Osteoporosis

as trabeculae thin, buckling easier \( \sigma^* \propto (\rho/\rho_0)^2 \)

once trabeculae begin to resorb, connectivity reduced, strength drops dramatically

modelling

- can't use unit cell or dimensional analysis (need to model local effects)
- finite element modelling

- initially - 2D Voronoi honeycomb
  - 2D representation of vertebral bone
  - 3D Voronoi foam - Shreekha Vajjibala

Voronoi honeycomb

- random seed points, draw perpendicular bisectors
- use a minimum separation distance to get cells of approximately uniform size
- FE analysis - each trabecula a beam element
- first calculated elastic moduli

- FE A results close to analytical model for random (isotropic) honeycomb (40 models, all same \( \rho^*/\rho_0 \), about 25x25 cells in each)
  - modulus is average of stiffness over entire material
Modelling: 2D Voronoi

2D Voronoi

- Next, calculated compressive strength of Voronoi honeycombs
  - each cell wall 1-3 beam elements
  - model non-linear elasticity & failure behaviour
  - 15x15 cells in model (random seeds ≠ isotropic)
  - cell wall assumed to be elastic-perfectly plastic $\frac{\sigma_s}{E_s} = 0.01 \quad \psi = 0.3$
  - for this value of $\psi$, transition between elastic buckling & plastic collapse stress at $\rho^* \psi_s = 0.035$ in regular hex. honeycomb

- Calculated compressive strength of honeycombs with $\rho^* \psi_s = 0.015, 0.035, 0.05, 0.15$
- generated 5 different Voronoi honeycombs at each $\rho^* \psi_s$

- compressive $\sigma$-$\epsilon$ behaviour:
  \[ \rho^* \psi_s > 0.05 \quad \text{strain softening, permanent def. on unloading} \]
  \[ \rho^* \psi_s < 0.035 \quad \text{non-linear elastic deformation - recoverable} \]
  \[ \rho^* \psi_s < 0.035 \quad \text{non-linear elastic deformation - recoverable} \]
  \[ \rho^* \psi_s < 0.035 \quad \text{strength: 0.6 to 0.8 of $\sigma^*_p$ periodic} \]
2D Voronoi

Relative density = 15% Plastic failure

2D Voronoi

Relative density 1.5%; elastic buckling failure

2D Voronoi

- Max. normal strains at nodes in honeycombs (linear elastic)
  - Voronoi honeycombs - normal distribution
  - Regular hexagonal honeycombs - dashed lines on plot
  - Normal strain in vertical cell walls in regular hex. honeycomb vs. mean normal strain in Voronoi
  - Oblique walls - bending - large strains
  - Voronoi honeycomb 5% of strains outside of range of strain in regular hex. honeycomb

- Decrease in strength associated with broader range of strains in Voronoi honeycombs
  - Minimum strength at $\rho^*/\rho_s = 0.05$

- Interaction between elastic buckling + plastic yield

\[ \sigma_u = \frac{\pi^2 E \delta}{l^2} = \frac{\pi^2 E \pi r^4}{4l^2 \pi r^2} = \frac{\pi^2 E (r/l)^2}{4} \]
2D Voronoi

Figure removed due to copyright restrictions. See Figure 5; Silva, M. J., and L. J. Gibson. "The Effects of Non-periodic Microstructure and Defects on the Compressive Strength of Two-dimensional Cellular Solids." *International Journal Mechanical Sciences* 39, no. 5 (1997): 549-63.
Voronoi honeycombs - defects

- randomly removed cell walls in both Voronoi + reg. hex. honeycombs
- analyzed both by FEA
- dramatic decrease in modulus + strength, compared with equivalent reduction in density by thinning of cell walls
  - $\rho^*/\rho_s = 0.15$ failure by yielding
  - $\rho^*/\rho_s = 0.015$ "elastic buckling"

Modulus + strength reduction similar for Voronoi + reg. hex. honeycombs

Percolation threshold for 2D network hexagonal cells $\geq 35\%$ strut removed

Vertebral trabecular bone - 2D model

- model adapted to reflect trabeculae more aligned in vertical + horizontal directions
- perturbed a square array of struts to get similar orientation & strut asm bar
- looked at reduction in number + thickness of longitudinal + transverse struts (independently)
2D Voronoi

2D Voronoi


Vajjhala et al, 2000
Vertebral Trabecular Bone

Vertebral Trabecular Bone

Figure removed due to copyright restrictions. See Figure 3: Silva, M. J., and L. J. Gibson. "Modelling the Mechanical Behavior of Vertebral Trabecular Bone: Effects of Age-related Changes in Microstructure." Bone 21 (1997): 191-99.

