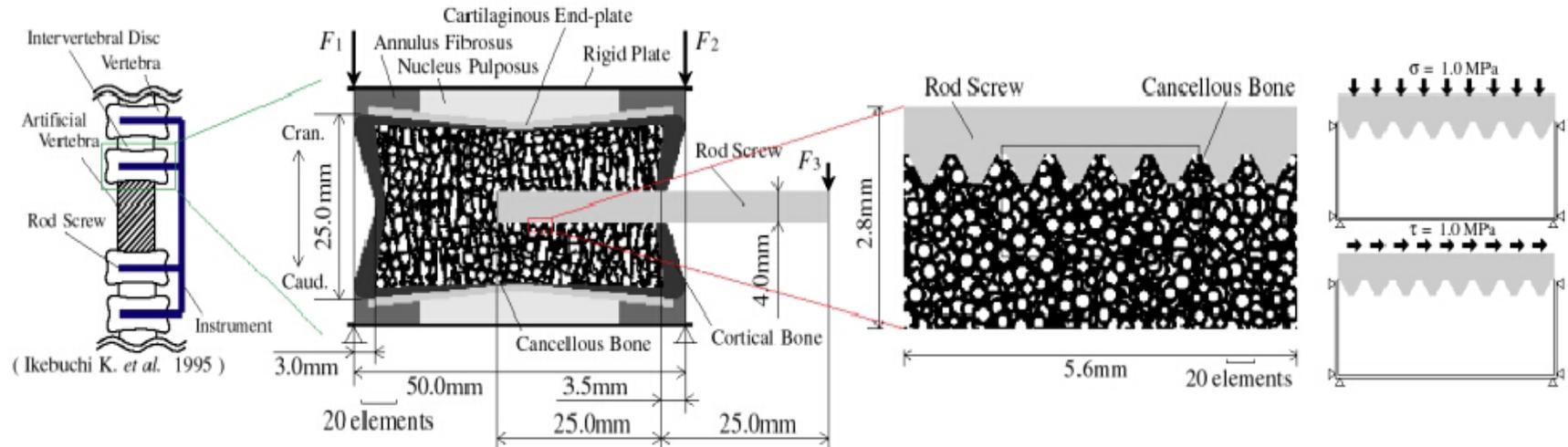


(a) 4th step



(b) 12th step

脊椎補強とねじ部の骨再生による形態変化のシミュレーション



海綿骨欠損部内の 骨梁形態形成シミュレーション

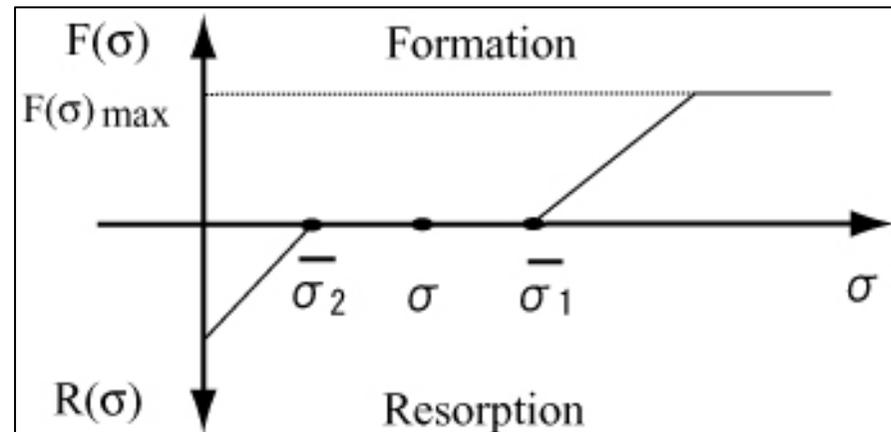
～ 反応拡散系によるモデル化～

骨梁パターン形成モデル

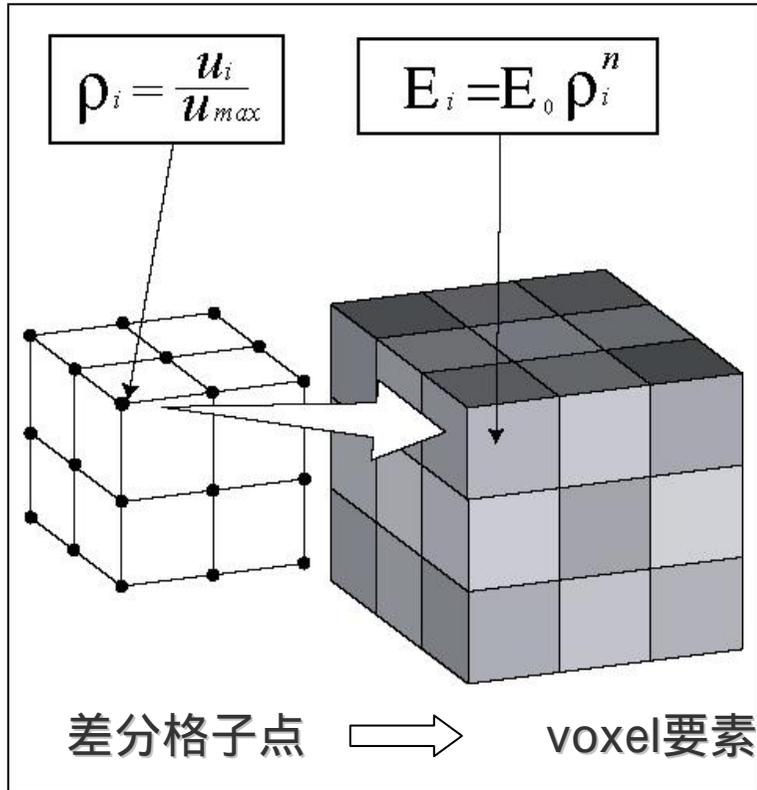
$$\begin{cases} \frac{\partial u}{\partial t} = f(u, v) + D_u \nabla^2 u + F(\sigma) \\ \frac{\partial v}{\partial t} = g(u, v) + D_v \nabla^2 v + R(\sigma) \end{cases}$$

