The role of modelling and simulation in *understanding* the stiffness & strength of bio-structures and implants

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"*All models are wrong but some are useful* "

-George Box

Implants and structures…

- Structural modelling of bio-structures
- Structure-property relationships
- Generic lattice models
- Cardiovascular Stents: plasticity and recoil
- Opthalmological scaffolds
- Porous implants: woodpile architecture
- Concluding remarks

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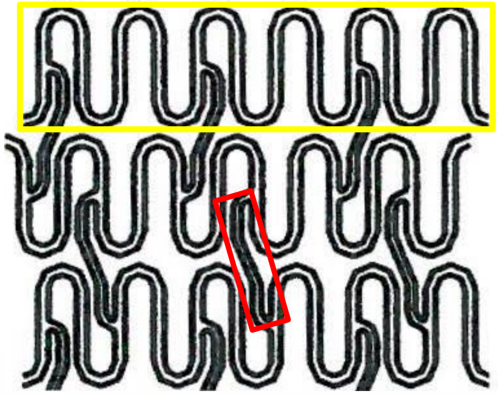
Bio-structures: structural mechanics

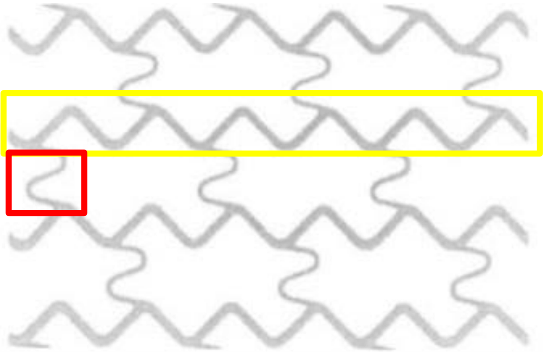
- Computer experiments are cheap
- Computer experiments save time
- Computer experiments cannot be as reliable as the real experiments
- But they provide excellent starting point for design of implants

“ In theory there is no difference between theory and practice. In practice, there is.”

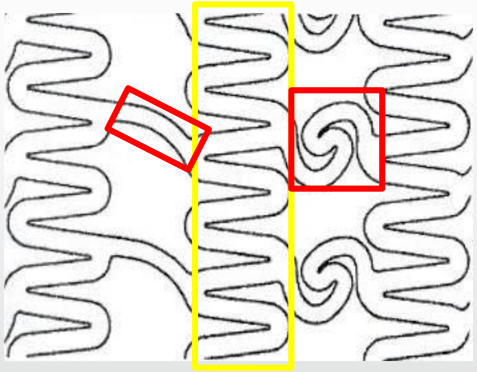
Stent architecture: Generic geometric features



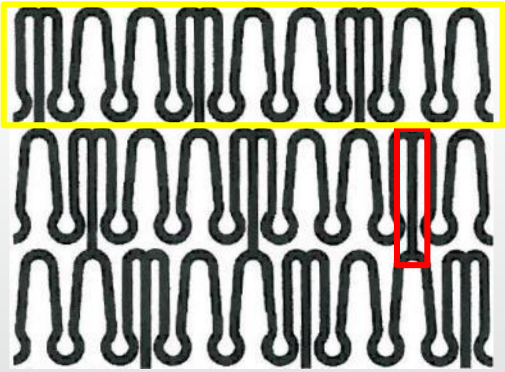
Coroflex stent pattern



Duraflex™ stent pattern



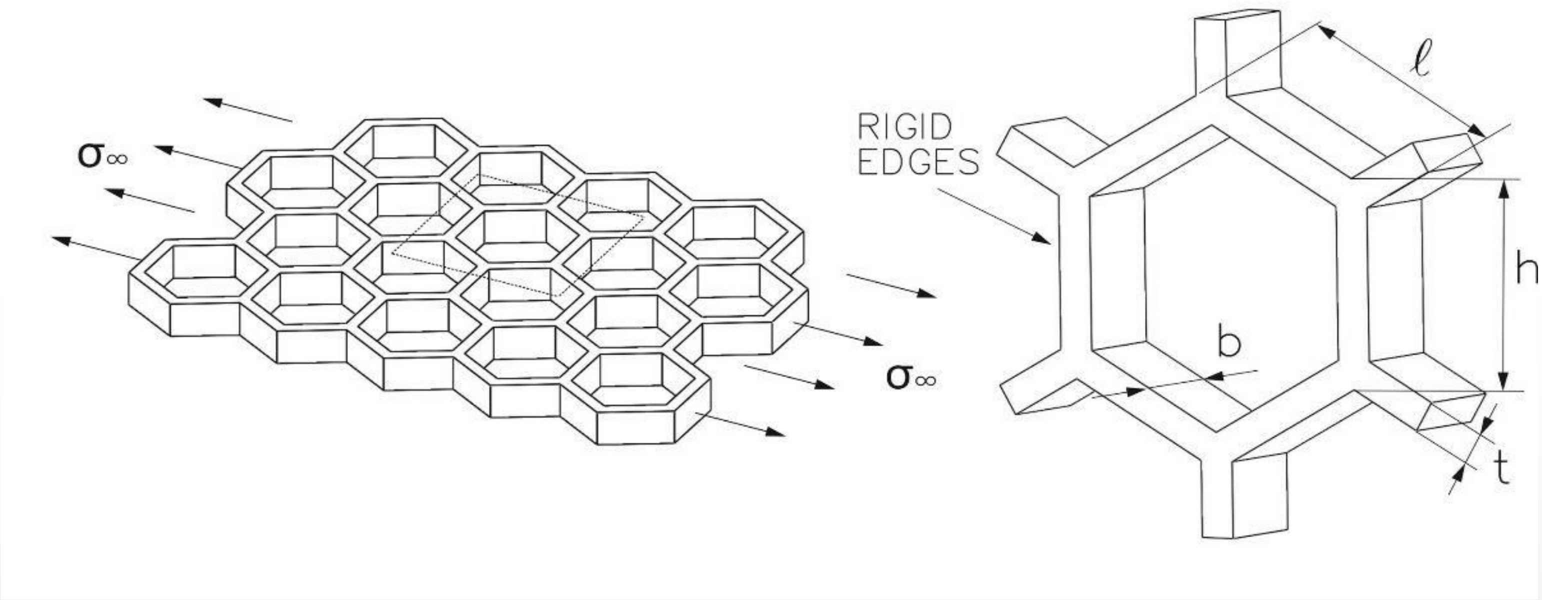
JOSTENT® Flex stent pattern

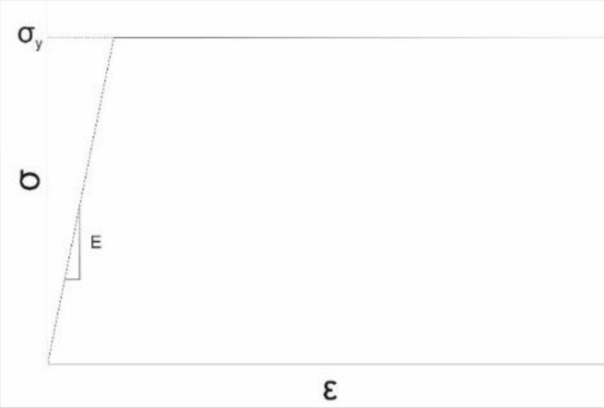


Multi-Link Ultra™ stent pattern

Serruys, Patrick W., and Michael JB Kutryk. "Handbook of coronary stents." (2011).

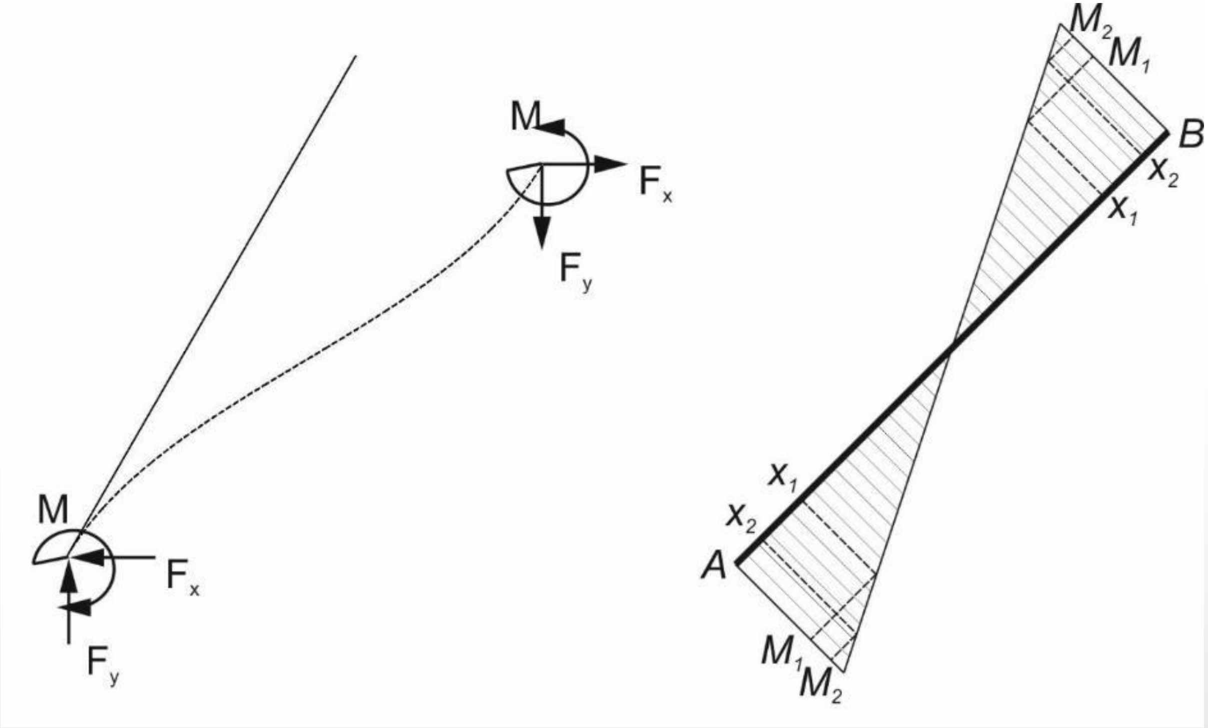
Geometric abstractions and what we can learn from them…





Materials abstraction: Elastic-perfectly plastic constitutive behaviour

Elasto-plastic bending of a cell-wall



$$F_x = \sigma_\infty \, (h + l \sin\theta)$$

$$\mathrm{M} = \frac{F_x l \sin\theta}{2}$$

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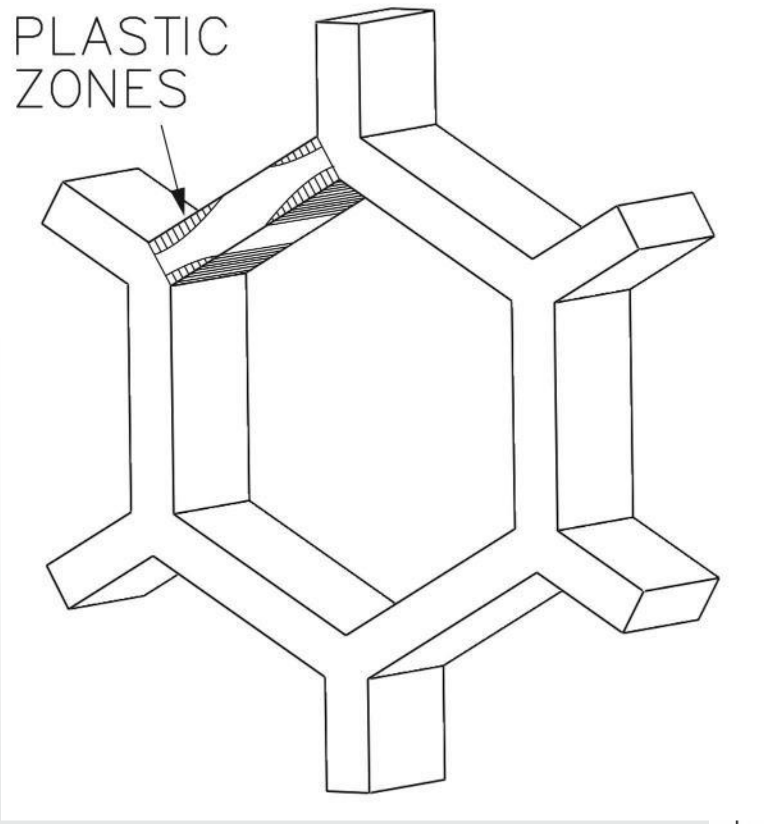
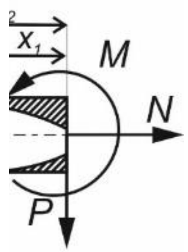
Elasto-plastic bending of a cell wall



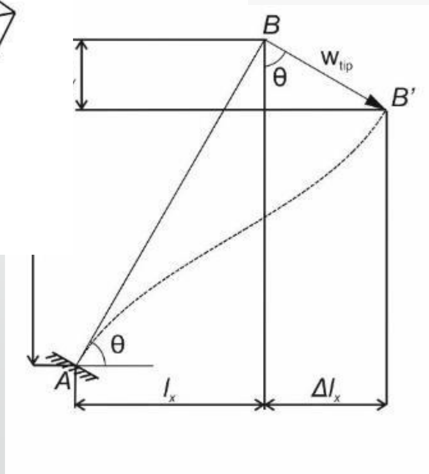


$$\varphi(n,m) = \begin{cases} m \\ 4(1-n)/\left(3-\dfrac{m}{1-n}\right)^2 \\ \dfrac{1}{\sqrt{(3(1-n^2)-2m)}} \end{cases}$$

