Mechanical behavior of bioinspired tiled composites as a function of geometry and material properties

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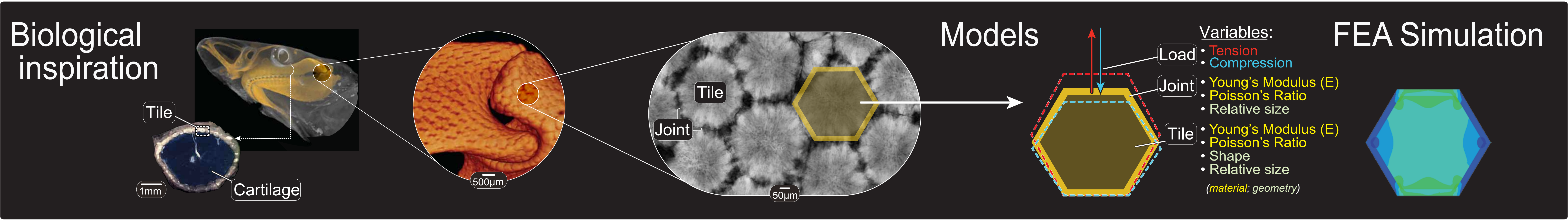
Research Aims

Nature has evolved a variety of solutions for load-bearing skeletal materials, marrying structure and mechanics in interesting ways. Our HFSP project investigates the skeletons of sharks and rays, composites with unique material properties and a tiled outer armoring particularly amenable to modeling. In this project we investigate the links between structure and function in tiled composites, using analytical modeling, CAD designs and finite element modeling, inspired by our investigations of shark and ray skeletal tissue ultrastructure.

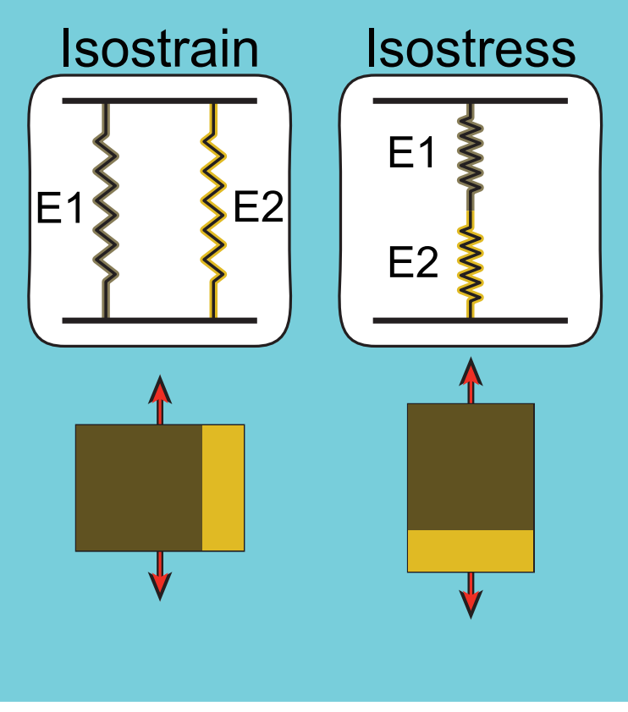


Variables:
- Load
  - Tension
  - Compression
- Joint
  - Young's Modulus (E)
  - Poisson's Ratio
  - Relative size
- Tile
  - Young's Modulus (E)
  - Poisson's Ratio
  - Shape
  - Relative size

(material; geometry)

Analytical models

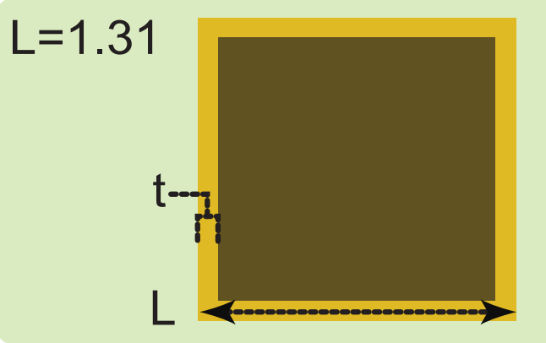
Analytical models for all tile shapes—based on Voigt/Reuss (isostrain/isostress) models for composites— allow us to investigate the effects of tile and joint geometry and material on the overall effective modulus of the tiled composite, while also acting as verification for our FE models.