D_u, D_v 拡散係数

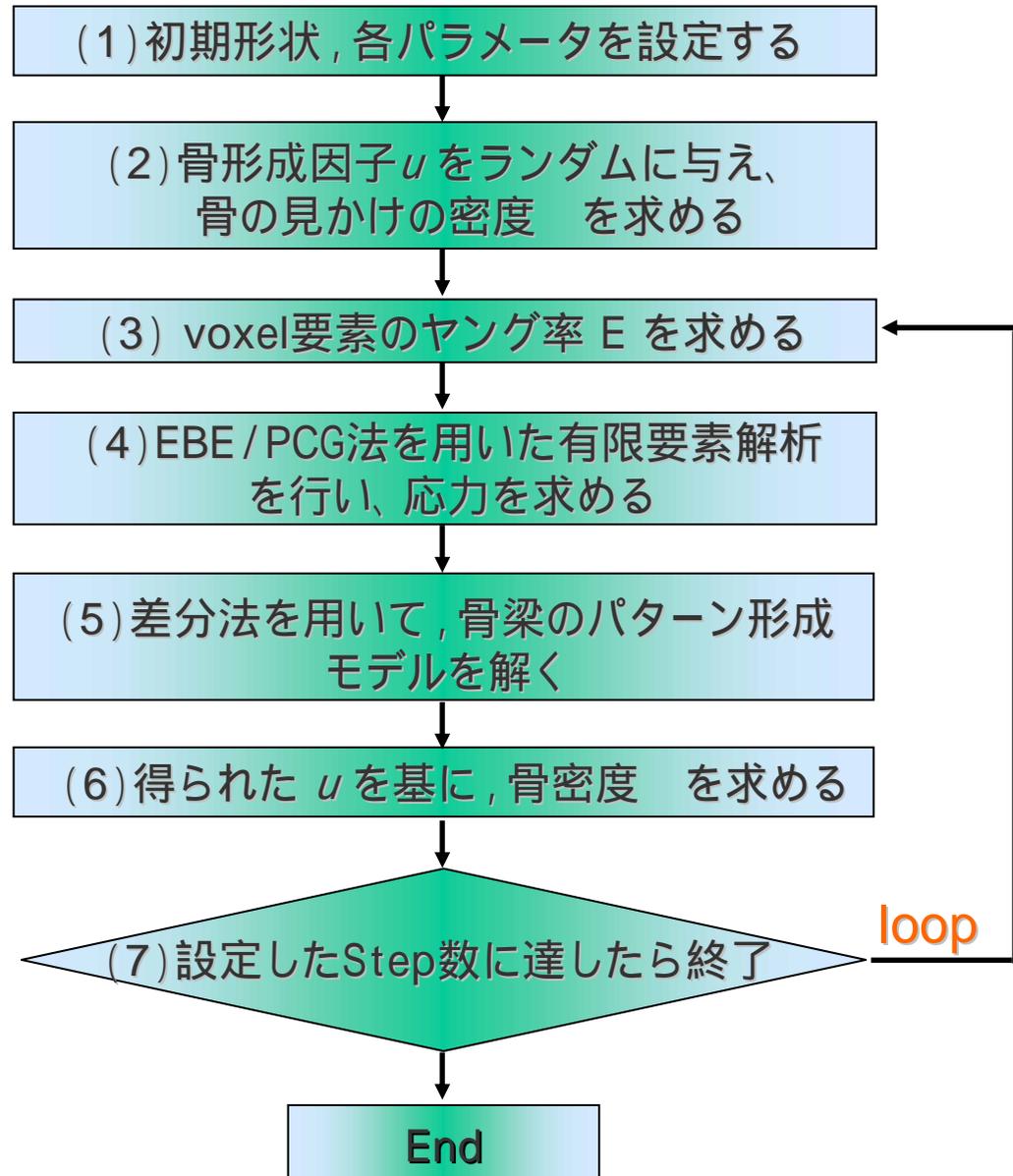
活性因子 u 骨形成因子
抑制因子 v 骨吸収因子



シミュレーション手順



成熟骨... $E_0 = 20\text{GPa}$
 $n = 3$



シミュレーションモデル

一辺2.5mmの立方体領域

分割数 : $50 \times 50 \times 50$

1要素の辺長 : $50 \mu\text{m}$

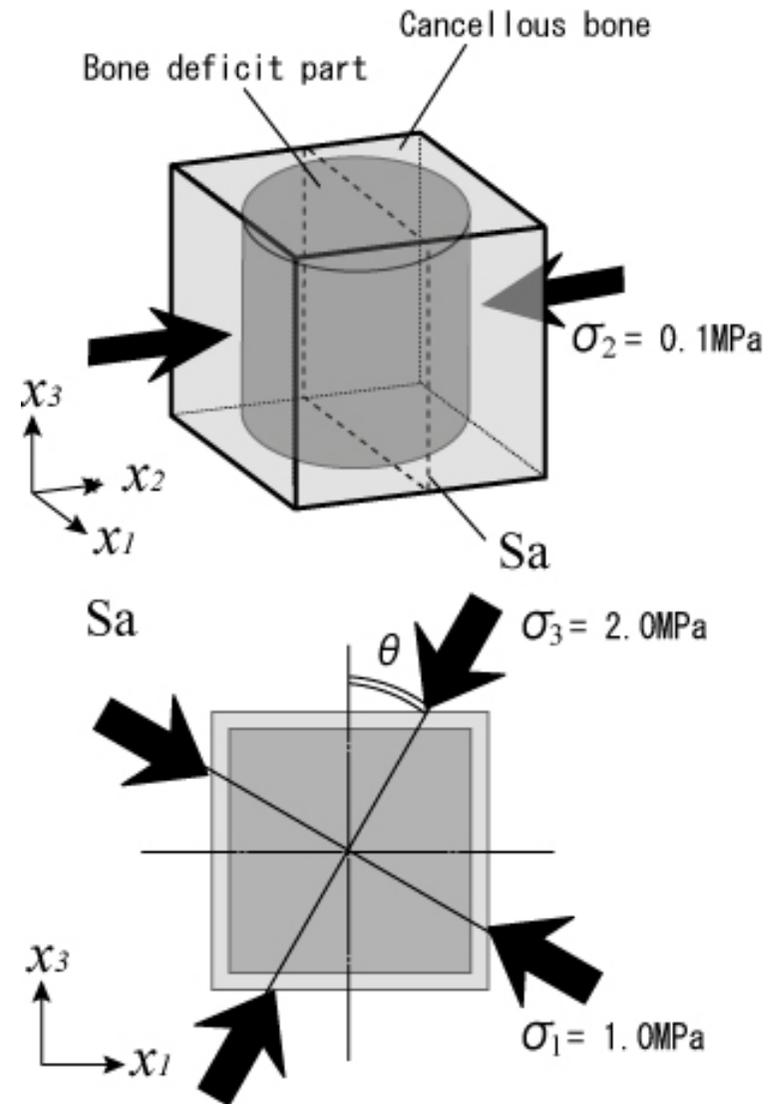
骨欠損部領域