Silva et al, 1997
Vertebral Trabecular Bone

Figure removed due to copyright restrictions. See Figure 4: Silva, M. J., and L. J. Gibson. "Modelling the Mechanical Behavior of Vertebral Trabecular Bone: Effects of Age-related Changes in Microstructure." Bone 21 (1997): 191-99.

Silva et al, 1997
Vertebral Trabecular Bone

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Vertebral Trabecular Bone

Vertebral Trabecular Bone

Figure removed due to copyright restrictions. See Figure 7: Silva, M. J., and L. J. Gibson. "Modelling the Mechanical Behavior of Vertebral Trabecular Bone: Effects of Age-related Changes in Microstructure." Bone 21 (1997): 191-99.
Vertebral Trabecular Bone

3D Voronoi model

- Same analysis, now with 3D Voronoi model
- Periodic $3 \times 3 \times 3$ cells, $\rho^*/\rho_s = 0.1$
- Used beam elements, FEA, linear elastic only
- Percolation threshold $\sim 50\%$, strut removed
- Comparison of 2D + 3D results for modulus: in 3D, modulus reduction more gradual than in 2D
- Also for 2D + 3D - modulus reduction similar for regular + Voronoi structures
3D Voronoi Model


Vajjhala et al, 2000
3D Voronoi Model


Vajjhala et al, 2000
Metal foams as bone substitute materials

- Metals used in orthopaedic implants (e.g., hip, knee)
- Co-Cr, Ti, Ta. Stainless steel alloys
- Biocompatible, corrosion resistant
- But moduli of metals > modulus of bone
  
  \[ E_{\text{Ti}} = 110 \text{ GPa} \quad E_{\text{CoCr}} = 18 \text{ GPa} \quad E_{\text{bulk bone}} = 0.01-2 \text{ GPa} \]
- Stress shielding can lead to bone resorption.

- To improve mechanical interaction between implant + bone
  
  - Porous sintered metal beads used to coat implants - promote bone ingrowth
  
  - Also, wire mesh coatings have been developed, primarily for flat implant surfaces
  
  - Recently, interest in using metal foams as coatings
  
  - Longer term, interest in using in replacement vertebral bodies

- Variety of processes for making metal foam implant coatings
Metal Foams: Microstructure

Ta, replicating PU foam with CVD

Ti, replication of PU foam by slurry infiltration and sintering

Ti, fugitive phase

Ti, foaming agent

Ti, expansion of Ar gas

Ti, freeze-casting (freeze-drying)

Ti, selective laser sintering

Ni-Ti, high temperature synthesis (powders mixed, pressed and ignited by, for example, tungsten coil heated by electrical current)


Image sources given in Cellular Materials in Nature and Medicine
Processing

(a) Replicate open cell polymethane foam
   - Pyrolyze Pu foam \( \rightarrow \) 2% dense vitreous carbon
   - Coat with Ta by CVD = struts 99% Ta, 1% C
   - Cell size 400-600 \( \mu \text{m} \); coating thickness 40-60 \( \mu \text{m} \) \( \rho^* \rho^* = 0.15-0.25 \)
   - "Trabecular metal" (Zimmer) trade name.
   - Ta forms surface oxide Ta2O5 - does not bond to bone

   - But, if treat with dilute NaOH, then heat to 300°C + cool, then
     Submerge in simulated body fluid (ion conc. matches human blood plasma)
     = get apatite coating on foam struts, which bonds to bone

(b) Infiltrate slurry of titanium hydride into open cell foam
   - Heat treat to decompose TiH2
   - Sinter remaining Ti (also removes initial foam)

(c) Fugitive phase methods
   - Mix TiB2 powder + fugitive phase powder
   - Heat to Ti (\( \sim 200^\circ \text{C} \)) to decompose filler, then to Ti2 (\( 1200^\circ \text{C} \)) to sinter Ti powder
Metal Foams: Processing

Foaming agent evolves gas at temperature at which polymer is liquid.