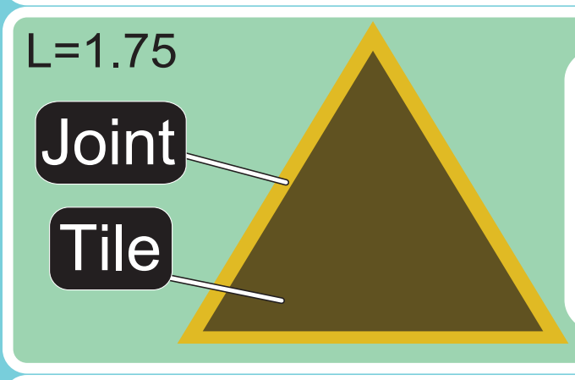
E1 = Tile modulus; E2 = Joint modulus

Effective modulus equation:

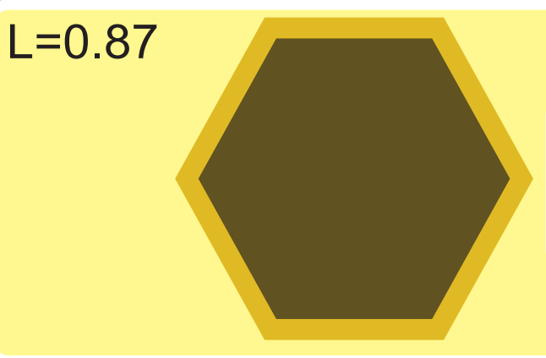
Assumptions/standardization:
- *All shapes have same perimeter*
- *Tile/joint Poisson's ratio = 0.0*
- *Joint modulus in tension = 1 GPa*
- *Joint thickness (t) = 1/20 hexagon width (8.7e^{-2})*



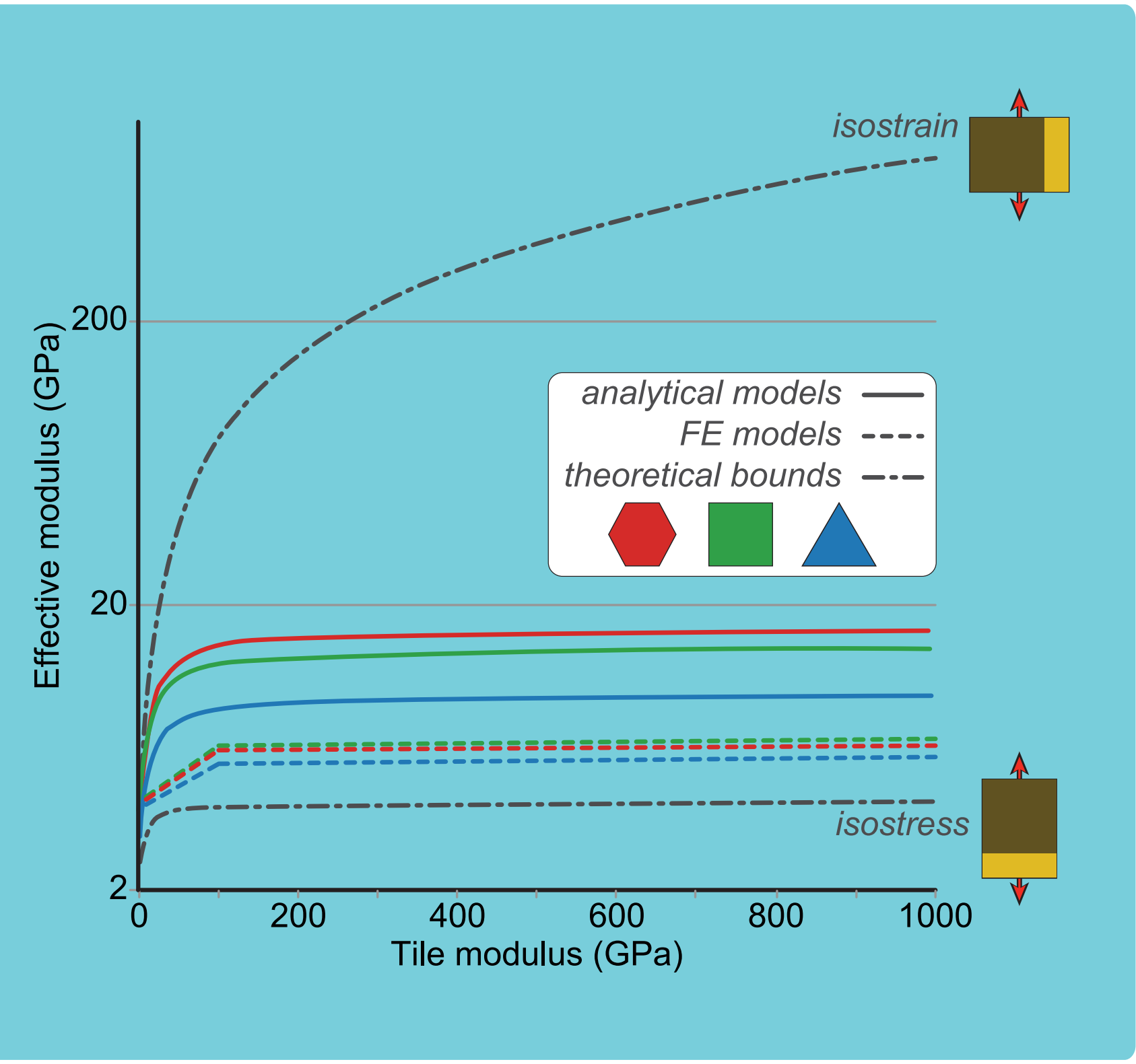
$$\frac{E2\,\left(E1\,\left(l^2 - l\,t + t^2\right) + E2\,t\,(l - t)\right)}{l\,(E1\,t + E2\,(l - t))}$$