円柱形状: 直径、高さ2.3mm

海綿骨を想定した領域

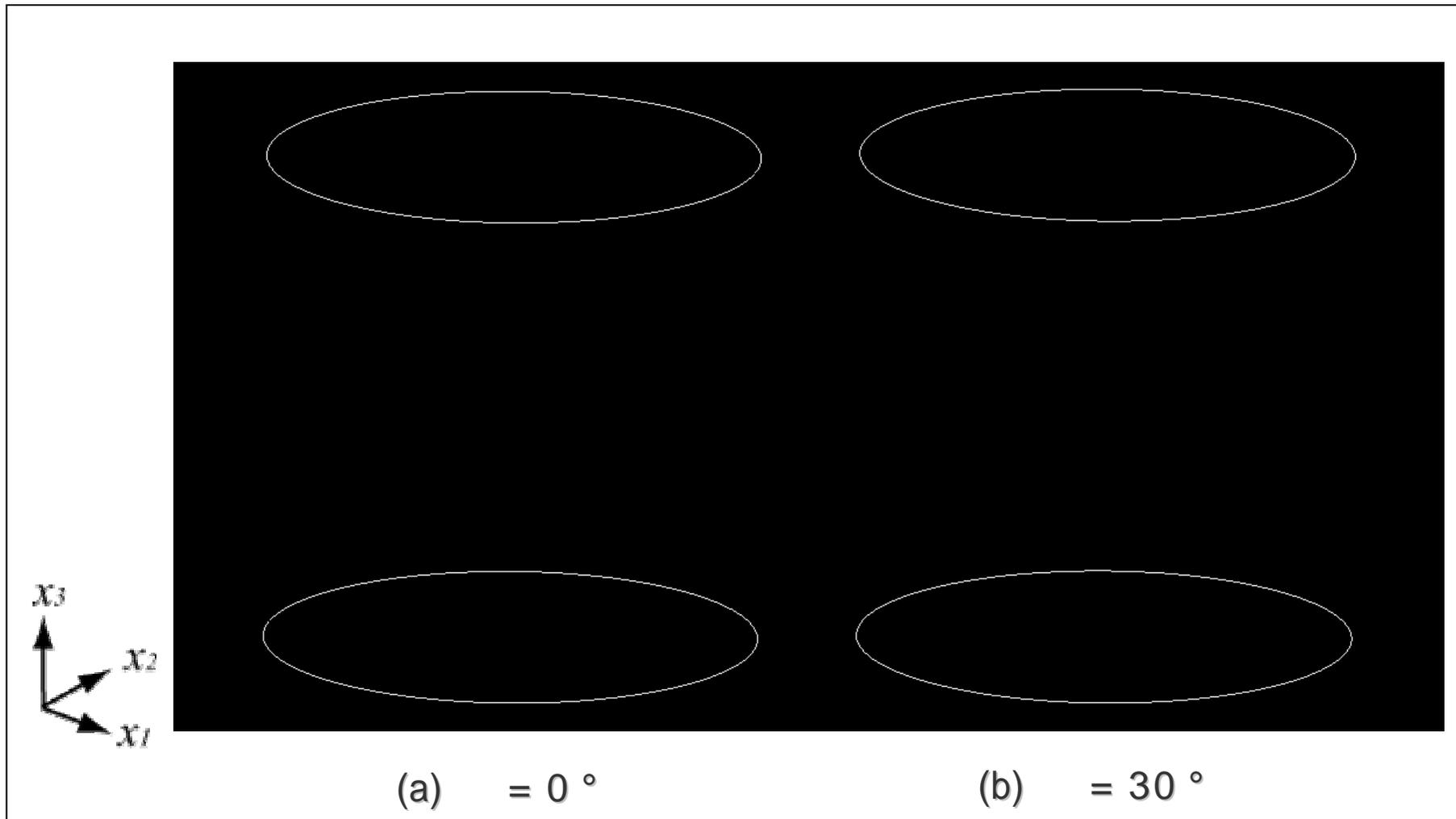
ヤング率 $E = 2.0\text{GPa}$

主応力方向 $\dots 0^\circ, 30^\circ$

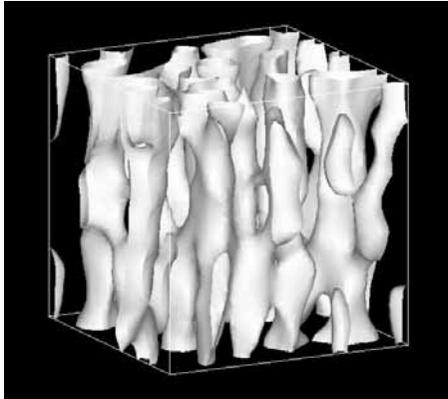


骨梁形成過程

骨密度 = 0.6 以上の時, 新生骨が石灰化



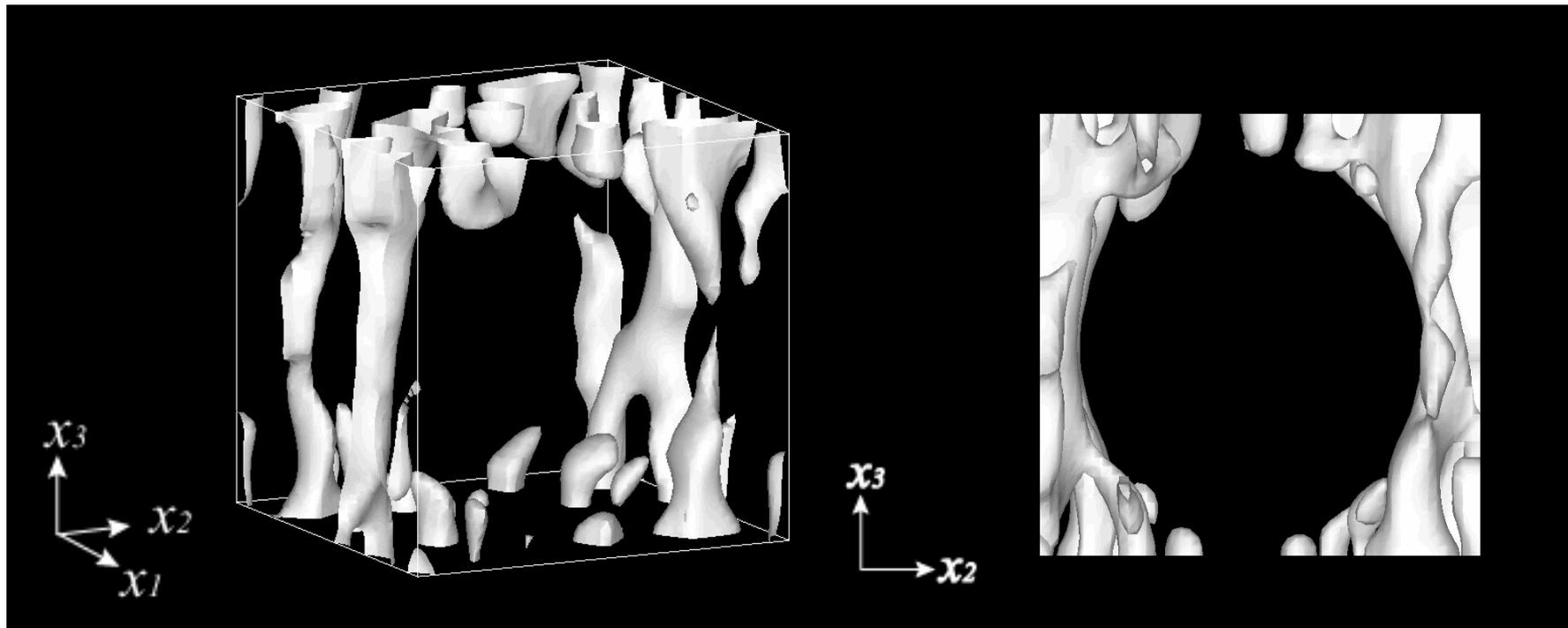
今後の展開



欠損部周囲の骨梁構造の影響