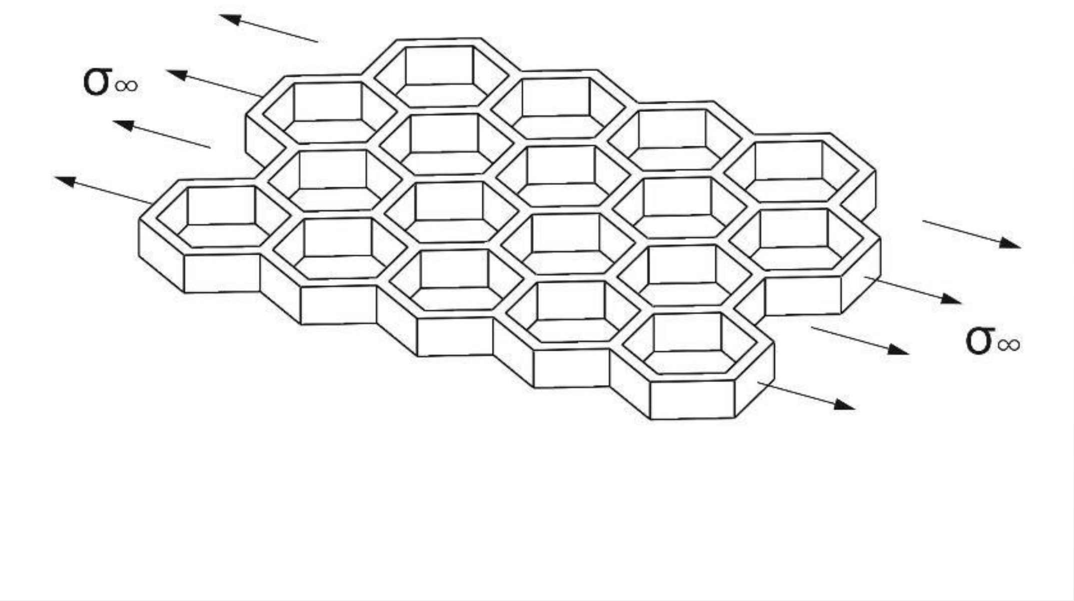
Integration along the beam

$$\Delta l_x, \Delta l_y$$

where $w_{tip} = \sqrt{\Delta l_x^2 + \Delta l_y^2}$

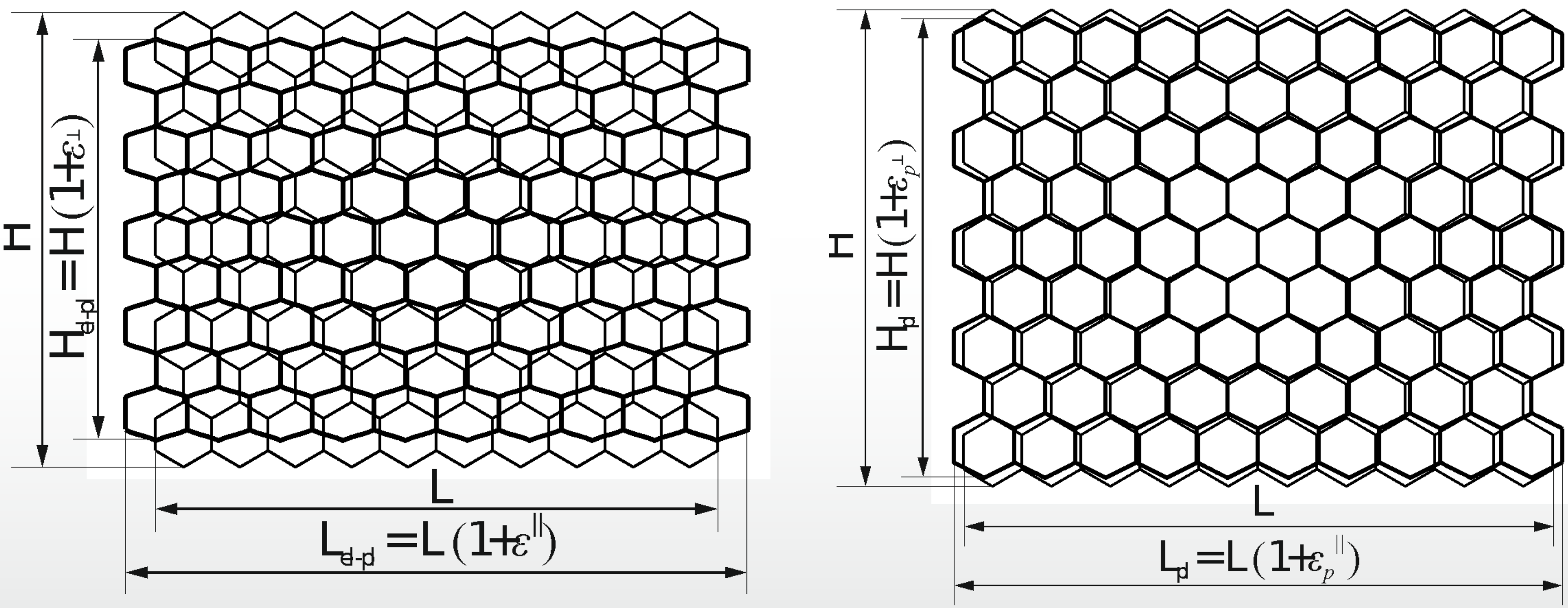


Elasto-plastic analysis of complete lattice



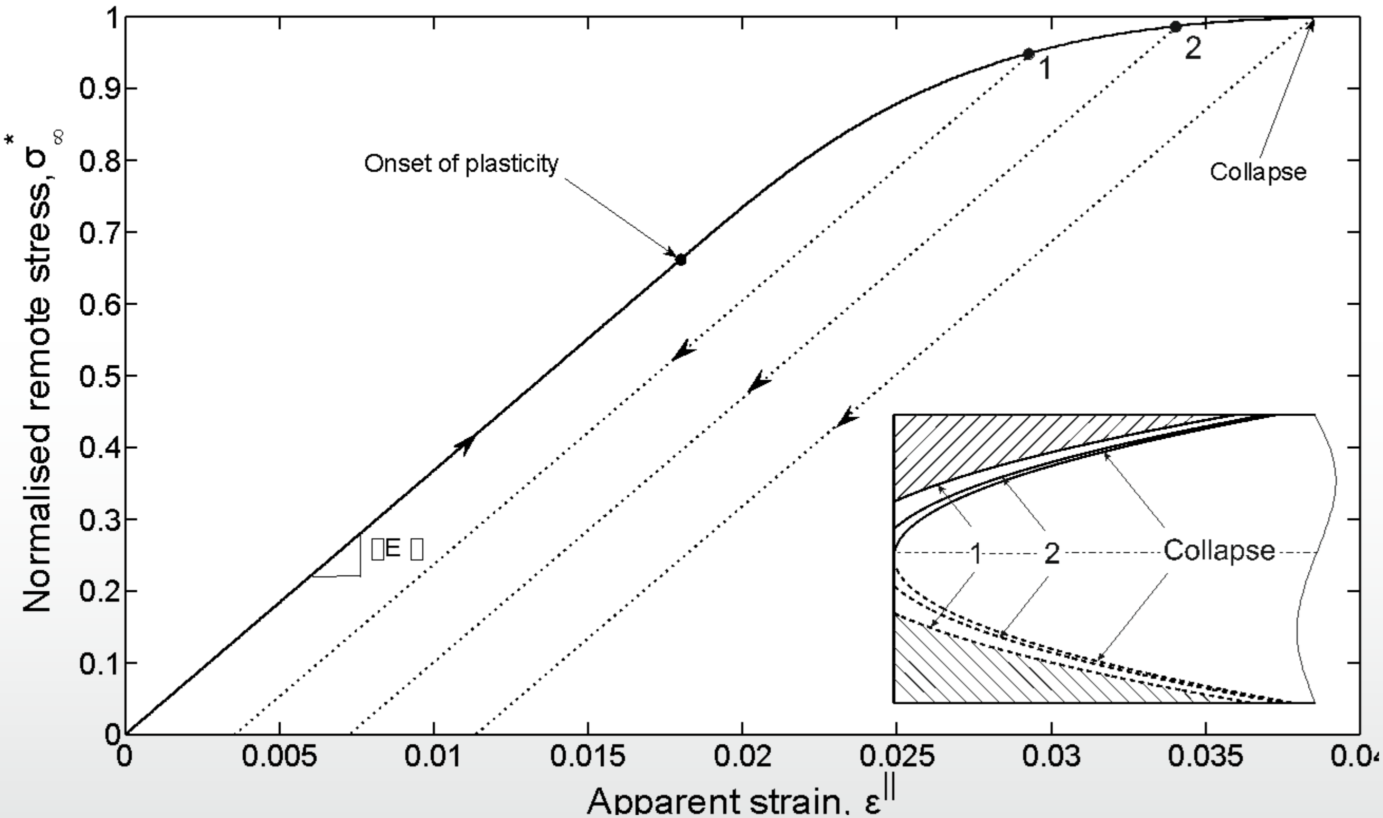
$$\varepsilon^{||} = \sqrt{\Delta l_x^2 + \Delta l_y^2}\,\frac{\tan\theta}{l} \qquad \varepsilon^{\perp} = \sqrt{\Delta l_x^2 + \Delta l_y^2}\,\frac{\cos\theta}{2l\sin\theta + h}$$

Elasto-plastic analysis and spring back



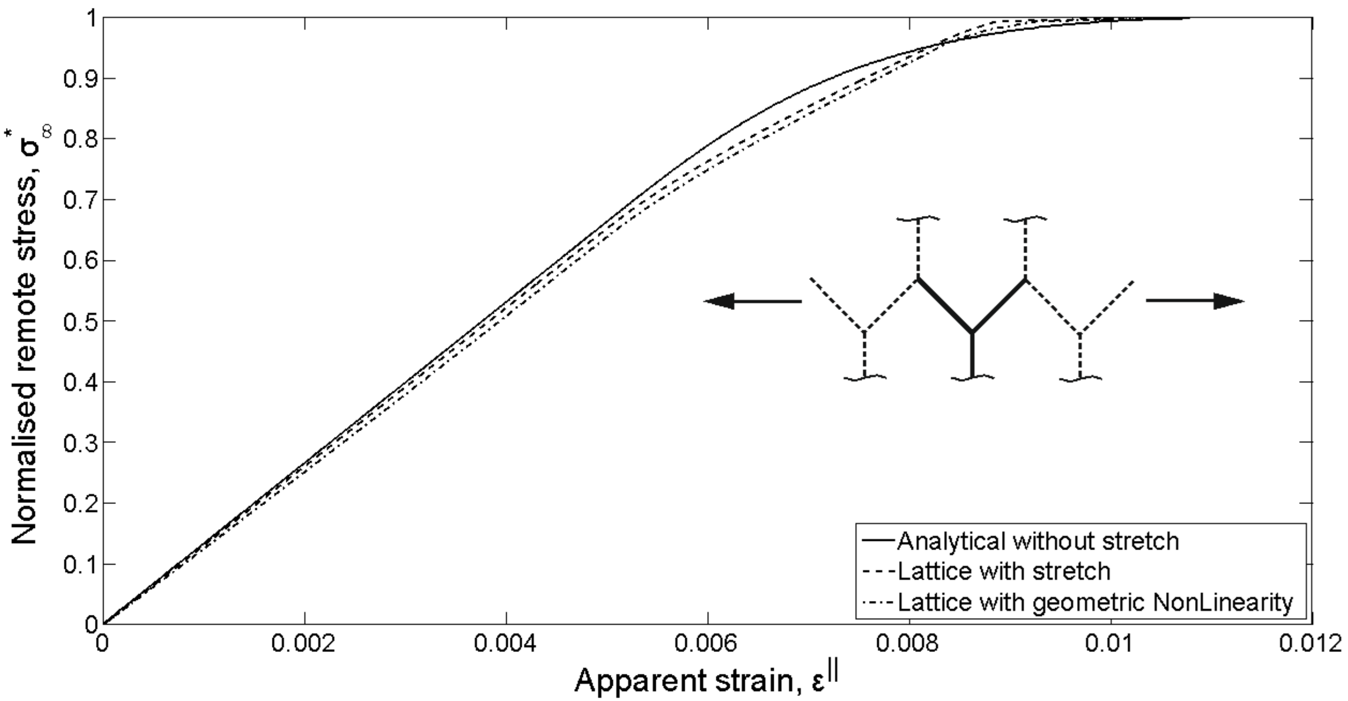
Elasto-Plastic deformation and spring back of an infinite honeycomb sheet subjected to a remote stress along the *x*-direction.

Apparent stress-strain curve



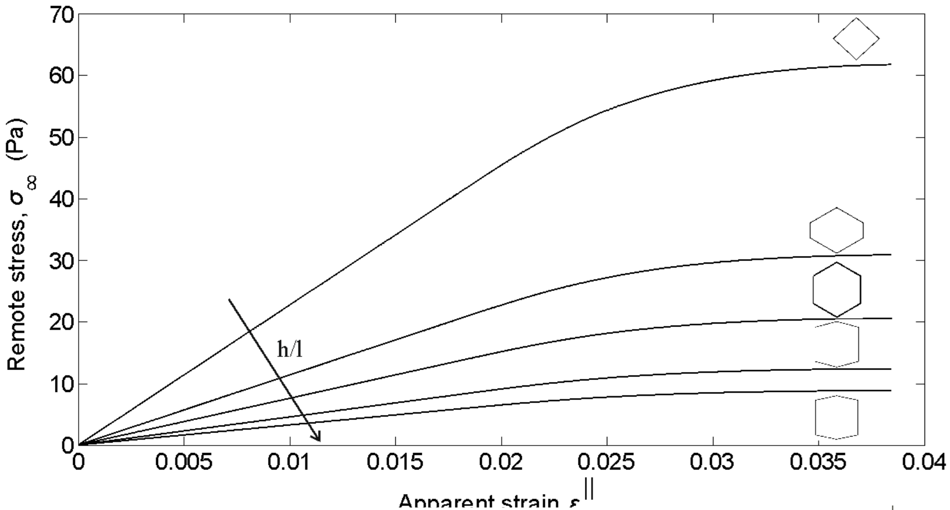
Tensile stress-strain curves for an infinite honeycomb sheet subjected to a remote uniaxial stress along the x-direction. The slope of the apparent stress-strain curve equals the apparent Young's modulus of the lattice with the tangent modulus diminishing beyond yielding.