$$\frac{E1\;E2\left(\frac{L\left(-0.22\,l^2 - 2.56\,l\,t + 1.79\,t^2\right)}{1.\,E1\,L - 13.77\,E1\,t - 2.\,E2\,L + 13.77\,E2\,t} + \frac{0.77\,(l - 2.32\,t)\,(l - 1.\,t)\left(l^2 - 2.82\,l\,t + 2.32\,t^2\right)}{0.5\,E1\,l\,t + E2\left(l^2 - 3.32\,l\,t + 2.32\,t^2\right)}\right)}{l^2}$$



$$\frac{E1\;E2\left(E1\,t\left(1.59`\,l^4 - 8.93`\,l^3\,t + 21.26`\,l^2\,t^2 - 22.05`\,l\,t^3 + 8.33`\,t^4\right) + E2\left(0.43`\,l^5 - 2.80`\,l^4\,t + 9.93`\,l^3\,t^2 - 21.26`\,l^2\,t^3 + 22.05`\,l\,t^4 - 8.33`\,t^5\right)\right)}{l^2\,(1.`\,E1\,t + 0.215`\,E2\,l - 1.`\,E2\,t)\left(1.`\,E1\,l\,t + 2.`\,E2\,l^2 - 6.65`\,E2\,l\,t + 4.65`\,E2\,t^2\right)}$$



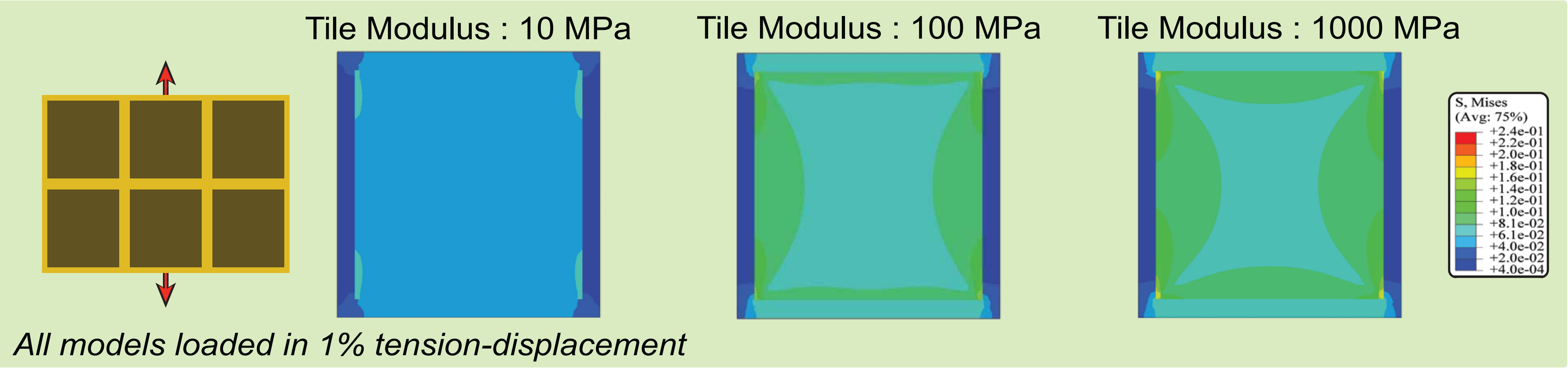
FE models

Finite element (FE) models allow visualization of stress, strain and other components of force in our tiling models, as a function of experimental variations in geometric and material properties:

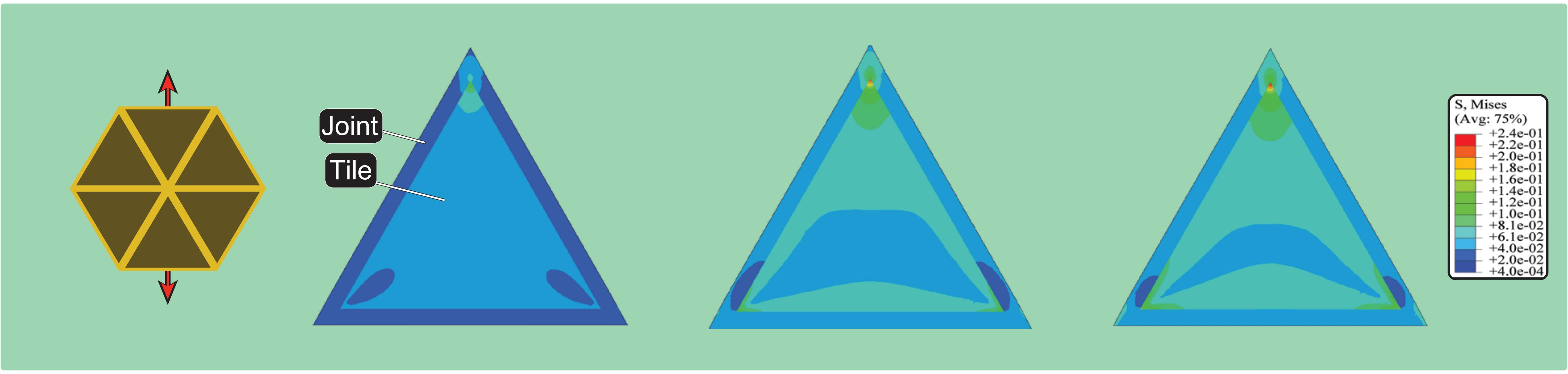
Tile modulus (MPa):
3000-100000
Joint modulus (MPa):
30-3000 (tension)
150-15000 (compression)
Poisson's ratio:
0.00 - 0.499
Joint thickness:
1/200-1/500 tile width

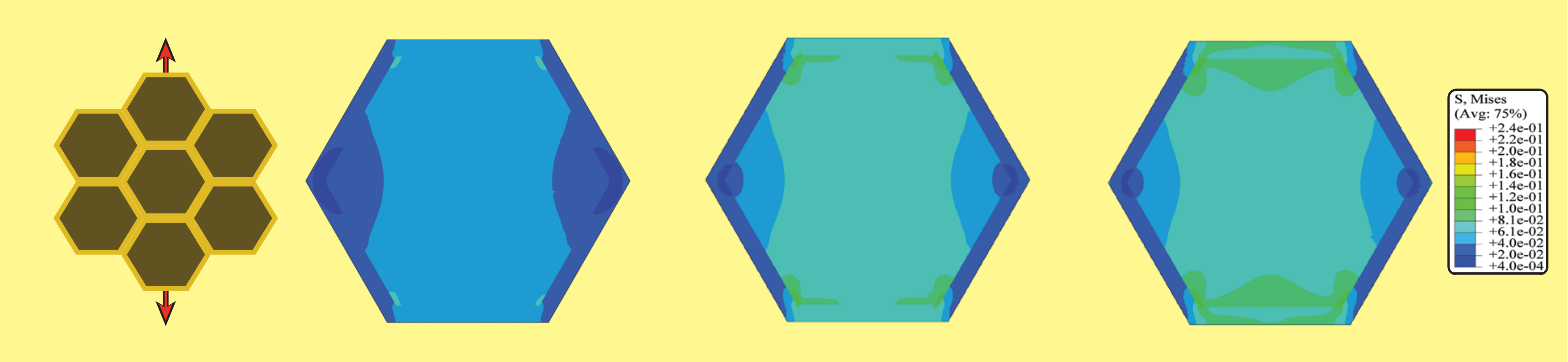
Tested ranges are based around experimental data on shark cartilage and other tissues:

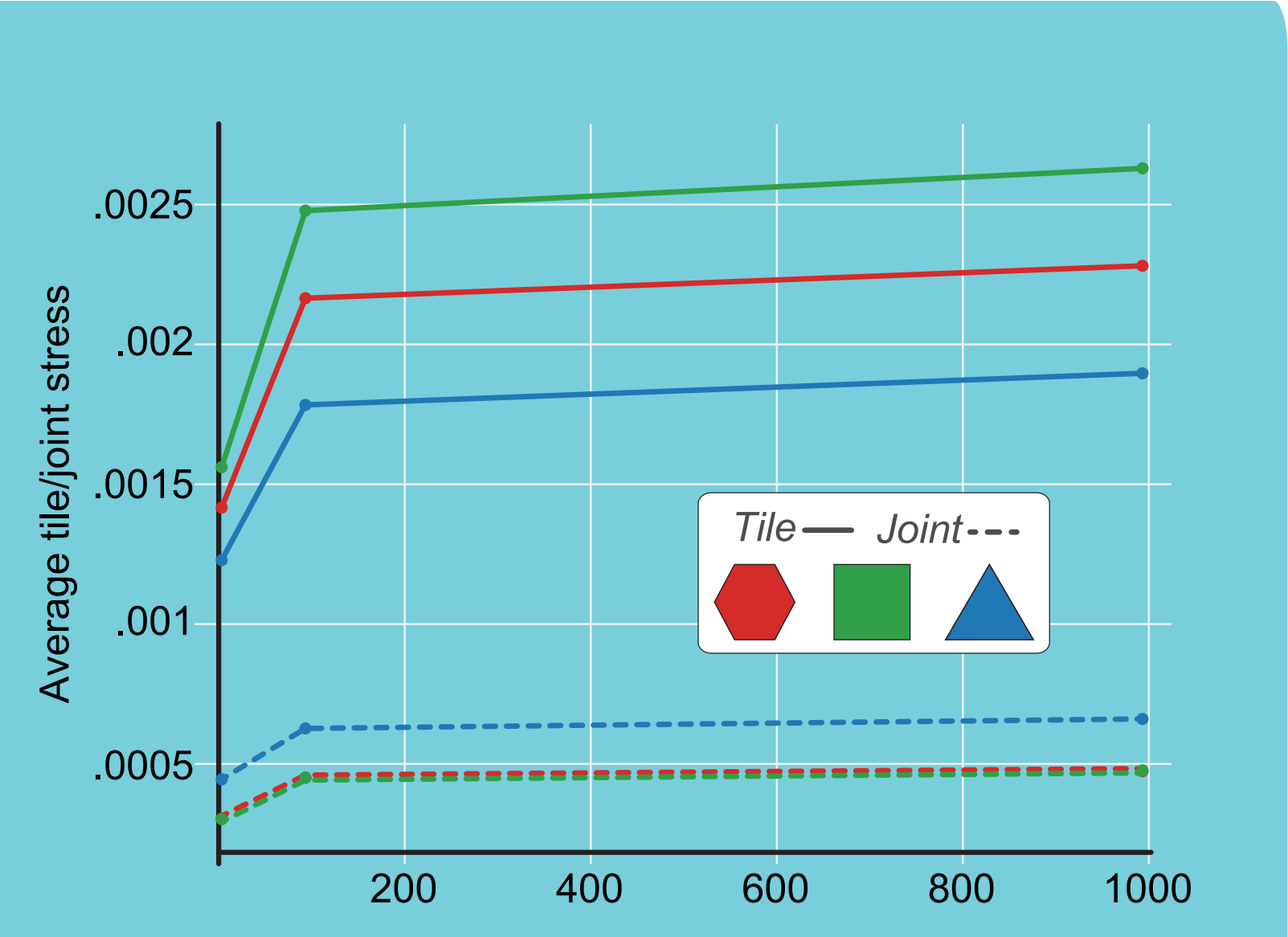
Tiles:
35000 MPa; 0.3 P.R.
Joints:
300 MPa (compression); 1500 MPa (tension); 0.3 P.R.; 1/500 width of tile