FREEZE-CASTING

Rapid Prototyping

Processes

(d) expansion of foaming agent
(e) freeze casting (freeze drying)
(f) rapid prototyping (3D Printing, selective laser sintering)

$\sigma$ - $\epsilon$ curves - similar to other foams

data for $E^*$, $\sigma^*$
Ti Foam: Stress-strain

Bone in Evolutionary Studies
Bone Structure in Evolutionary Studies

- Phylogenetic chart - big picture - structural biomaterials (mineralized)
- Sponges - first multicelled animal
  - Calcarea: CaCO₃ spicules (needles)
  - Hexactinellida: SiO₂ - "glass sponges"
- Demospongiae: most sponges - some have SiO₂ spicules
  - Spong m (type of collagen)

- Cnidarians - eq. Corals, jellyfish
  - Corals CaCO₃
- Mollusca - bivalves, snails, octopus
  - If mineralized CaCO₃
- Arthropods eq. hexapoda (insects), arachnide (spiders), crustaceans (shrimp, lobster)
  - Exoskeleton of insects + spiders: chitin
  - Crustaceans: chitin may be mineralized with CaCO₃
Vertebrates

- cyclostomata - jawless fish - lampreys hagfish
  - no vertebra - notochord
  - no bone
- chondrichthyes - sharks, rays, skates
  - cartilaginous skeleton - some mineralization, but not true bone
- actinopterygii - ray finned fish
  - true bone
  - 450 million years ago (MYA)

Bone structure + loading

- bone grows in response to loading
- bone structure reflects mechanical loading + function e.g. quadruped vs biped
- evolutionary studies have looked at trabecular bone architecture + density.
**METAZOA**

From: *The Timetree of Life*. Hedges, S. B., and S. Kumar (eds.) © 2009 Oxford University Press. All rights reserved. This content is excluded from our Creative Commons license. For more information, see [http://ocw.mit.edu/help/faq-fair-use/](http://ocw.mit.edu/help/faq-fair-use/).
Venus Flower Basket
(*Euplectella aspergillum*)

- Hierarchical structure
- Remarkably stiff, tough
- Joanna Aizenberg (Harvard)
- Aizenberg et al (2004) Biological glass fibers: correlation between optical and structural properties. PNAS
Fig. 2. A timetree of vertebrates. Times of divergence are averages of estimates from different studies listed in Table 3. Abbreviations: C (Carboniferous), Cm (Cambrian), CZ (Cenozoic), D (Devonian), J (Jurassic), K (Cretaceous), Np (Neoproterozoic), O (Ordovician), P (Permian), Pg (Paleogene), PR (Proterozoic), S (Silurian), and Tr (Triassic).

Common ancestor of all boned vertebrates roughly 450 MYA

(Hagfish video)
Trabecular bone studies in human evolution

*Oreopithecus bambolii* (book et al, 1999)

- 7–9 MYA late Miocene hominid, found in Italy
- quadraped or biped?
- compared trabecular architecture in ilium in apes, *O. bambolii*, humans
- only had 2 fragments of ilium - left + right
- took radiographs of both + digitally reconstructed a single ilium

Comparison
(a) posterosuperior margin - marginal handles thicker than apes
(b) anterolateral margin - iliac bundle relatively structured compared to apes
(c) anteroinferior margin - well developed a-c spine not seen in apes
(d) supra acetabular area - high density region

Collectively, observations suggest *O. bambolii* trab. architecture in ilium more similar to humans than apes

- suggests habitual bipedal locomotion (humans - obligatory bipeds)
Trabecular architecture:
Ilium

Figure removed due to copyright restrictions. See Figure 1: Rook L., et al. "Oreopithecus was a Bipedal Ape after All." Proceedings of the Natural Academy of Sciences 96 (1999): 8795-99.
Digitally reconstructed ilium

Figure removed due to copyright restrictions. See Figure 2: Rook L., et al. "Oreopithecus was a Bipedal Ape after All." Proceedings of the Natural Academy of Sciences 96 (1999): 8795-99.
Comparison of trabecular architecture

Figure removed due to copyright restrictions. See Figure 3: Rook L., et al. "Oreopithecus was a Bipedal Ape after All." Proceedings of the Natural Academy of Sciences 96 (1999): 8795-99.