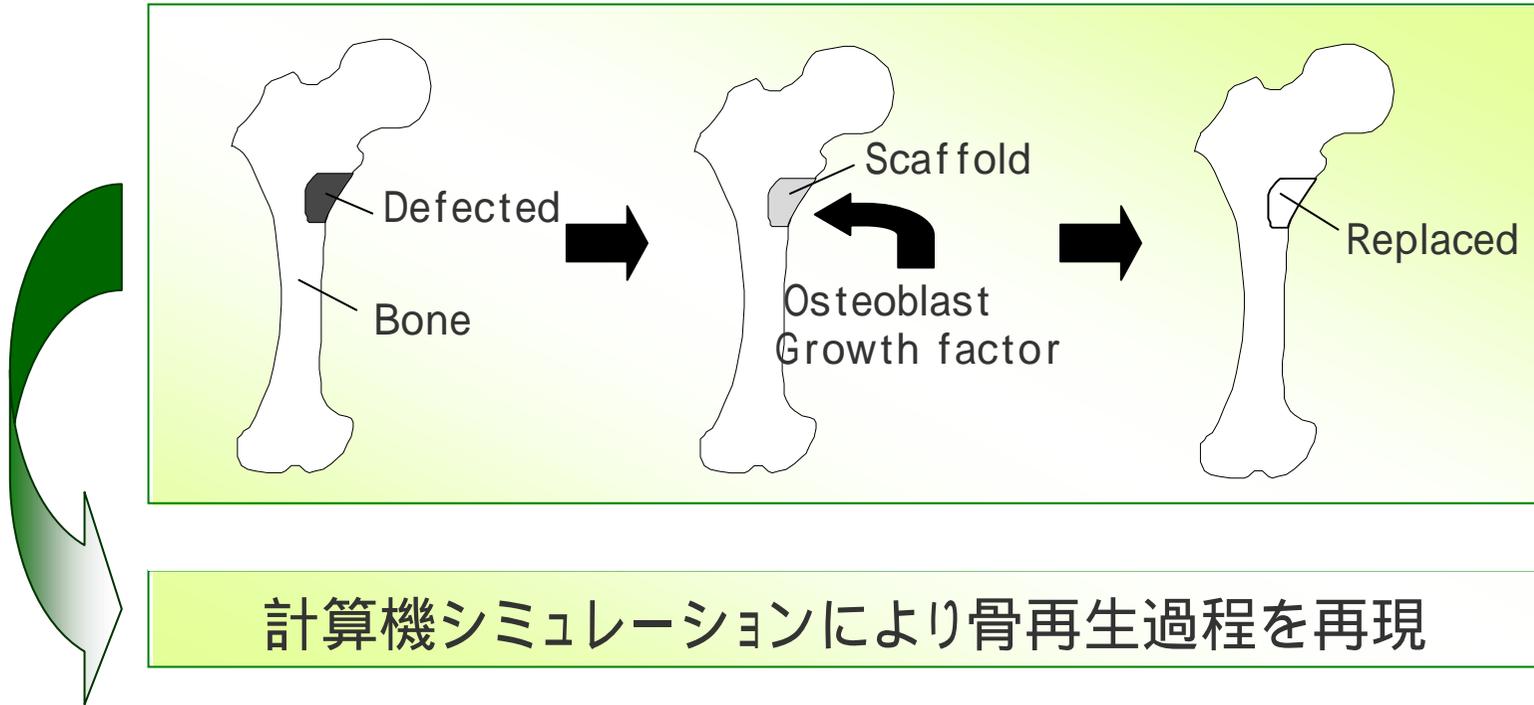
本シミュレーションモデルで作成した骨梁構造
円孔状の欠損



Scaffold の内部構造寸法が 再生骨梁構造に与える影響

～ 骨再生シミュレーションによる検討～

背景と目的



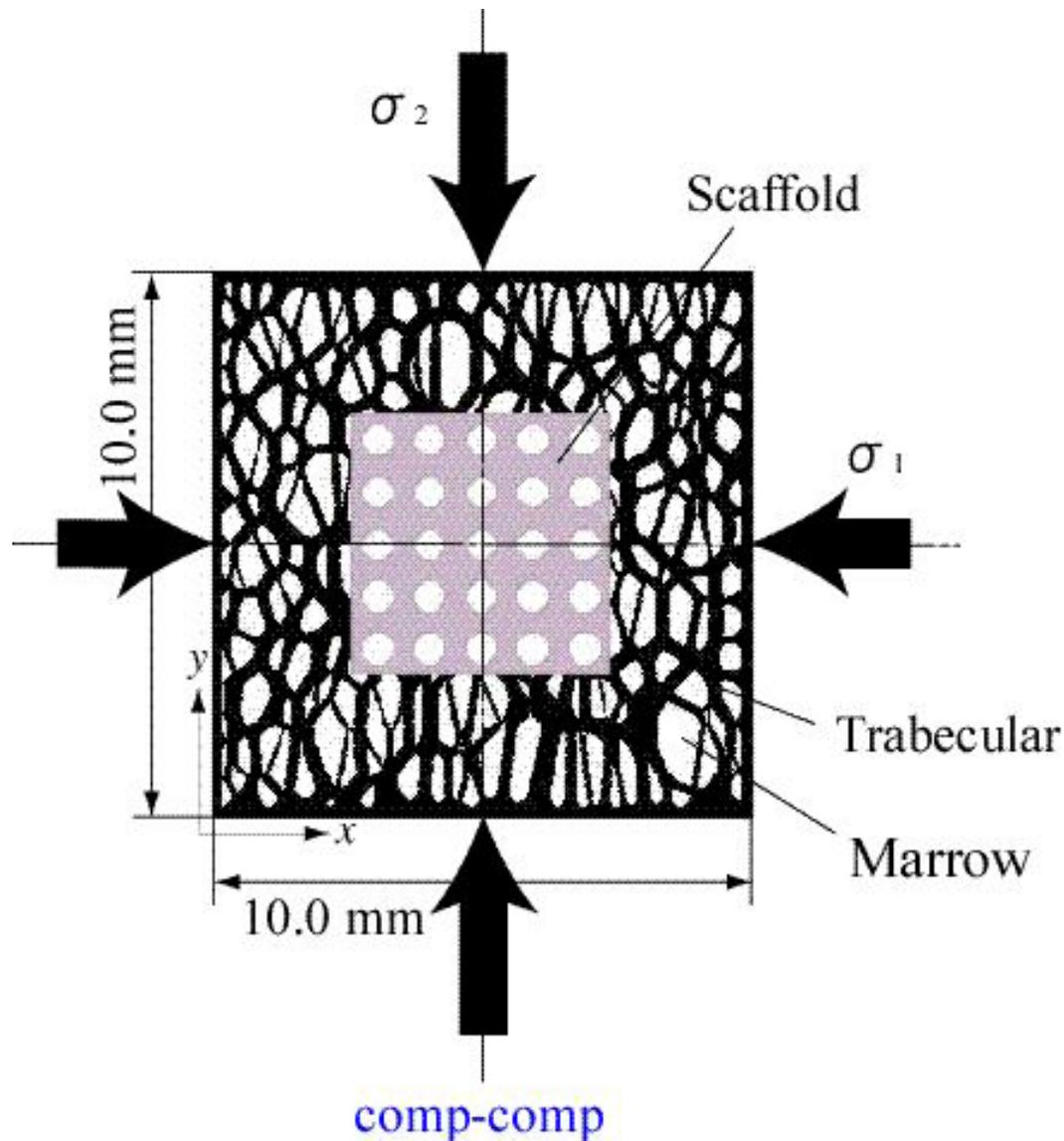
Scaffold内部構造の最適な設計は重要な課題

Scaffoldの内部構造寸法

再生骨梁構造に与える影響

骨梁特徴量により評価

シミュレーションモデル



250 × 250 elements
Voxel size : 40 μm