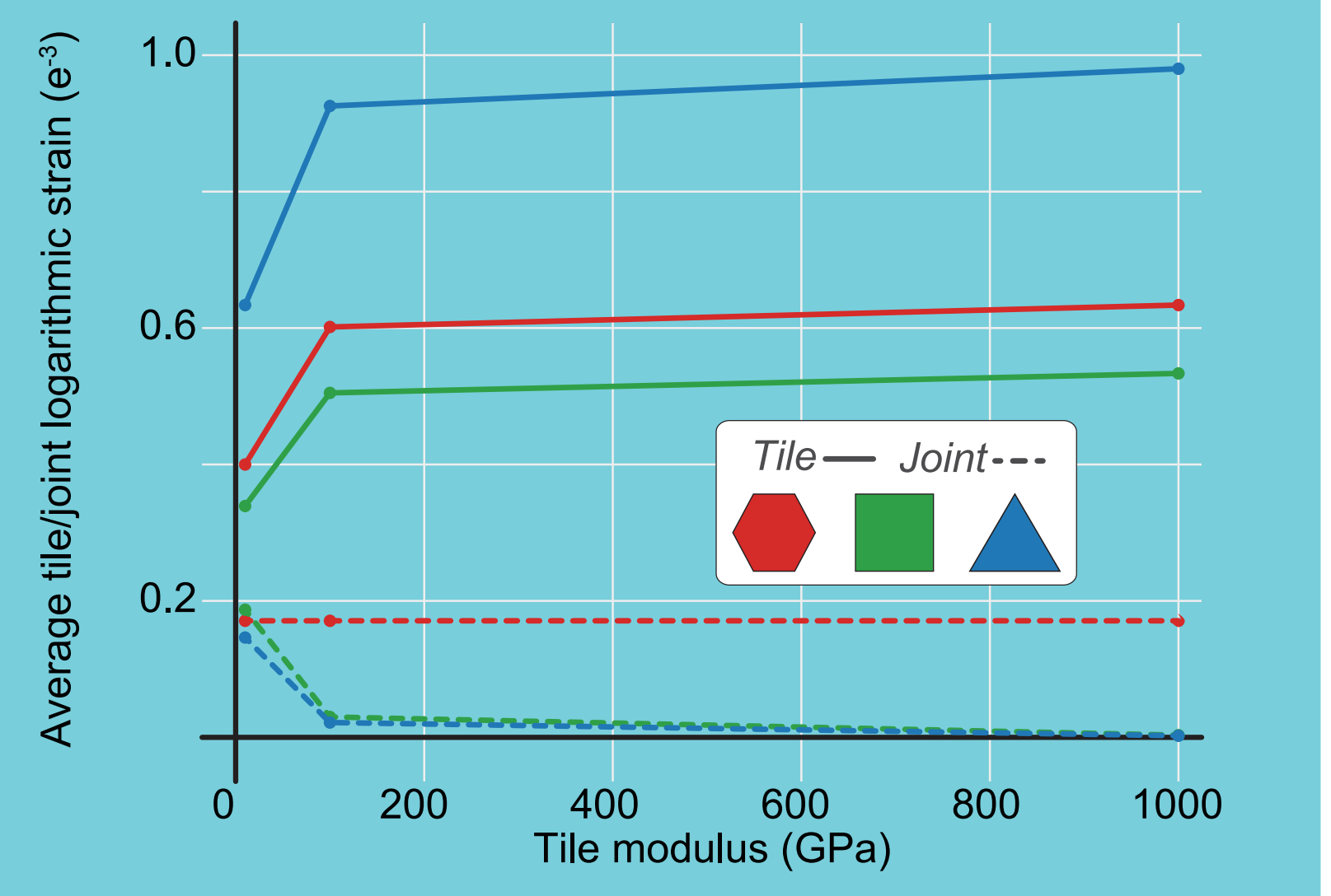


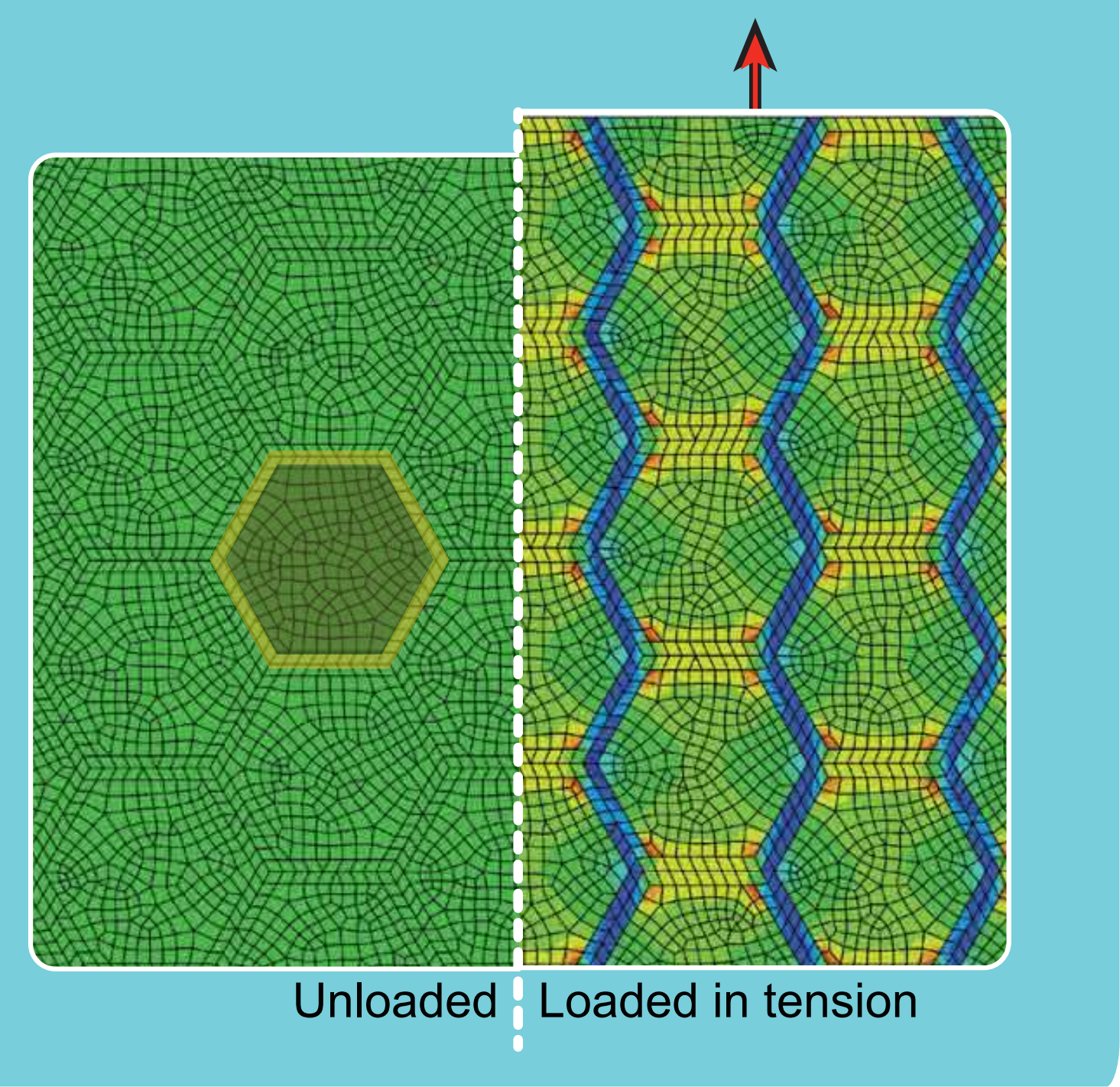
All models loaded in 1% tension-displacement