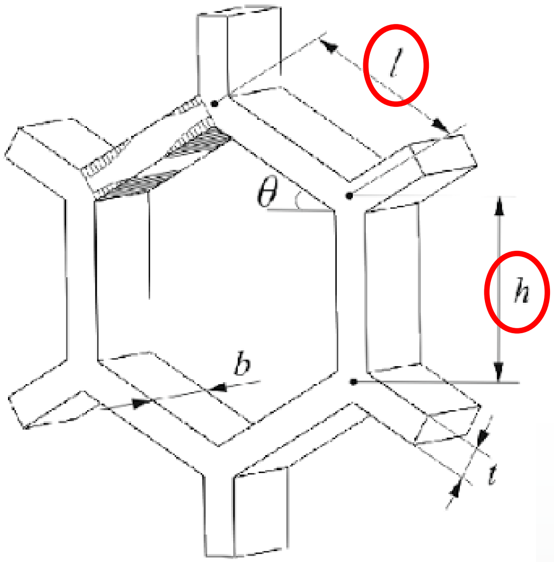
Analytical Vs Numerical

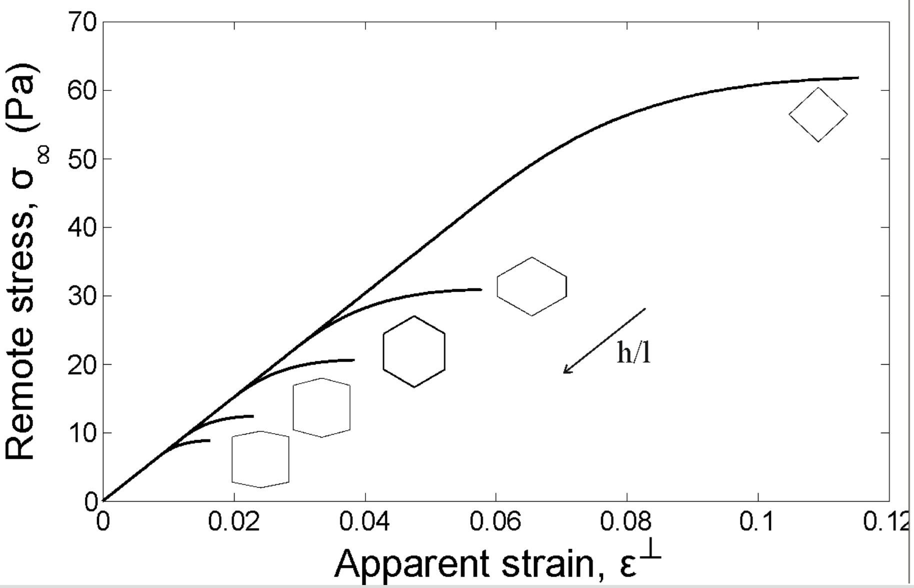


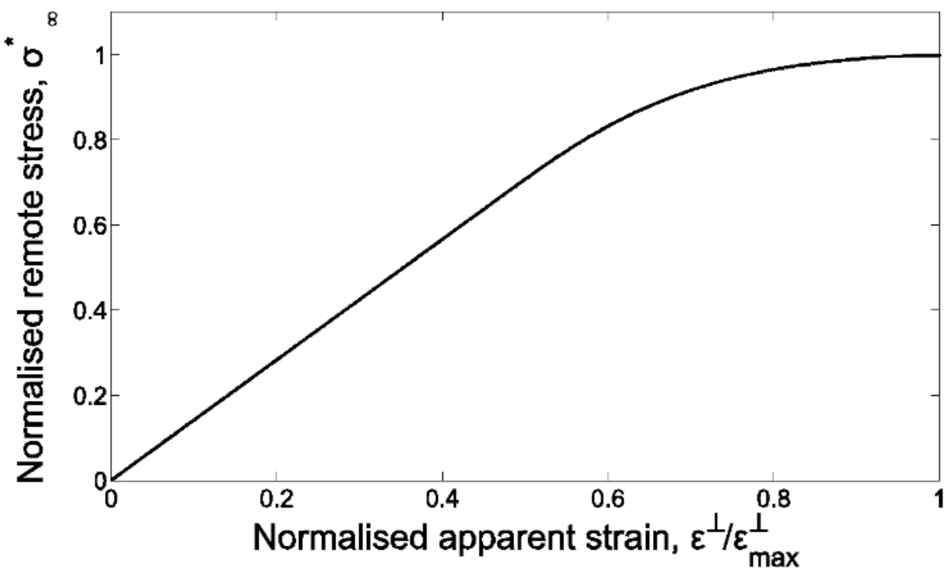
The analytical stress-strain curve is plotted against the response obtained from the finite element analysis to show the effect of cell wall stretch and shear correction on the elastoplastic response of hexagonal lattices.

Parametric study: h/l

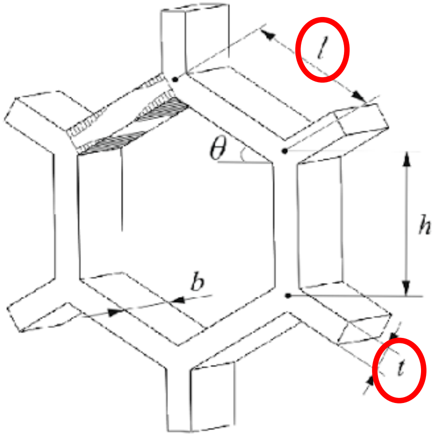


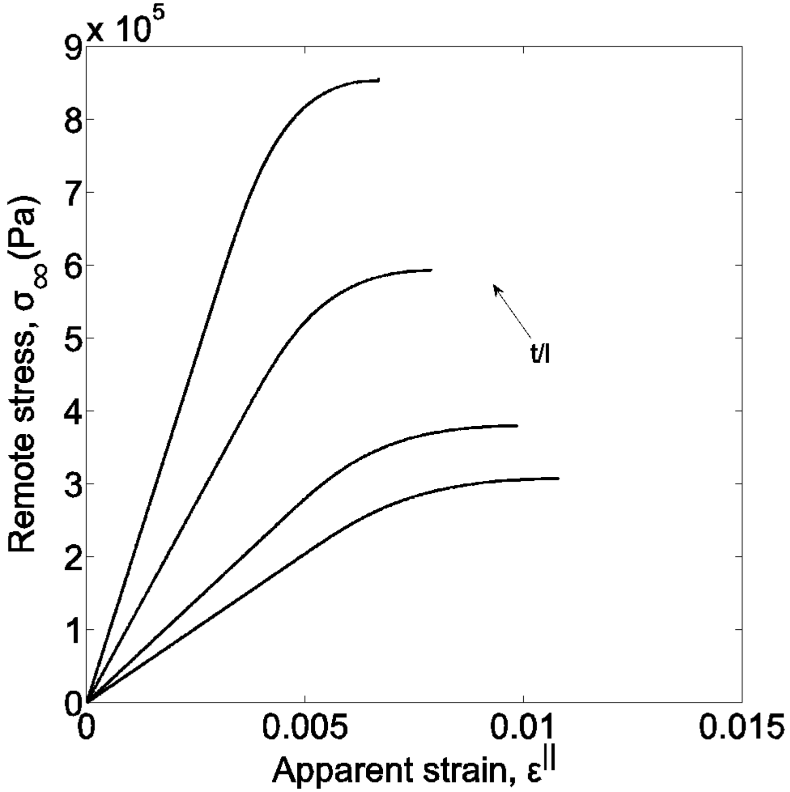


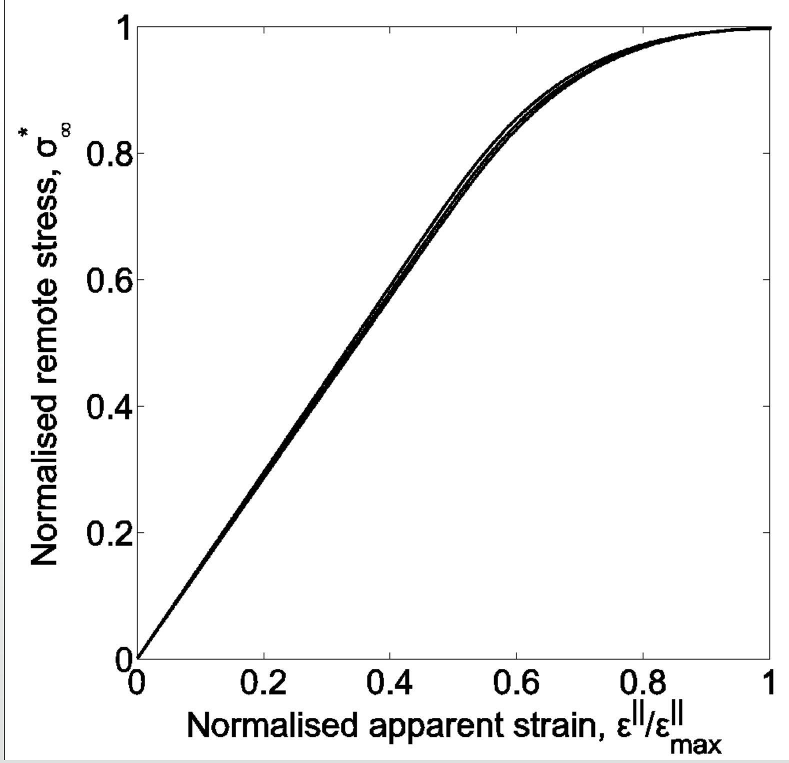




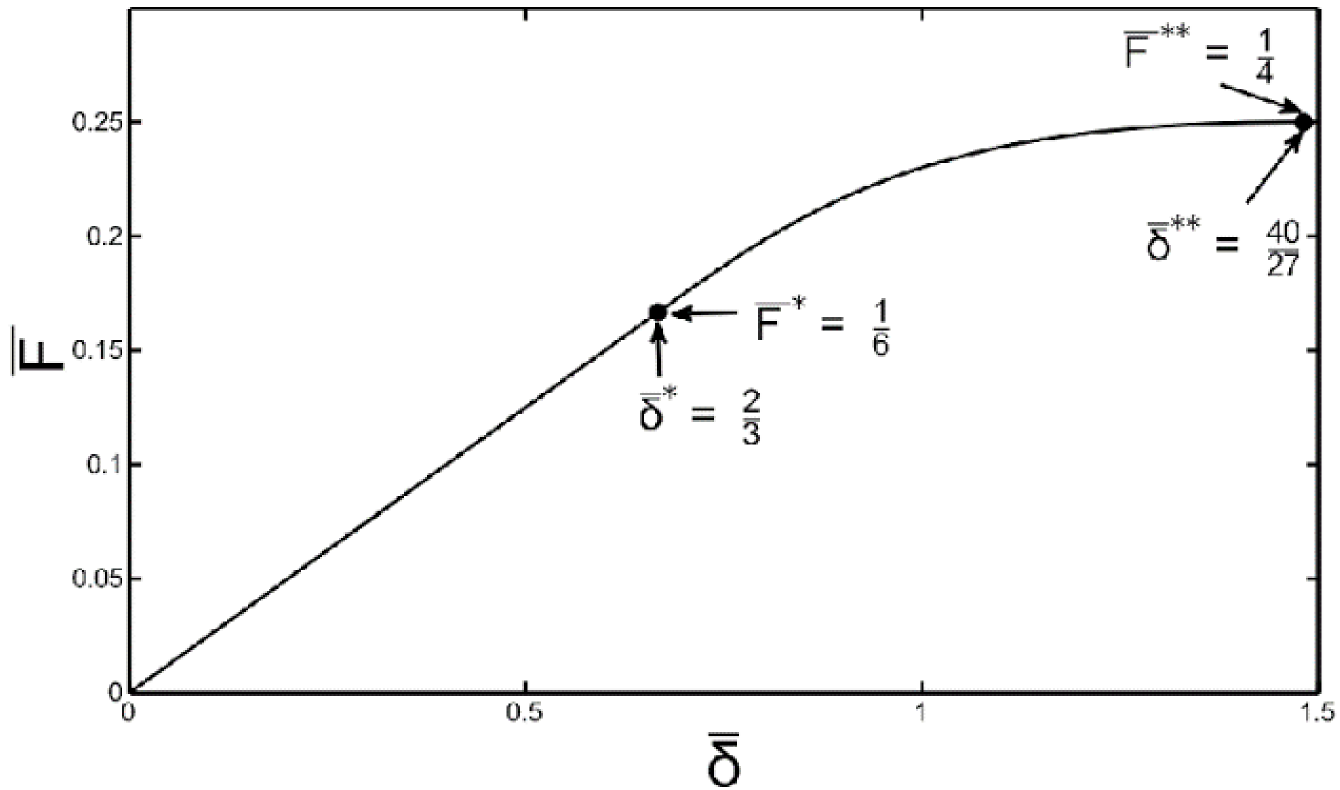
Parametric study: t/l



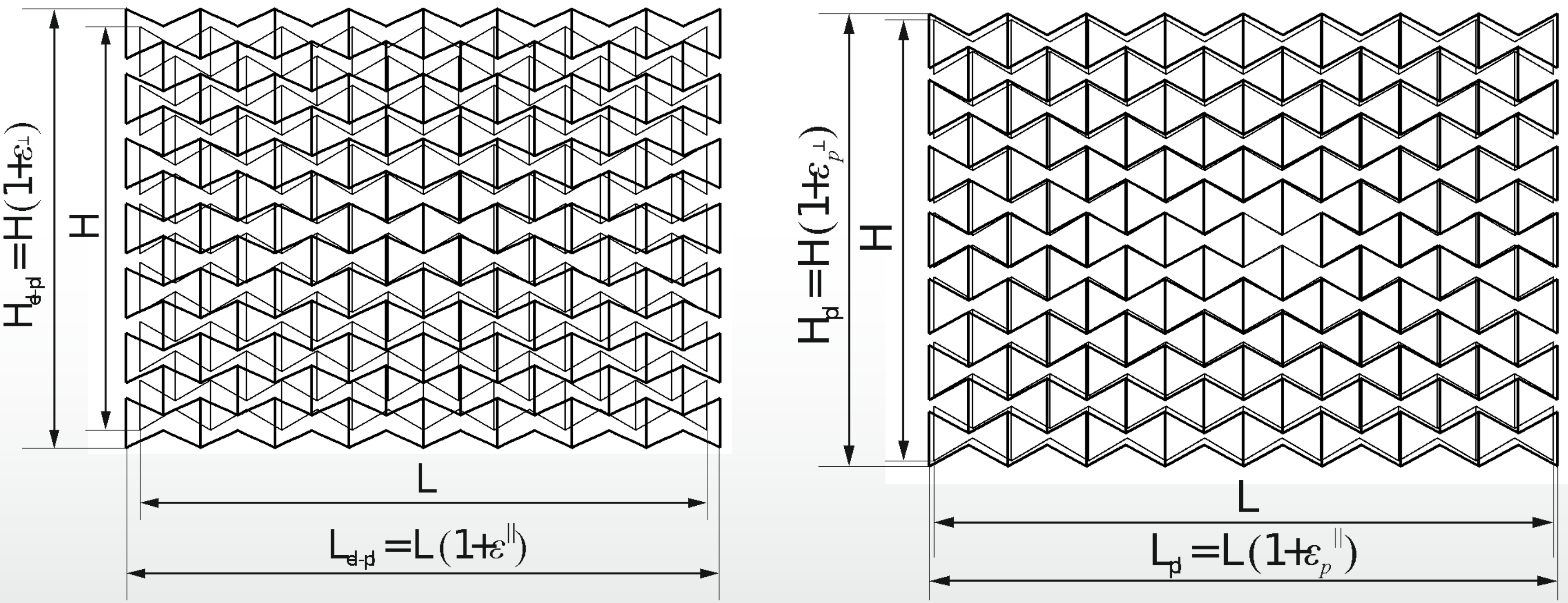




Renormalisation of variables and data collapse



Auxetic response: plasticity and recoil



Deformation of an auxetic lattice structure through plastic phase when loading is applied in the horizontal direction. Note the accompanying lateral expansion. Spring back upon release of load showing longitudinal as well as lateral contraction