$E_b = 20 \text{ GPa}$, $\nu_b = 0.3$
 $E_s = 10 \text{ GPa}$, $\nu_s = 0.3$

$\sigma_1 = -1.0 \text{ MPa}$
 $\sigma_2 = -2.0 \text{ MPa}$

時間ステップ
骨形成を1日40 μm
として Voxel size に反映

Scaffoldの内部構造寸法

設計変数

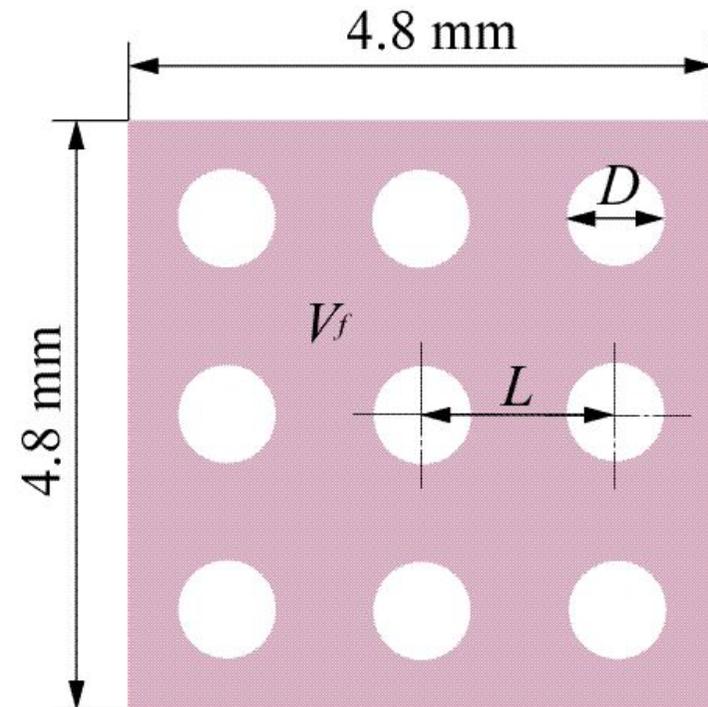
D : 空孔径

L : 中心間距離

(V_f : 体積分率)