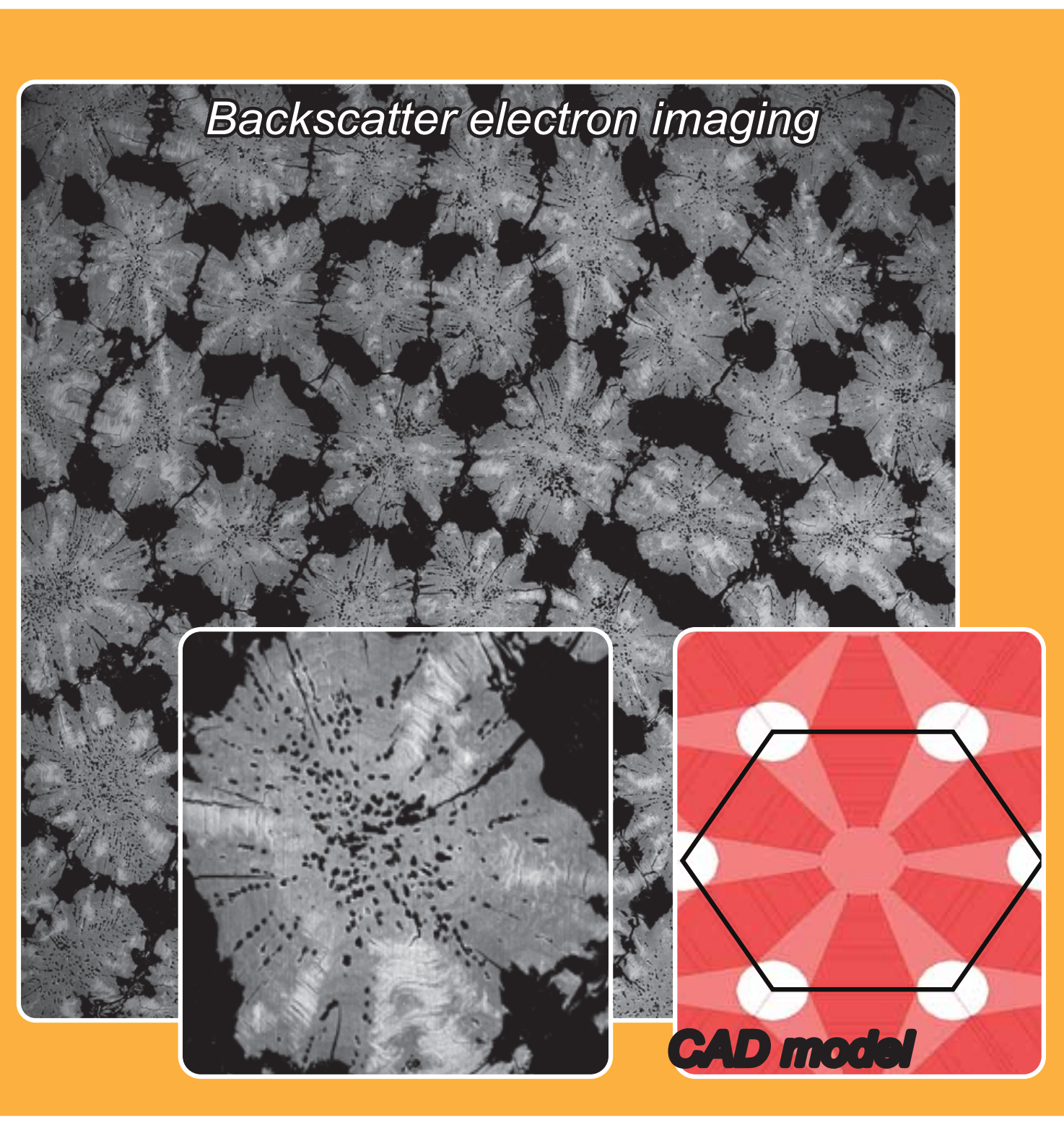


Future directions

BIO-REALISTIC MODELS

We aim to include more biological features (e.g. regions of higher stiffness and mineral density, observed in our ultrastructural analyses) to help understand how each feature adds performance factors to our base models.