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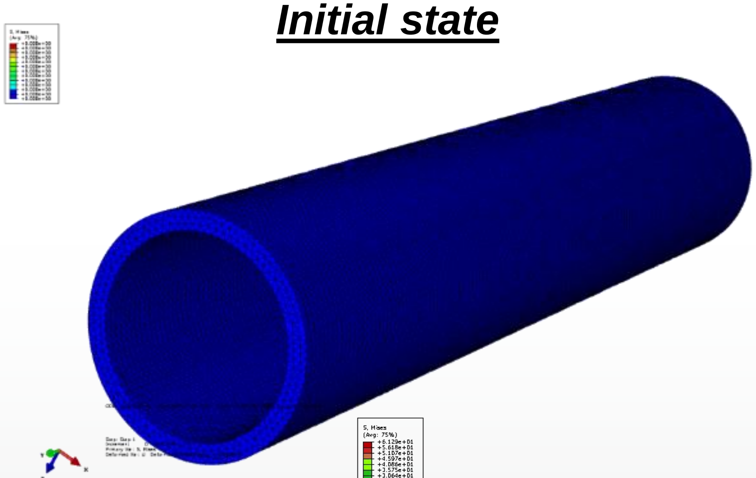
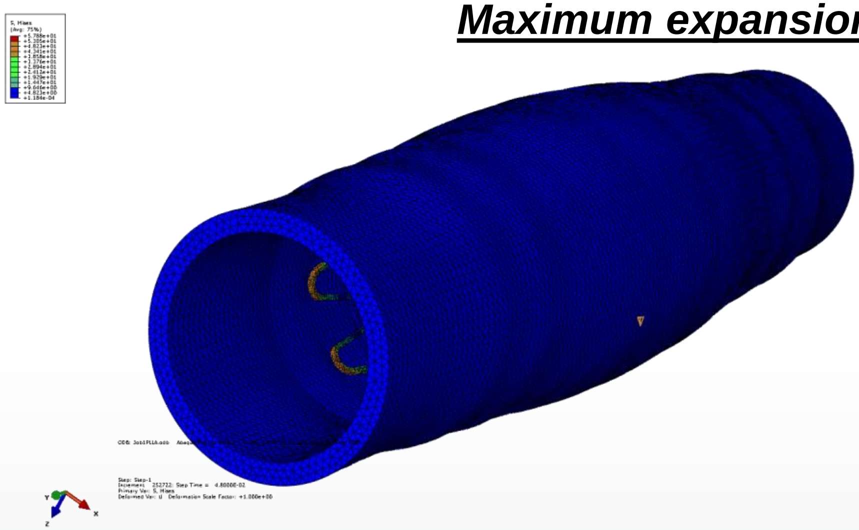
Results on stress/strain fields and recoil

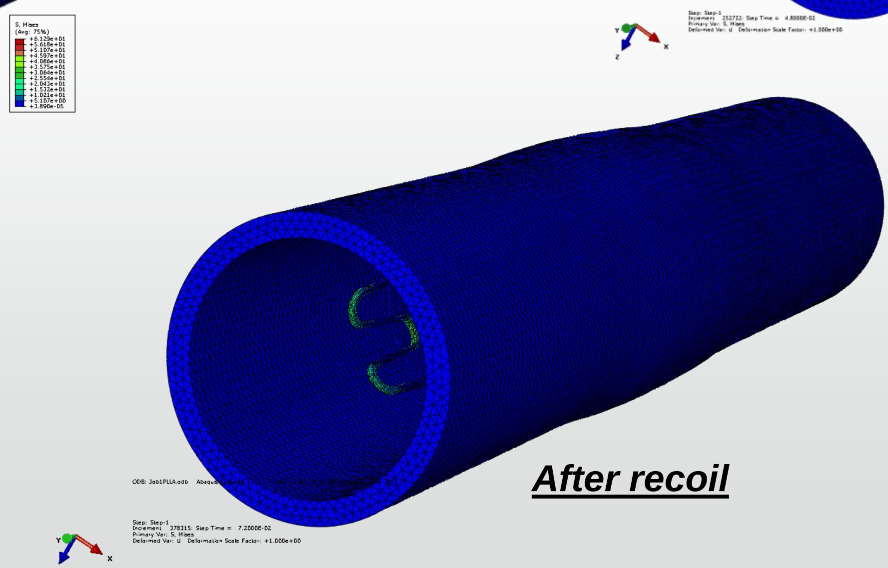
PLLA stent expansion

Initial state



Maximum expansion

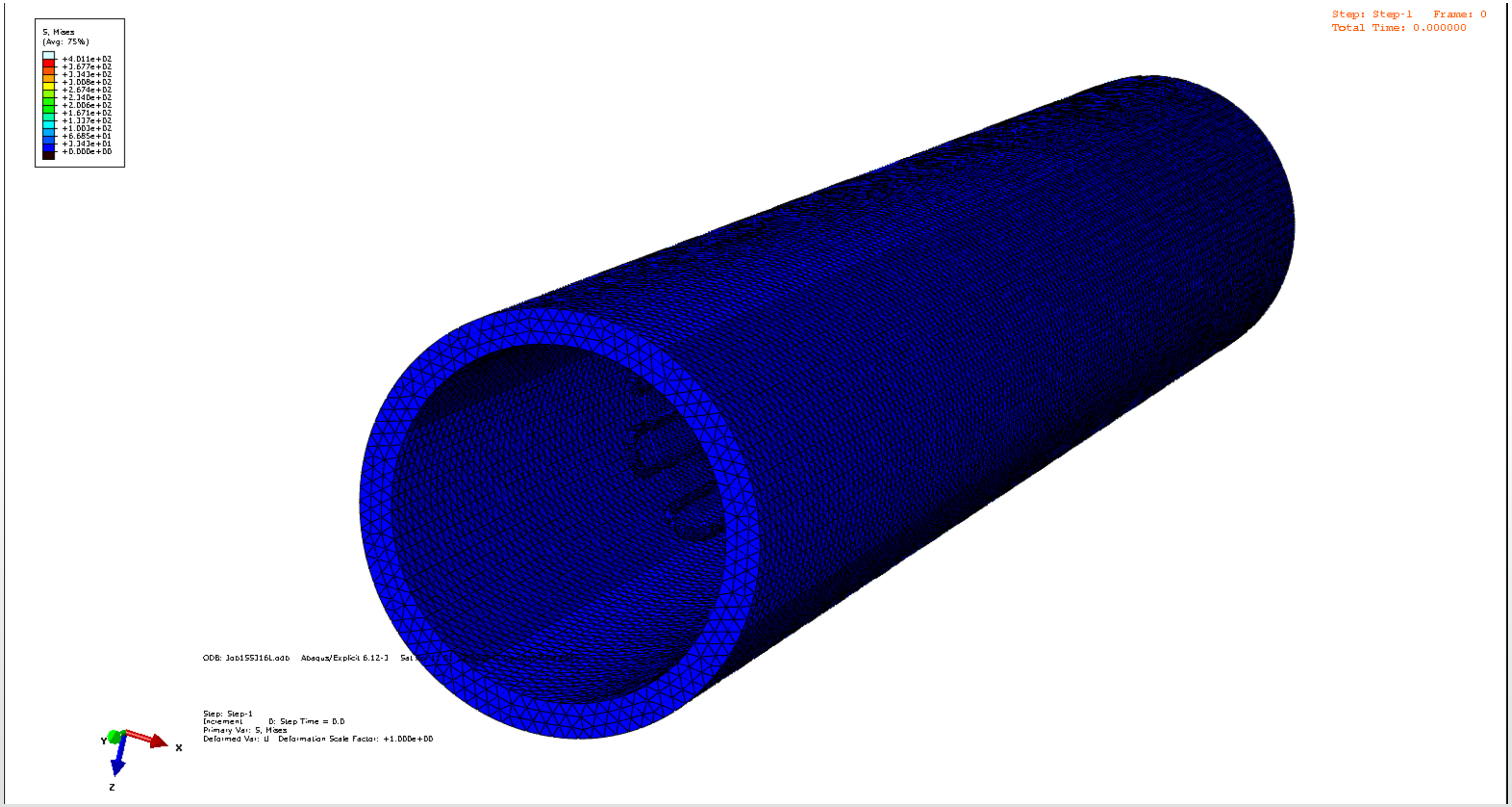




After recoil

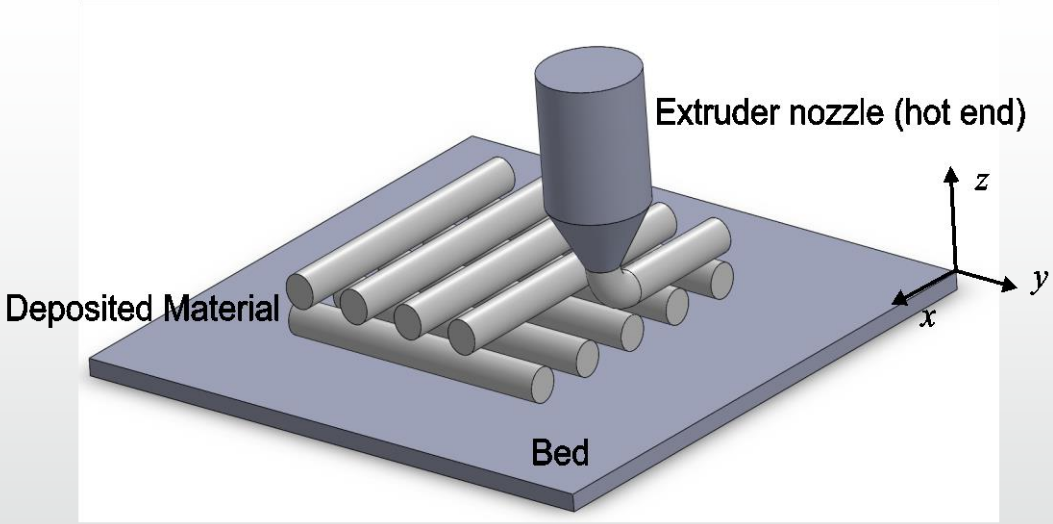
Results on stress/strain fields and recoil

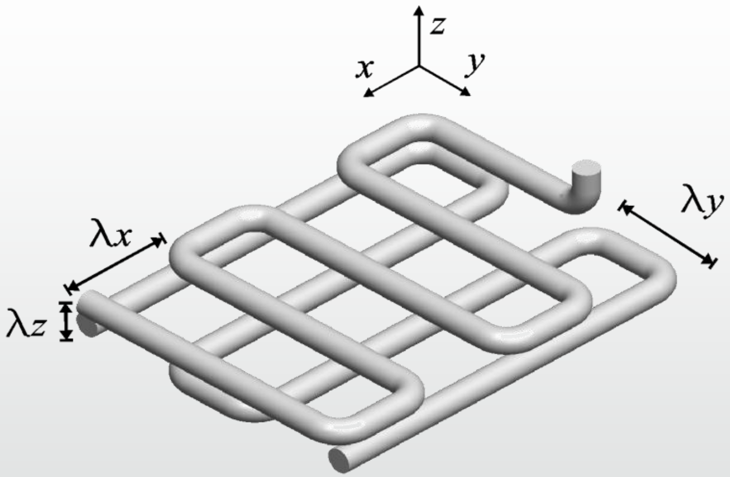
PLLA stent expansion



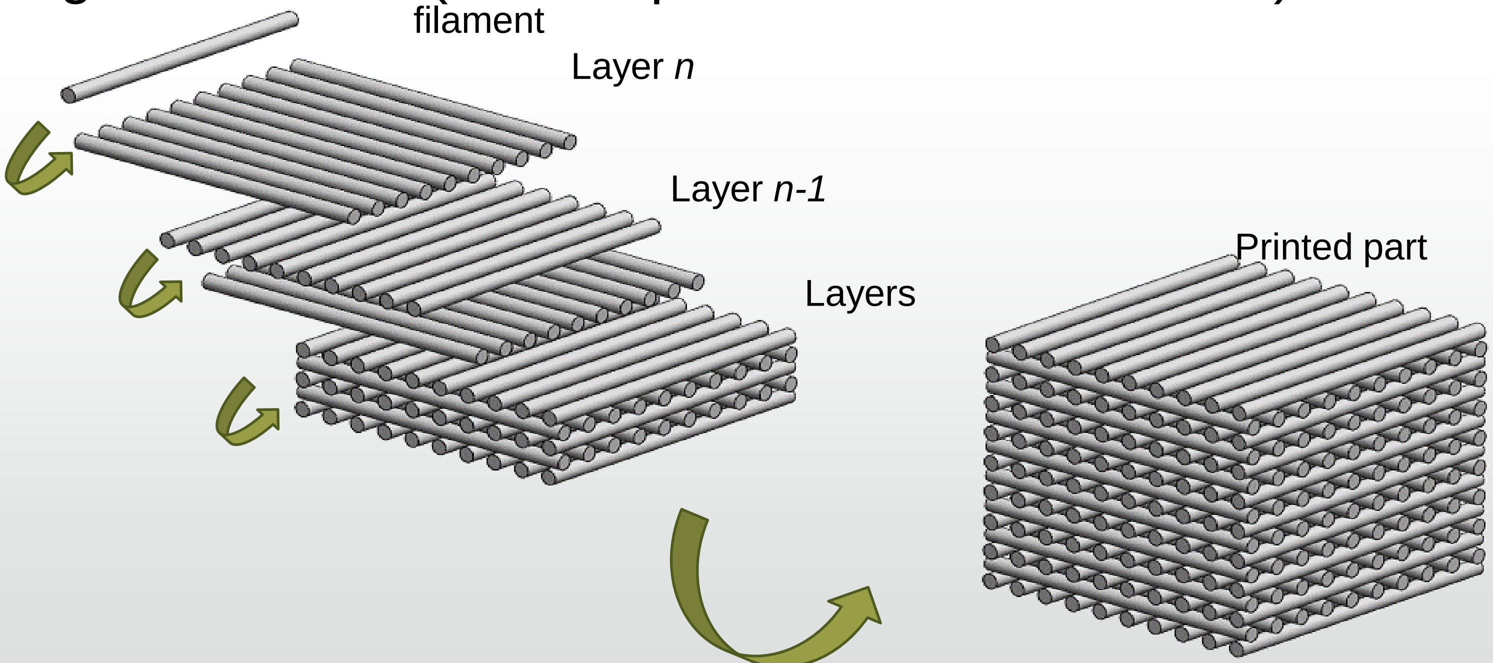
Additive manufacturing of lattice structures