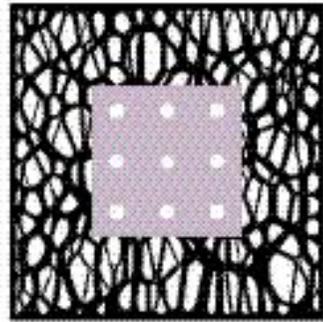


D, L の2つの設計変数の値を定めることにより初期構造を決定

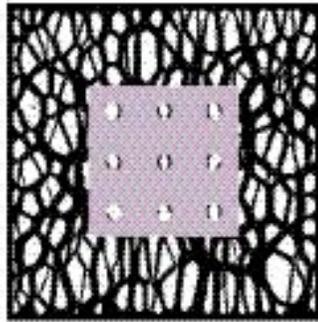


120 × 120 elements

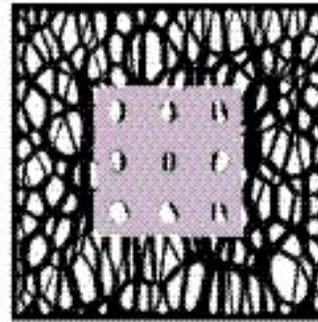
Scaffoldを用いた骨再生過程



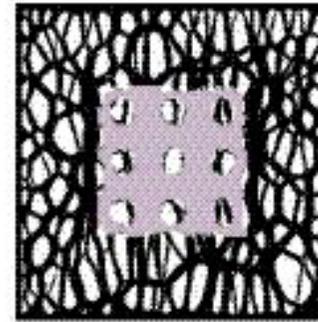
Initial



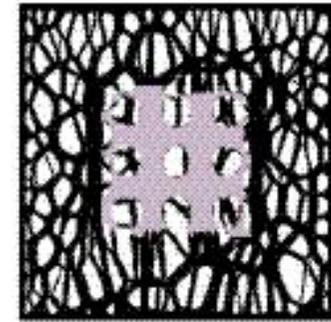
10 days



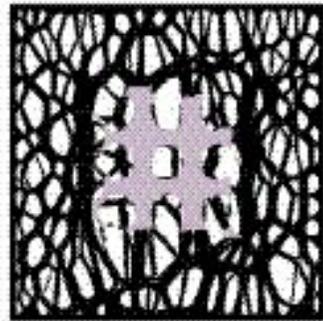
20 days



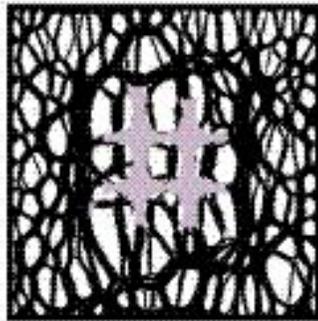
30 days



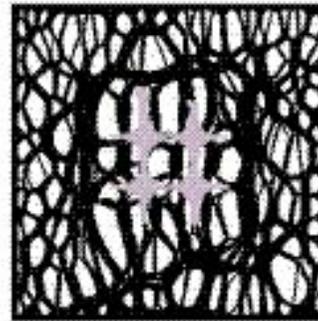
40 days



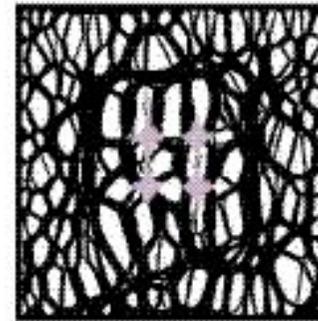
50 days



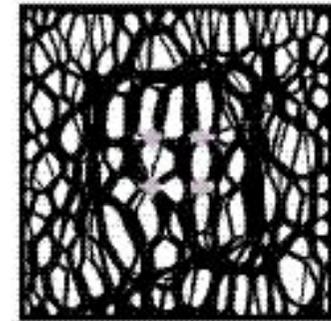
60 days