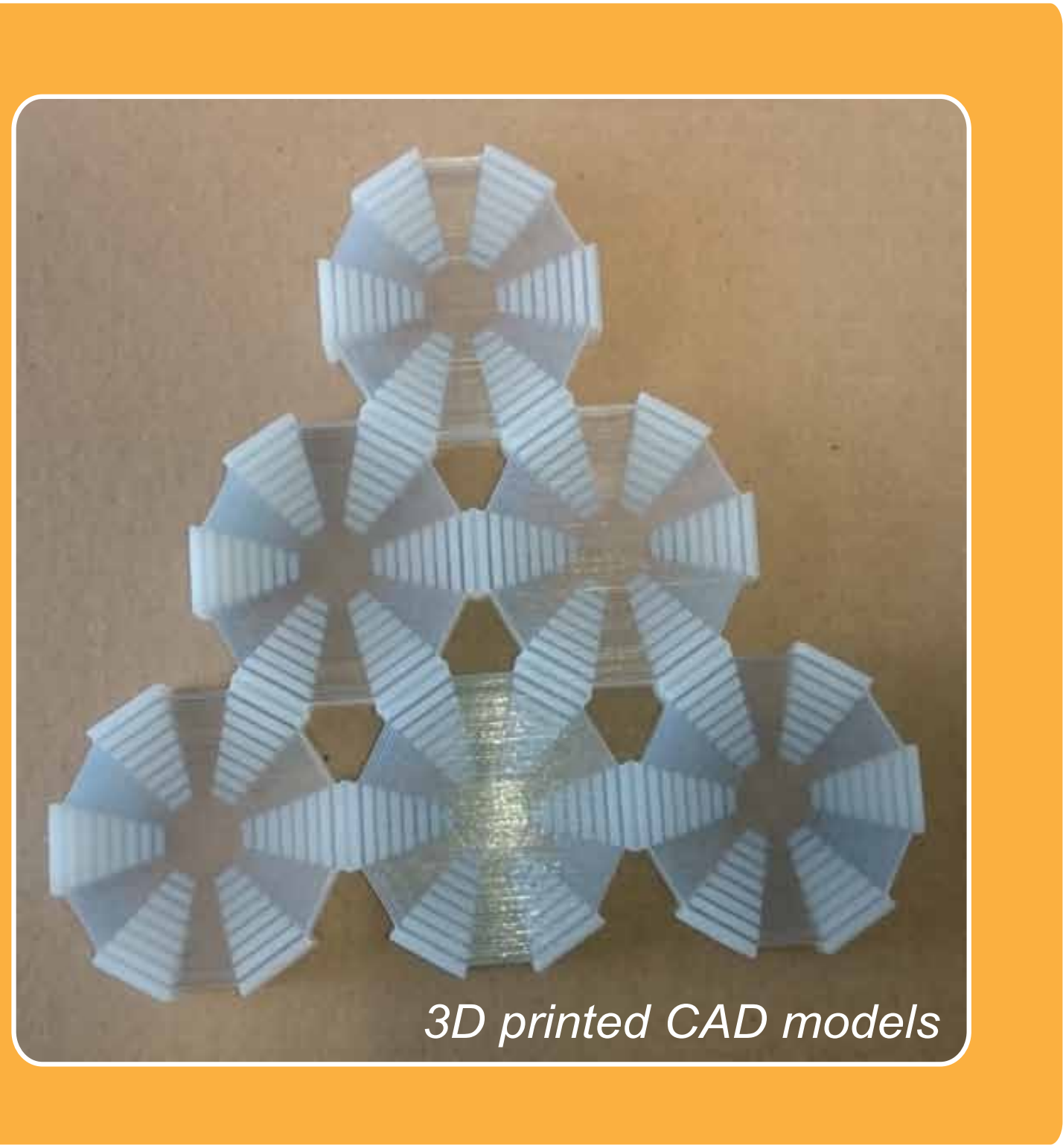
Backscatter electron imaging of shark skeletal tissue



3D-PRINTED MODELS

3D-printed versions of our FE models will allow mechanical testing and verification of failure modes, while helping us investigate the manufacturing feasibility of our composite designs.

3D printed tessellated skeletal piece from microCT data


3D printed CAD models

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