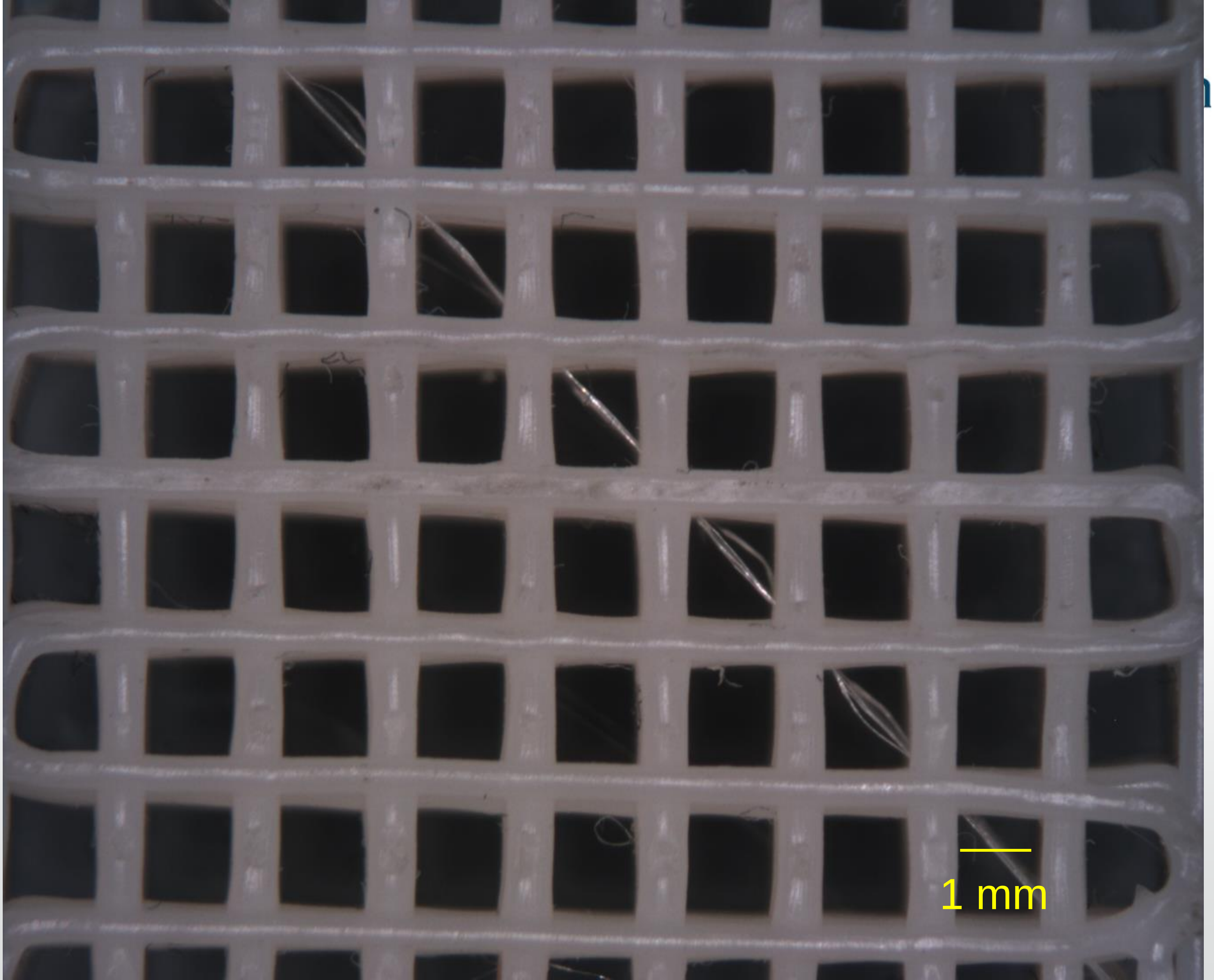
Fused deposition modelling (FDM)

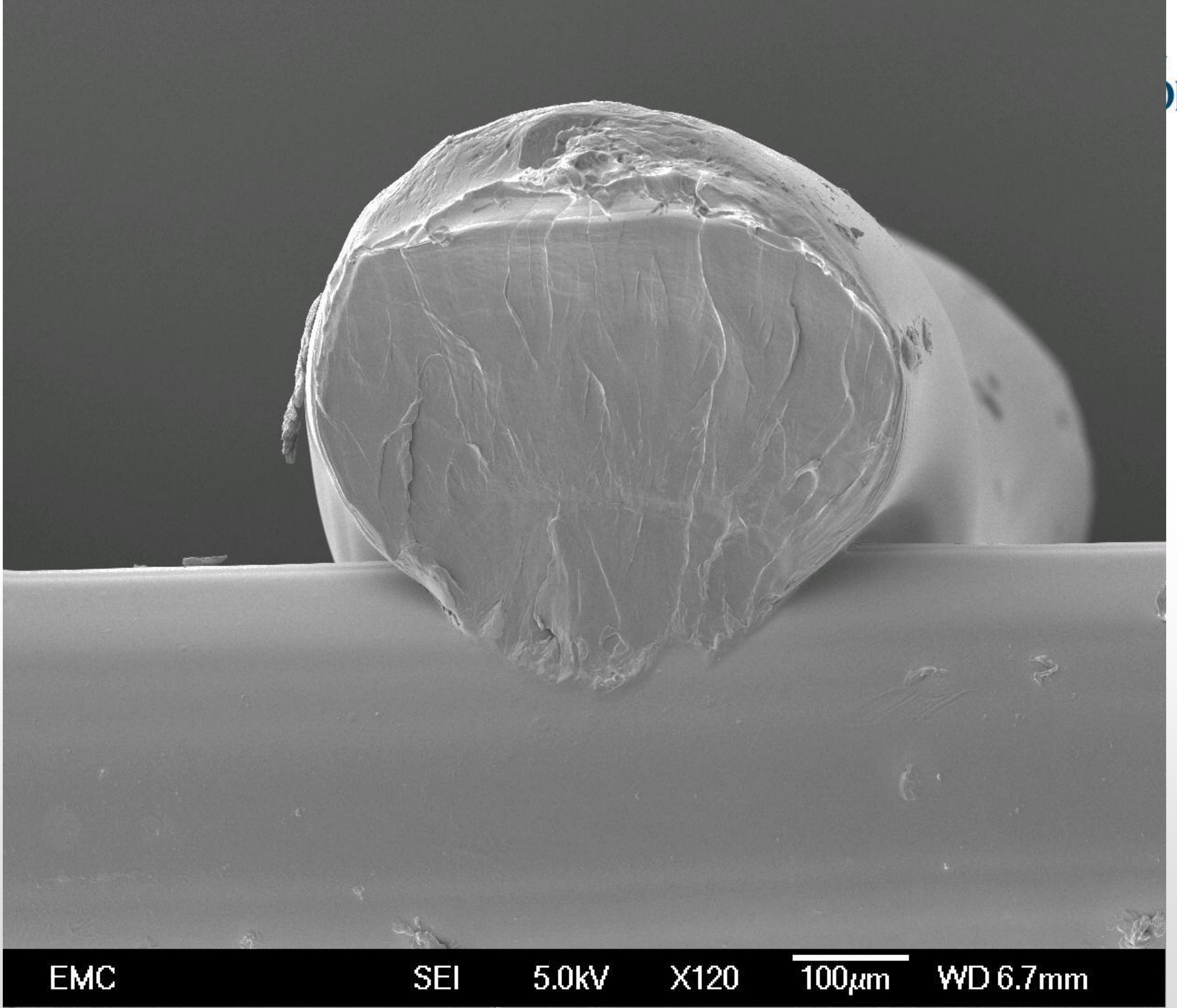




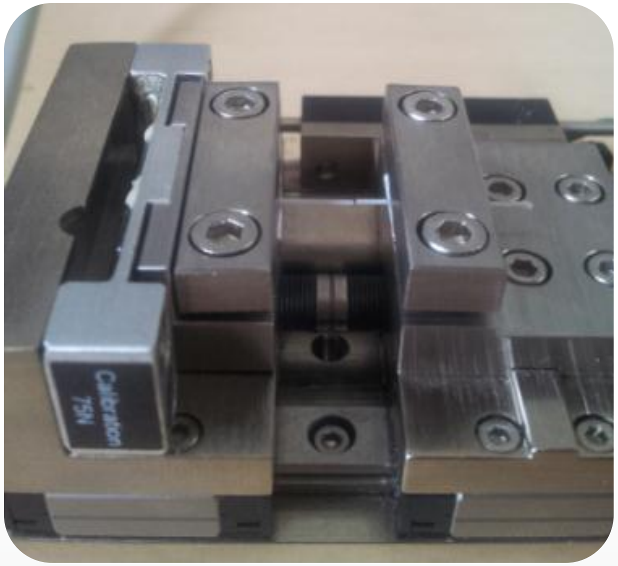
- The lattice consists of a stack of filaments (in a woodpile arrangement) fabricated using additive manufacturing.
- Inevitable to have structures with preferential direction when using this method (orthotropic constitutive relations).