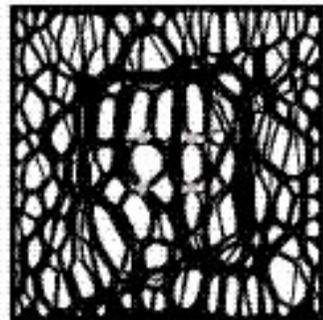
70 days



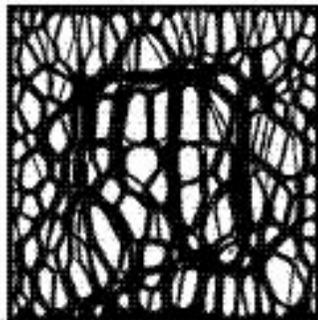
80 days



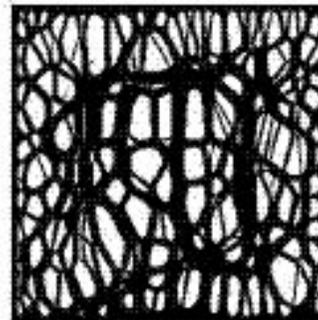
90 days



100 days



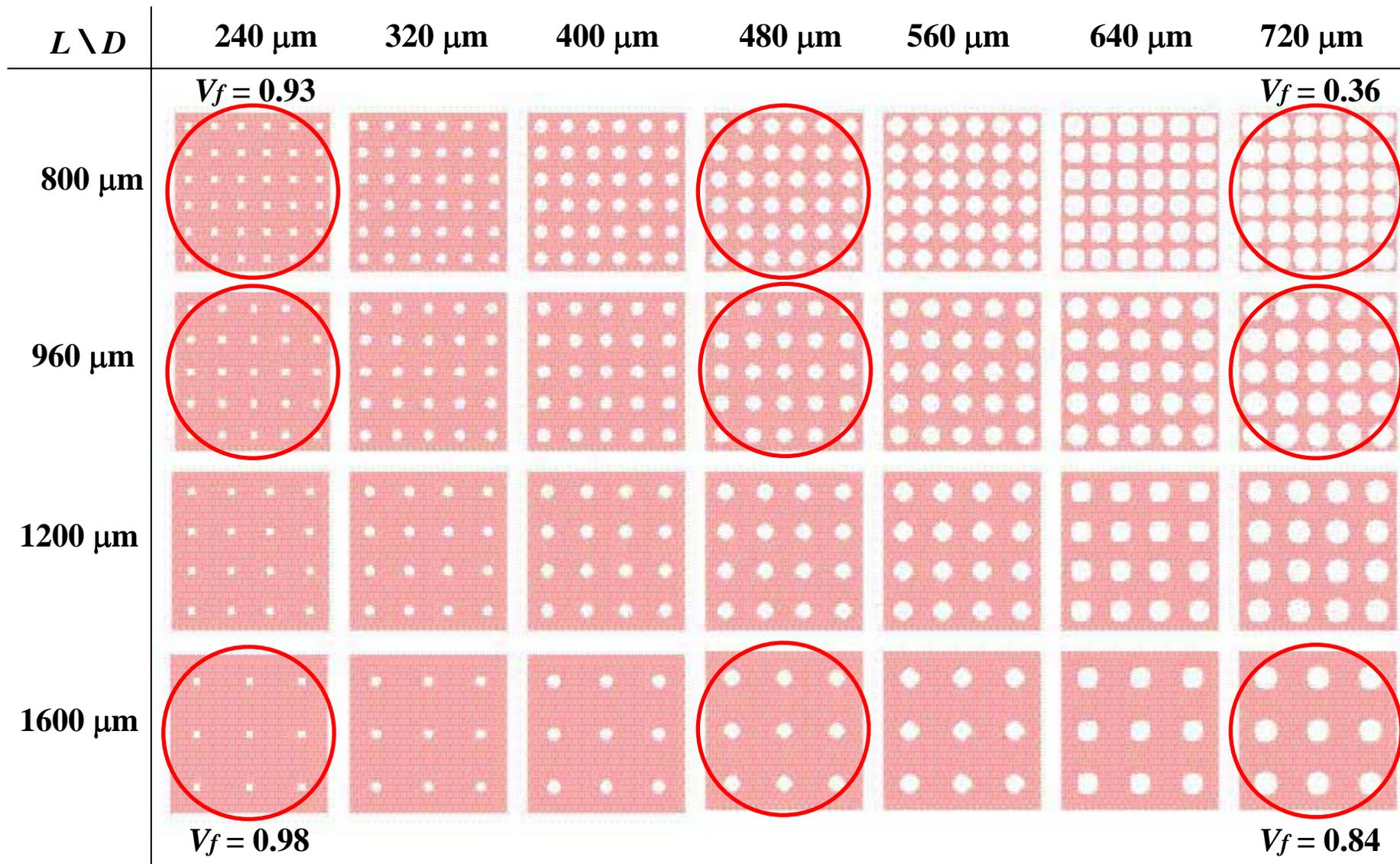
110 days



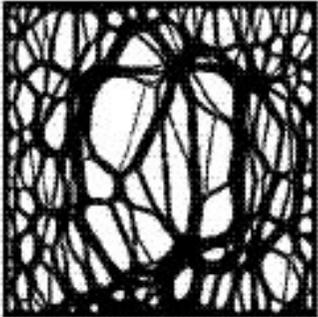
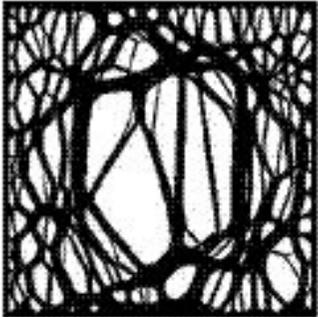
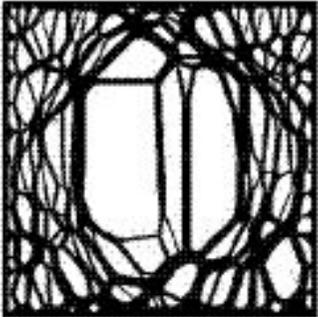
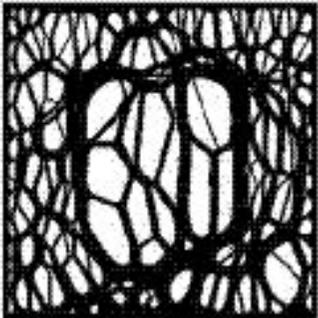
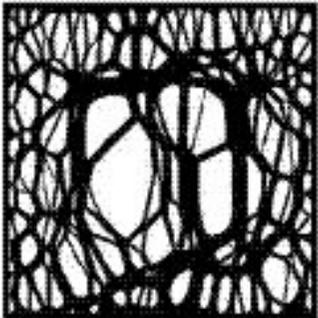
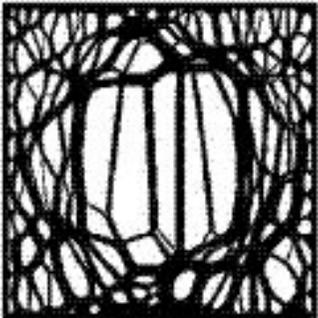
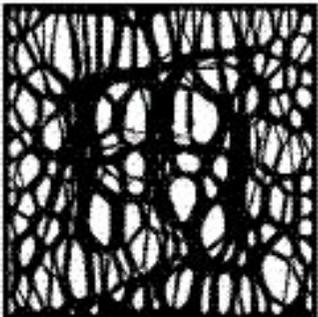
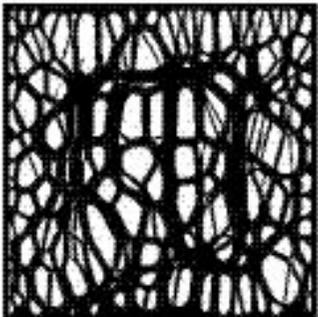
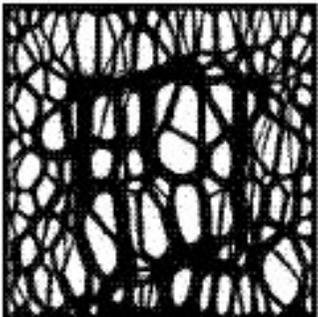
120 days