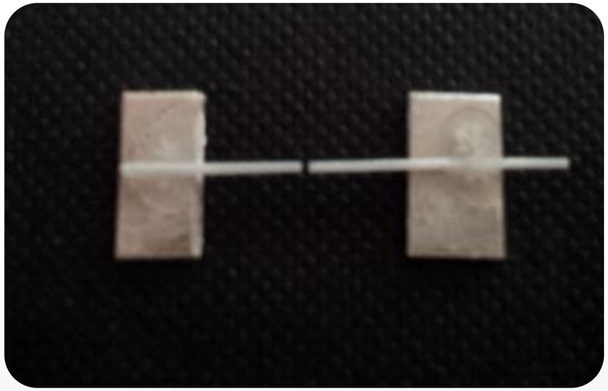


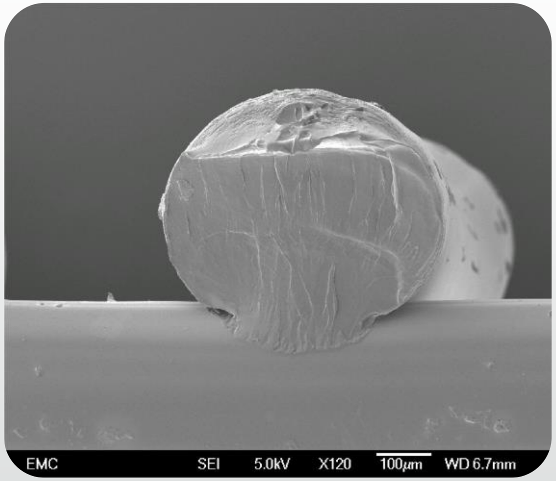

1 mm


EMC
SEI
5.0kV
X120
100μm
WD 6.7mm

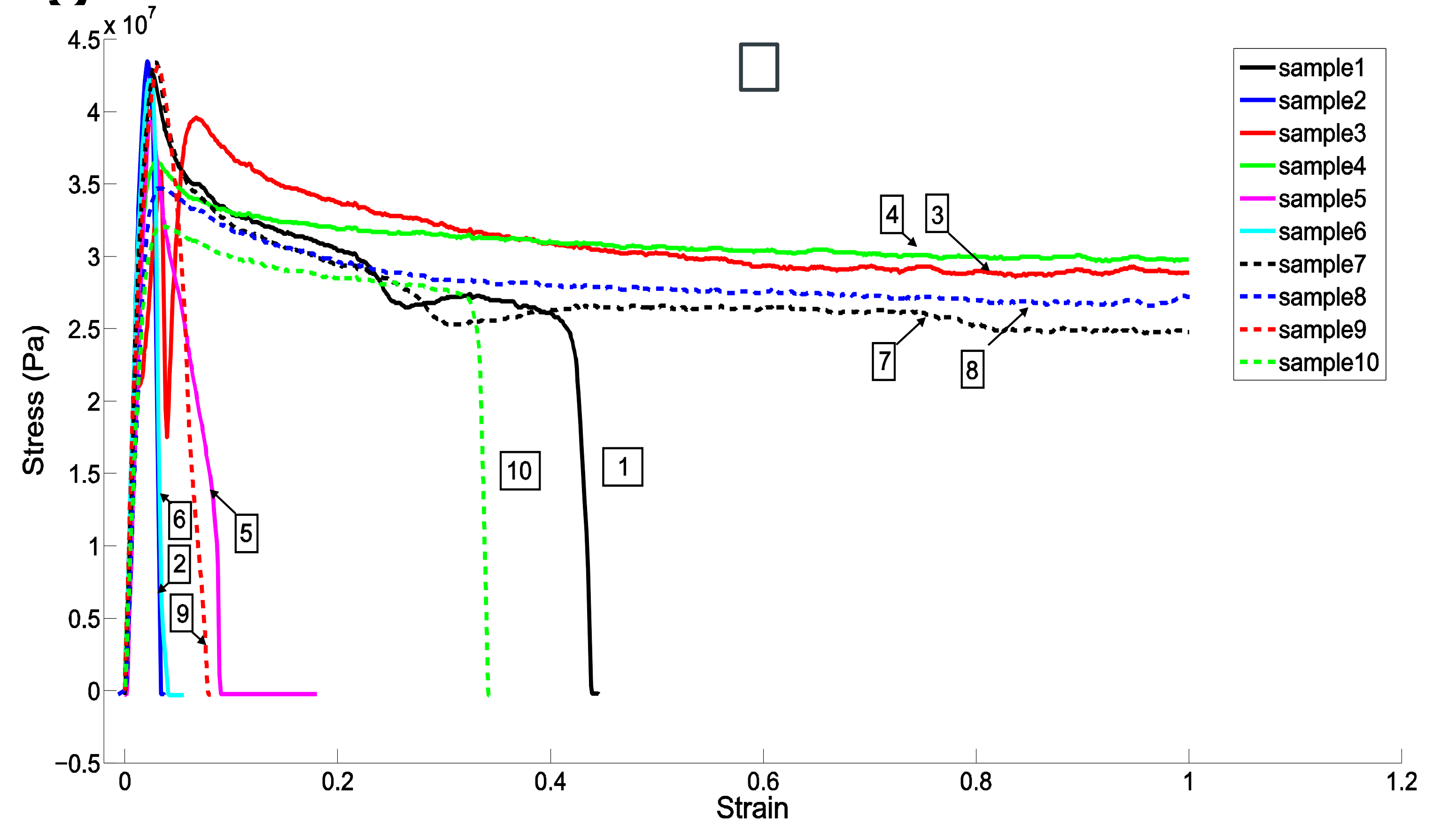
Single filament characterisation







Single filament characterisation

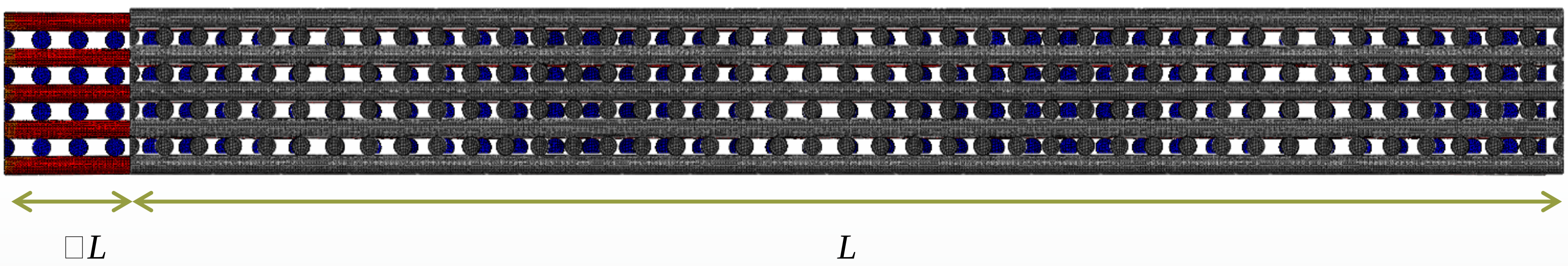


Moc
in e
vari

$$E_m = 2.29\ GPa$$

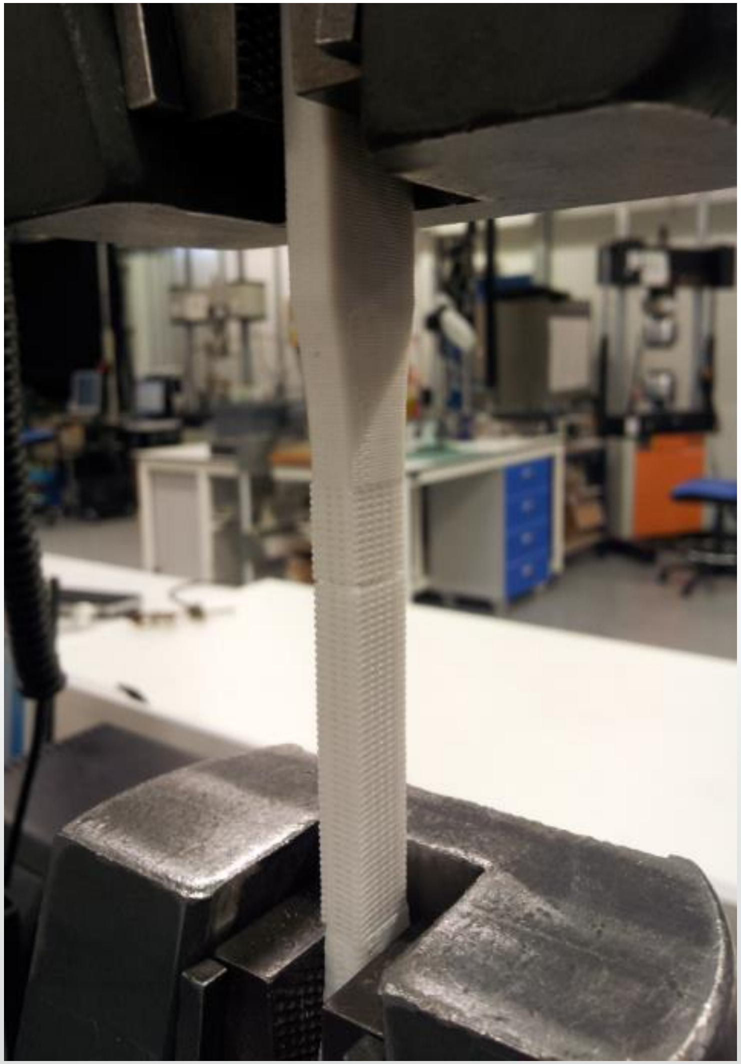
Range reported in literature
1.4 – 4.2 GPa

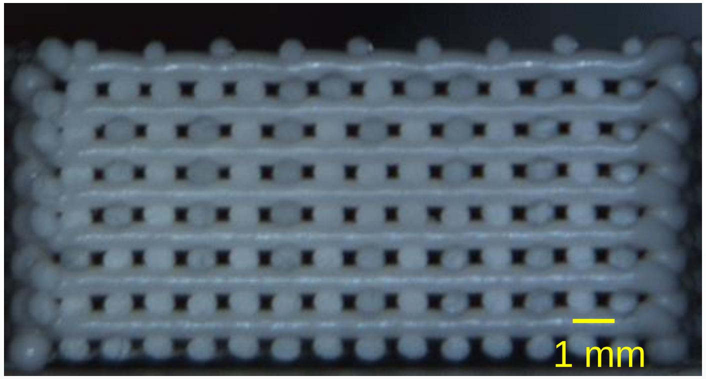
Young’s modulus along the fibres



$$\langle E \rangle = E_m f(geometry)$$

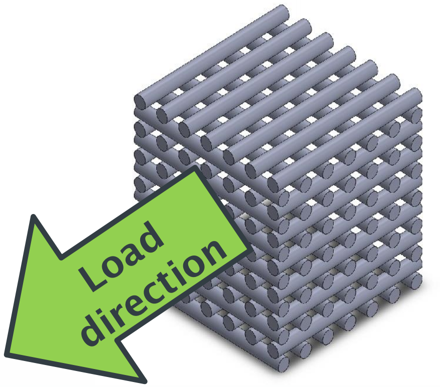
Test samples (ASTM standard D638)

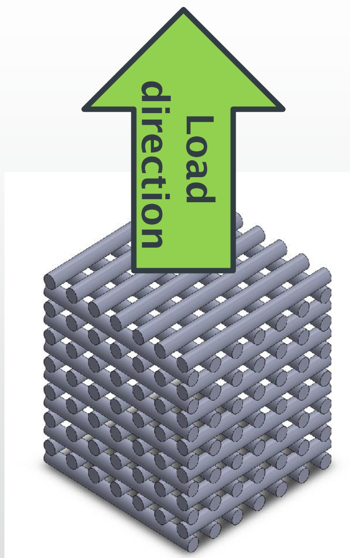


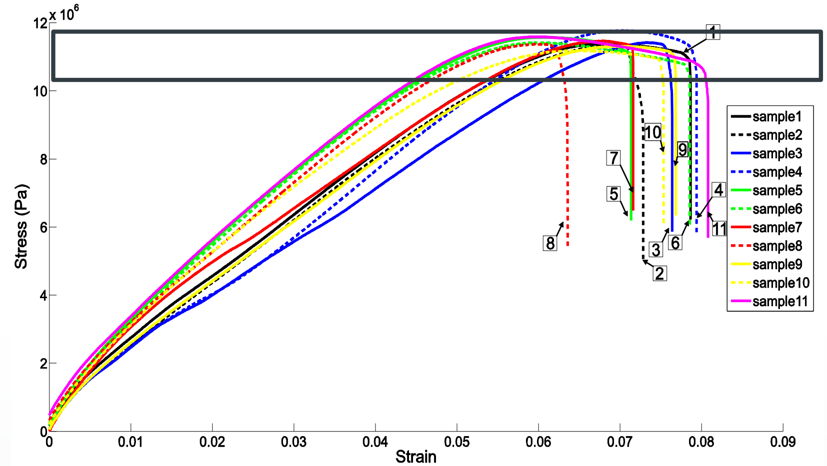


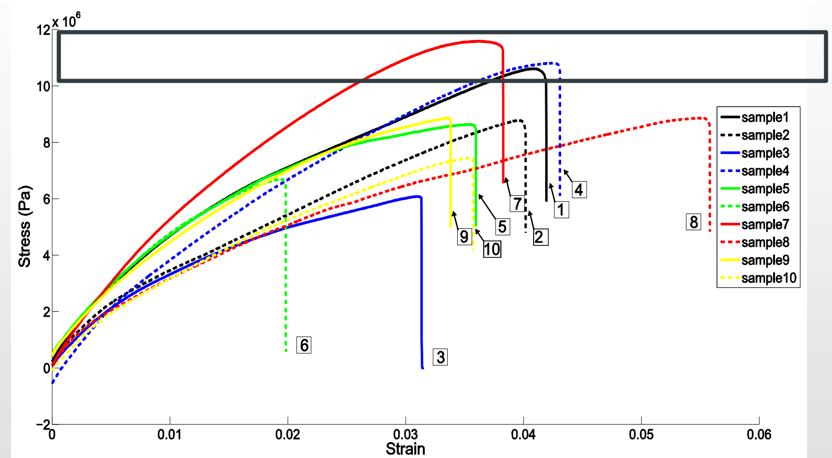
Along the filaments

Tensile tests results



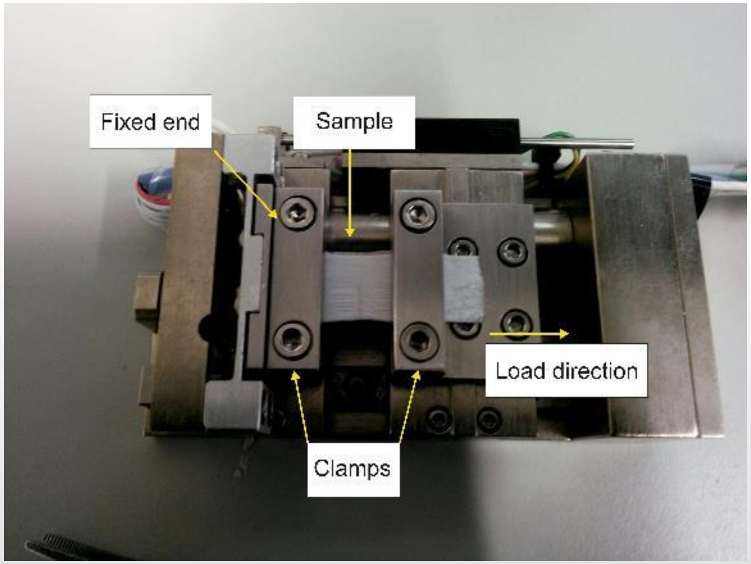


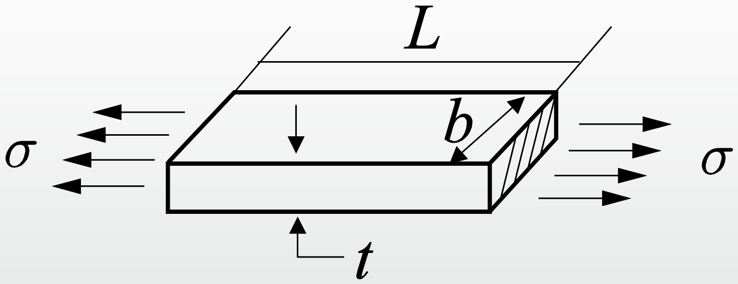


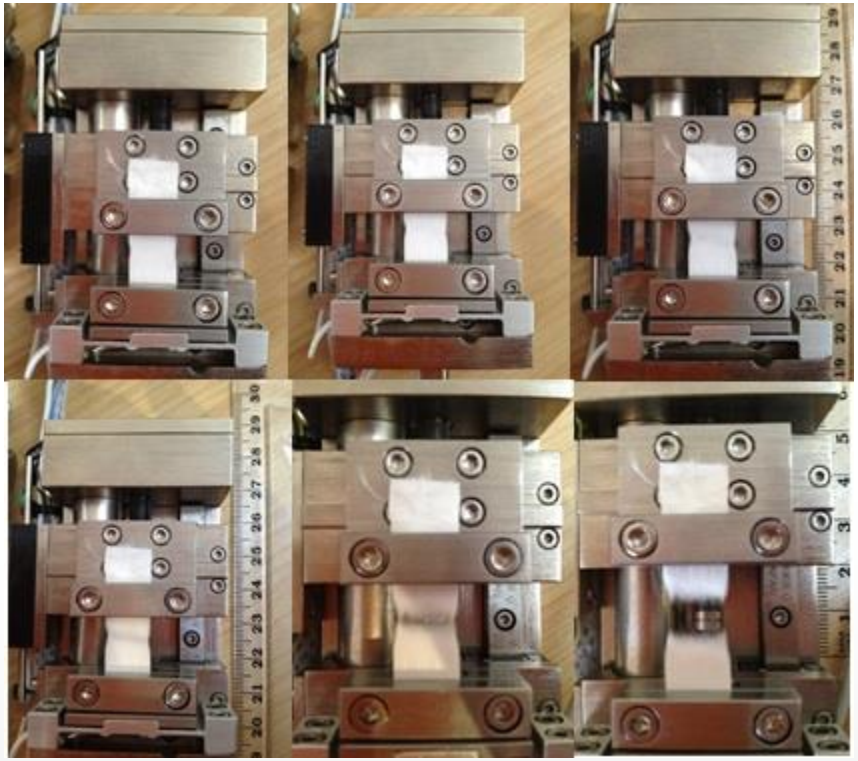


Opthalmological scaffolds

-Electrospun fibre material
-Interconnected random network

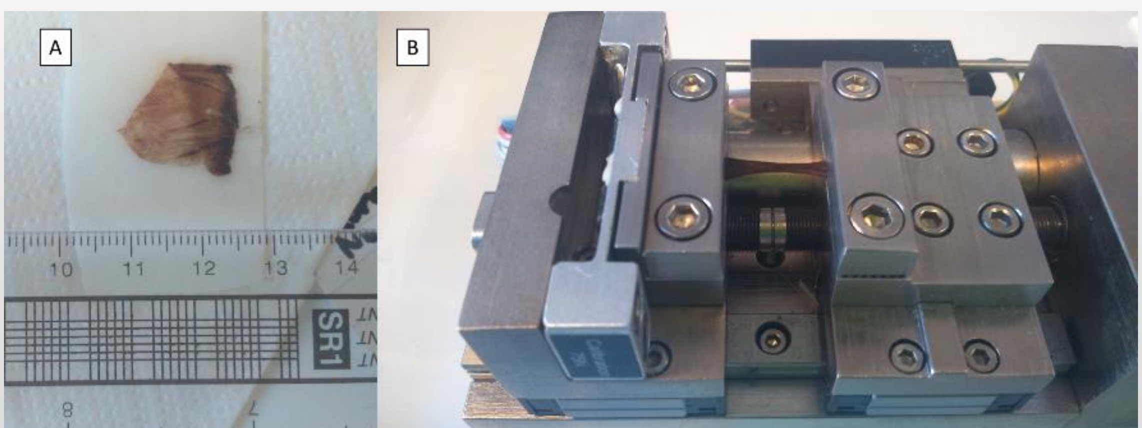




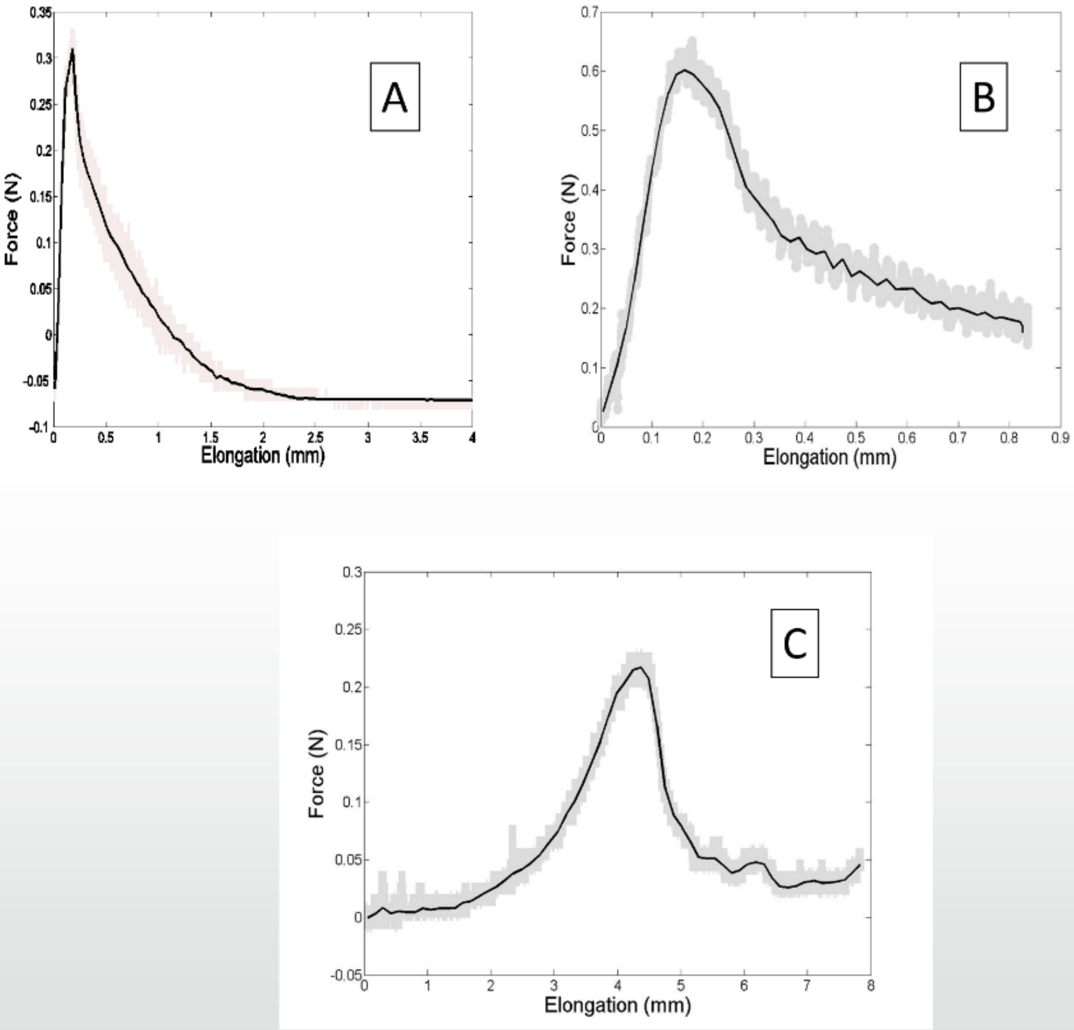


Testing protocol

-Scaffold
-Bruch’s membrane



Measured elastic response: scaffold vs BrM

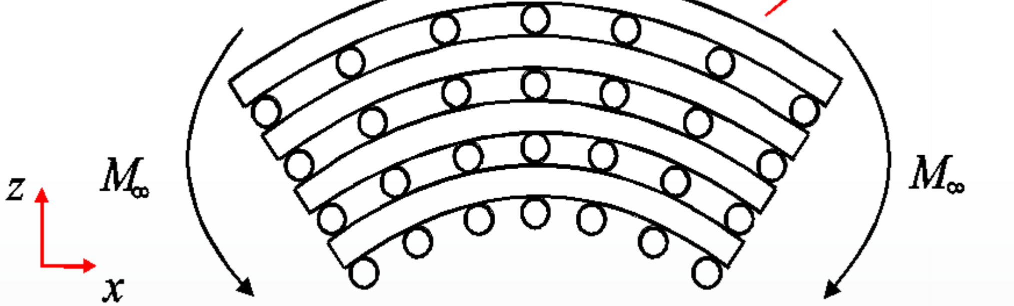


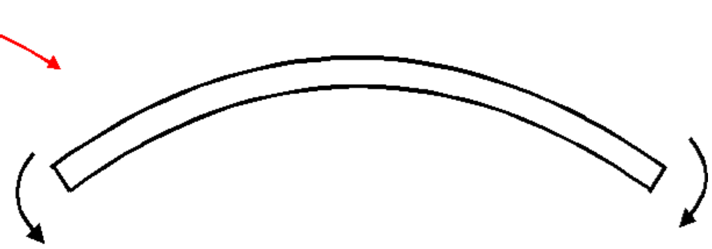
I am never content until I have constructed a mechanical model of the subject I am studying. If I succeed in making one, I understand. ***Otherwise, I do not.***

— ***Baron William Thomson Kelvin***

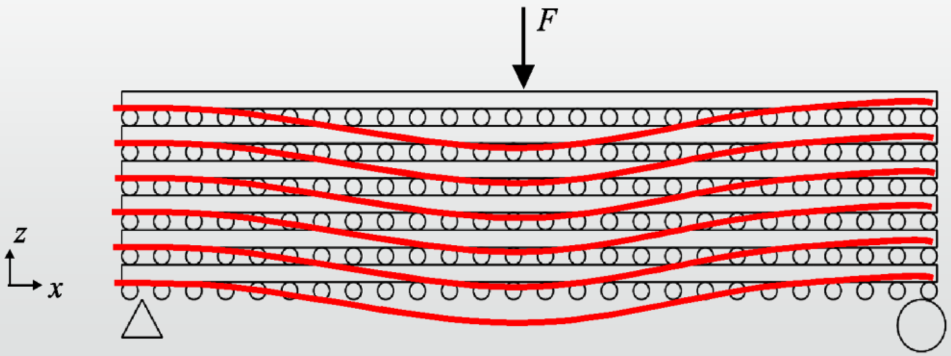
Randomness may be a blessing!

Flexural properties of lattice structures





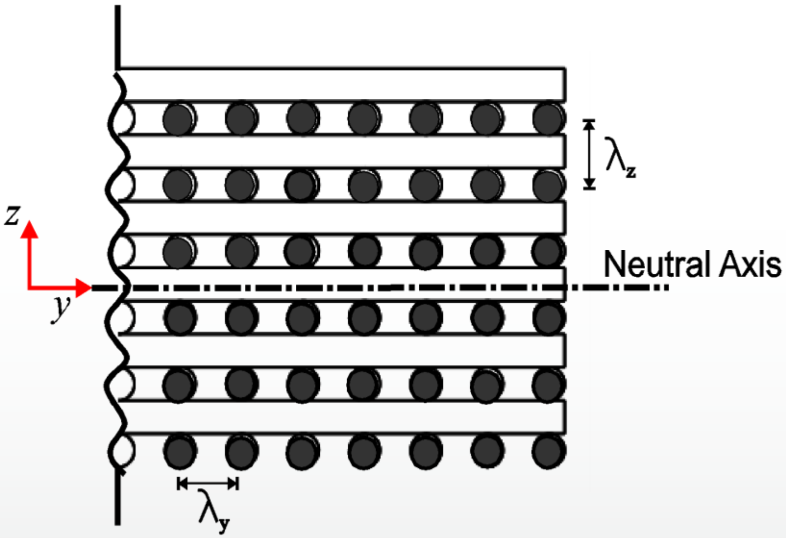
single filament deformation mechanism



$$\left\langle \frac{M_\infty}{\square} \right\rangle = \left\langle \frac{M_i}{\square_i} \right\rangle g(geometry)$$

$$\left\langle \frac{M_\infty}{\square} \right\rangle = E_m \langle I \rangle$$

Bending stiffness (parallel axis theorem)



Even number of layers

$$\langle I_1 \rangle = I_a + a\left(\frac{\square_z}{2}\right)^2$$

$$\langle I_i \rangle = I_a + a\left(\frac{3}{2}\square_z\right)^2$$

$$\langle I \rangle = N_y \sum_1^{N_z} I_i\, f(\square_z)$$

$$\langle I \rangle = f(\square_z)$$

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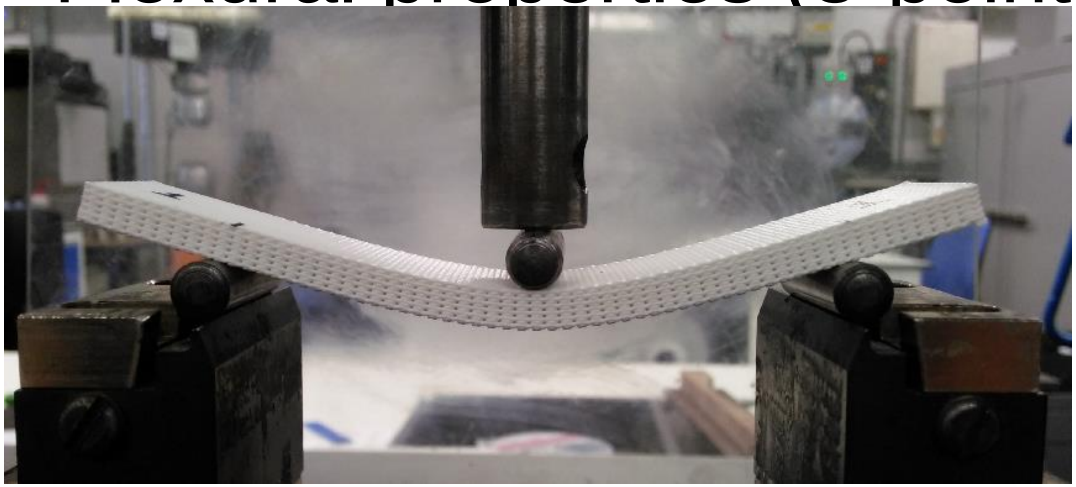
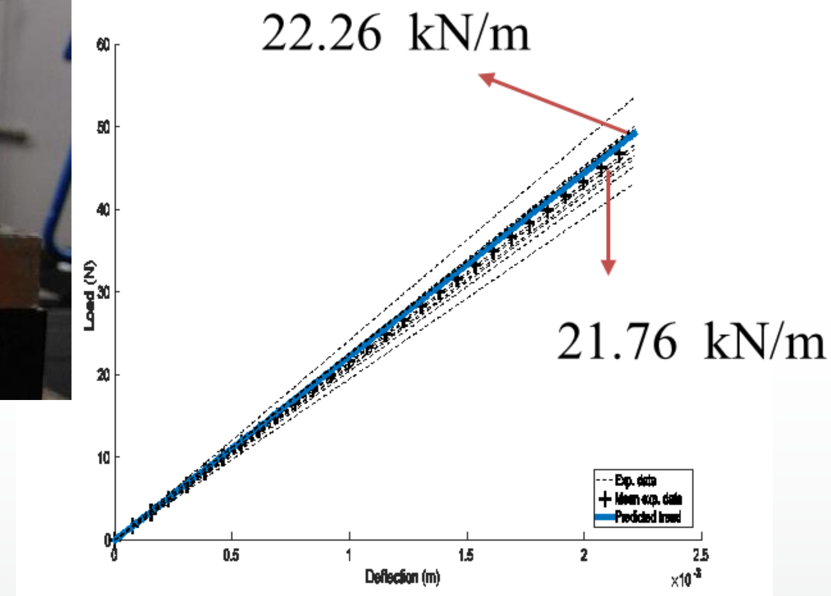
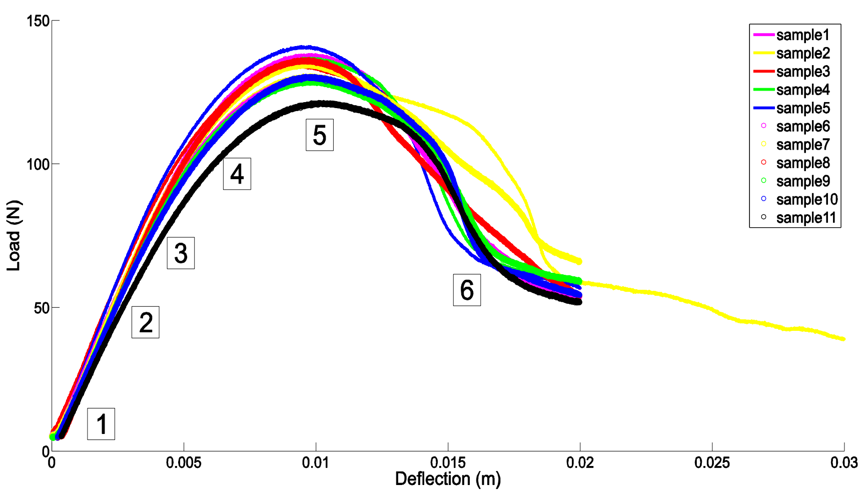
Flexural properties (3-point bending)