初期 空孔内部表面より
骨が形成されている。
120 days Scaffoldは完全
に吸収されて、欠損領
域に骨梁構造が形成。

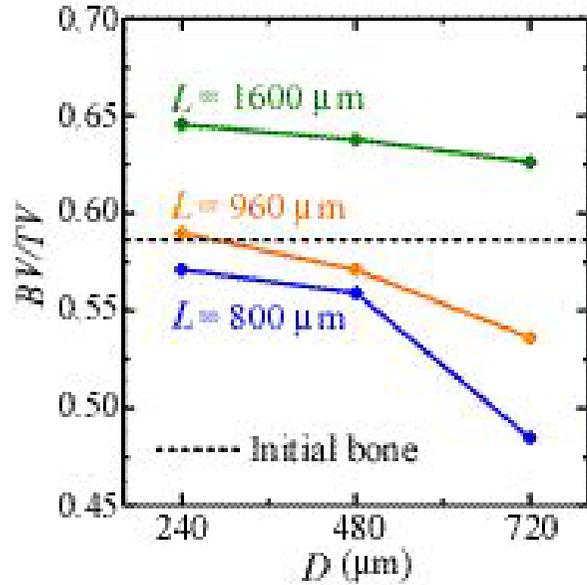
Scaffoldの初期構造



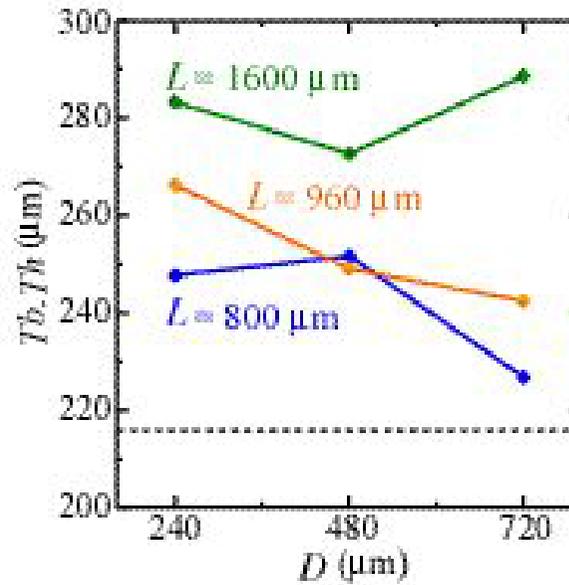
海綿骨およびScaffoldの形態変化 (120 days)

| $L \setminus D$ | 240 μm | 480 μm | 720 μm |
|--------------------|---|--|---|
| 800 μm |  |  |  |
| 960 μm |  |  |  |
| 1600 μm |  |  |  |

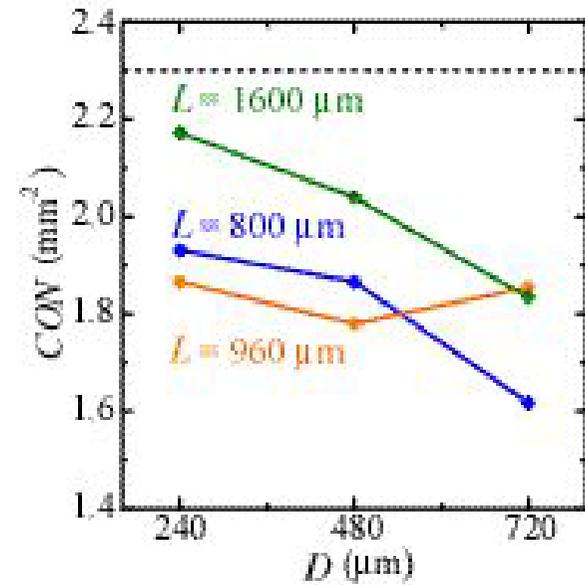
再生された骨梁構造の評価



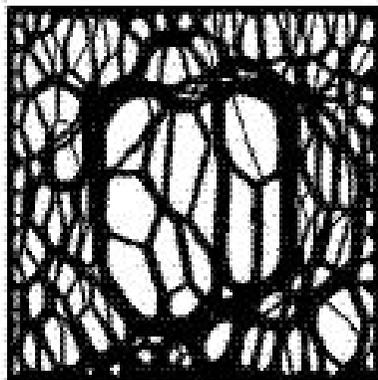
骨梁の平均体積分率



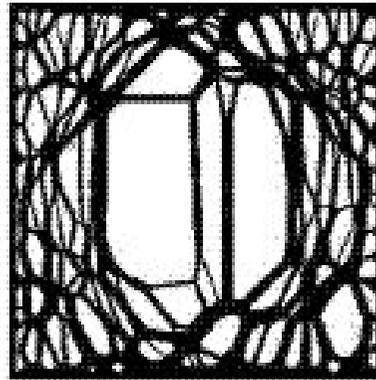
骨梁の平均厚さ



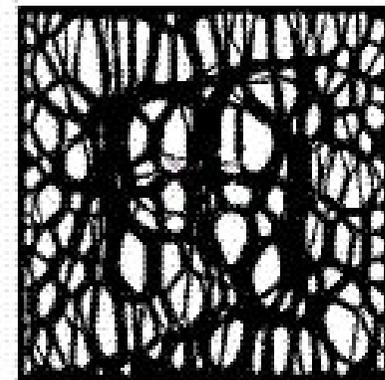
単位面積あたりの連結数



$(D, L) = (240 \mu\text{m}, 960 \mu\text{m})$



$(D, L) = (720 \mu\text{m}, 800 \mu\text{m})$



$(D, L) = (240 \mu\text{m}, 1600 \mu\text{m})$

The image features a serene sunset scene over a vast body of water. The sky is a mix of soft pinks, oranges, and yellows, transitioning into a pale blue. The water below reflects these colors, creating a shimmering effect. In the center of the image, the word "End" is written in a bold, red, italicized serif font.

End