Influence of through-the-thickness shear

Fixed end

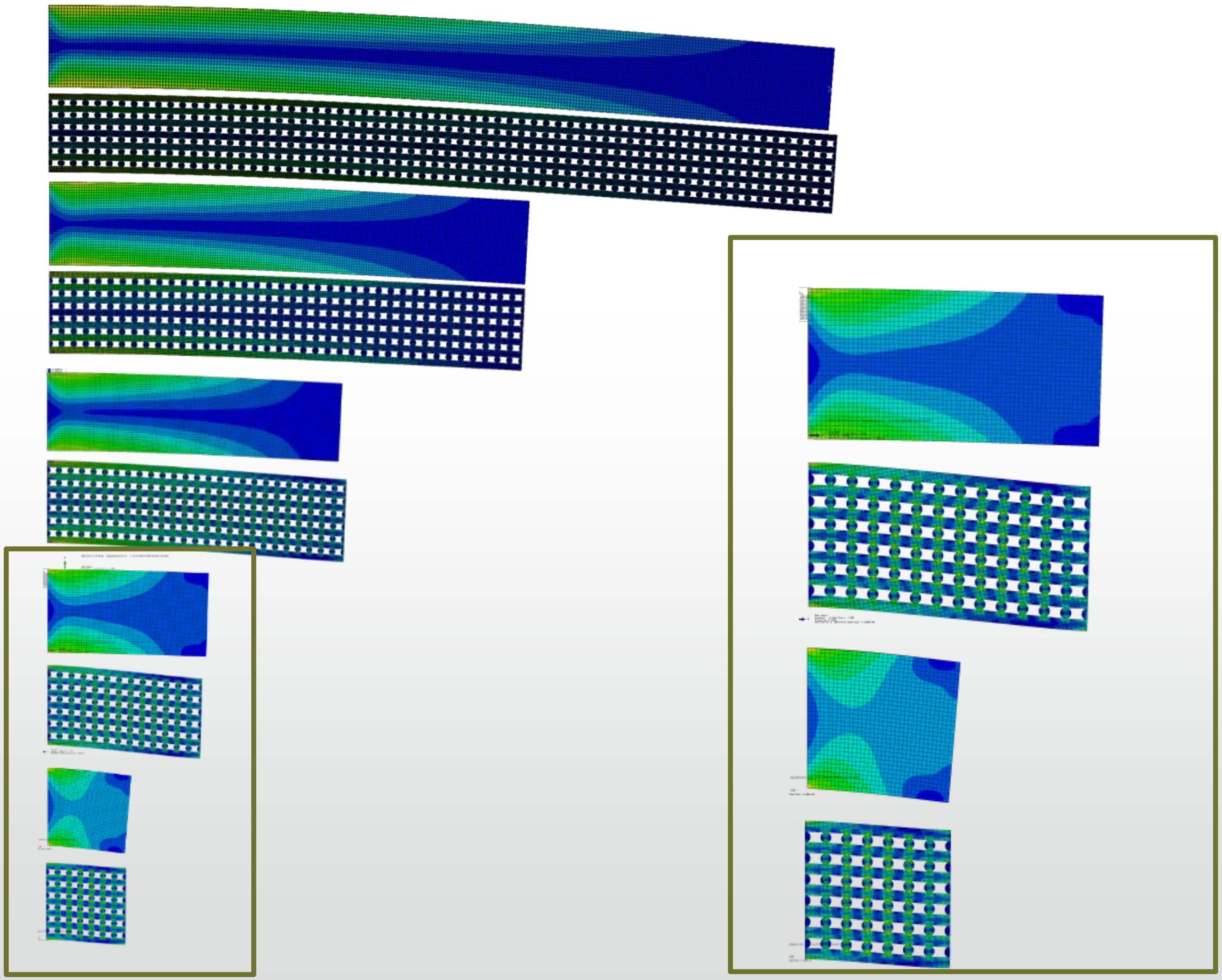
1:10

1:6

1:4

1:2

1:1



Timoshenko's deflection of a cantilever beam

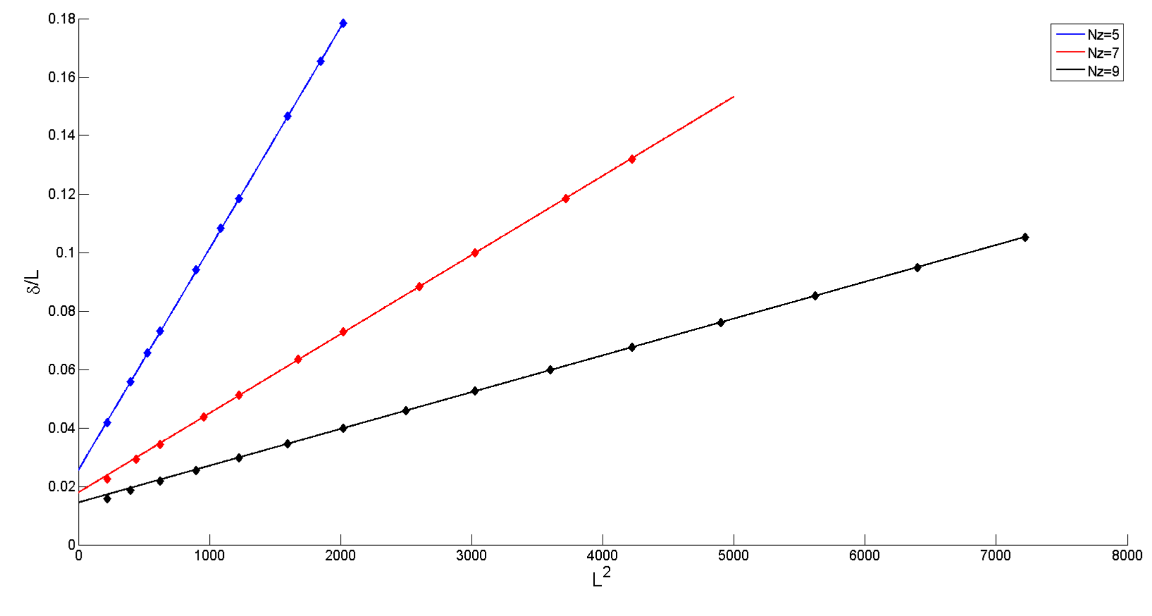
$$\delta = \frac{F}{3EI}L^3 + \frac{F}{\square GA}L$$

Function to quantitatively characterise the influence of bending and shear

$$\frac{\delta}{L} = F\left(\frac{1}{3EI}L^2 + \frac{1}{\square GA}\right)^*$$

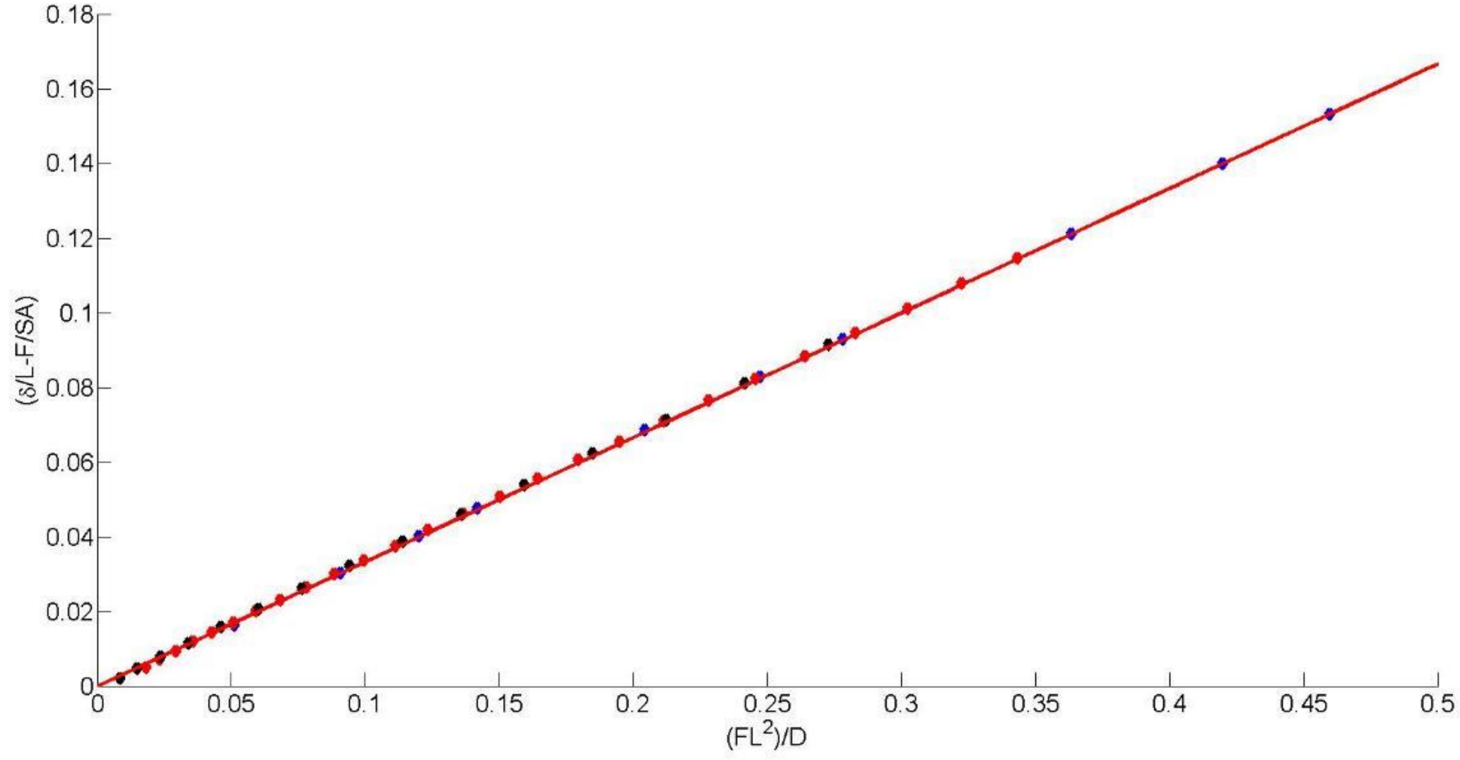
The slope gives bending stiffness information

The intercept gives the shear influence



*Scales linearly with the magnitude of the force F.

$$\delta = \frac{F}{3EI}L^3 + \frac{F}{\kappa GA}L$$



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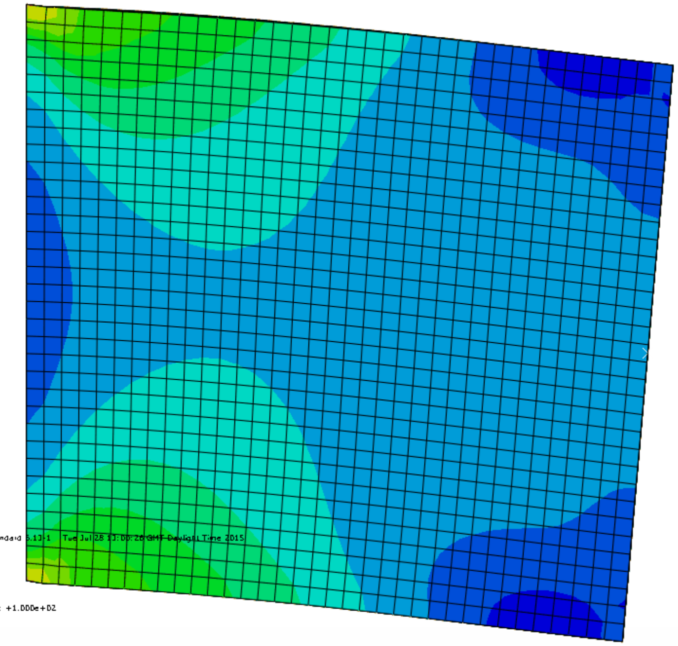
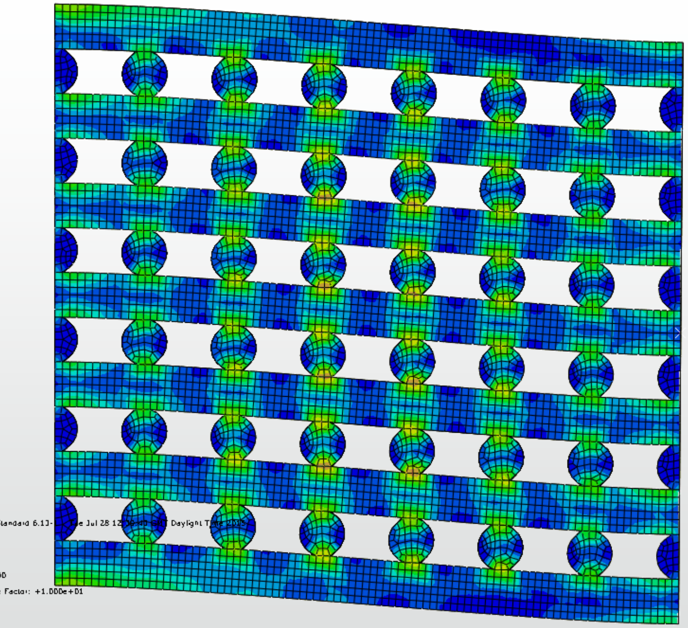
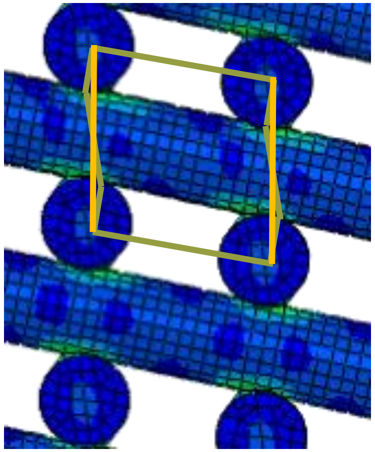
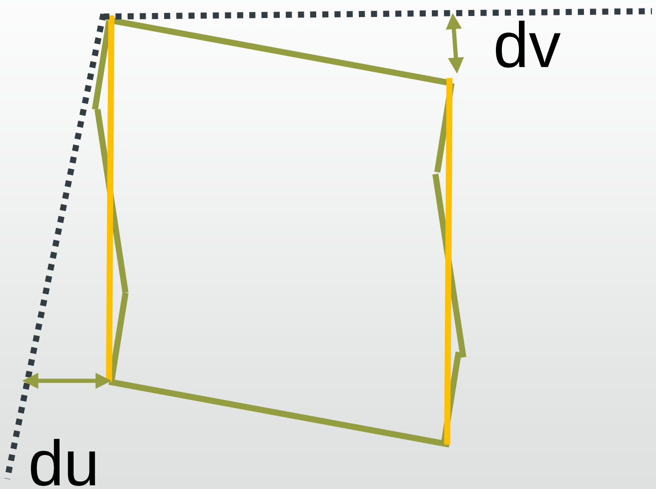
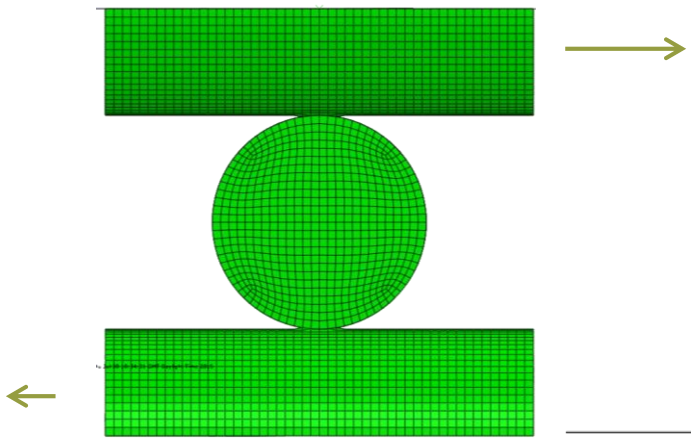


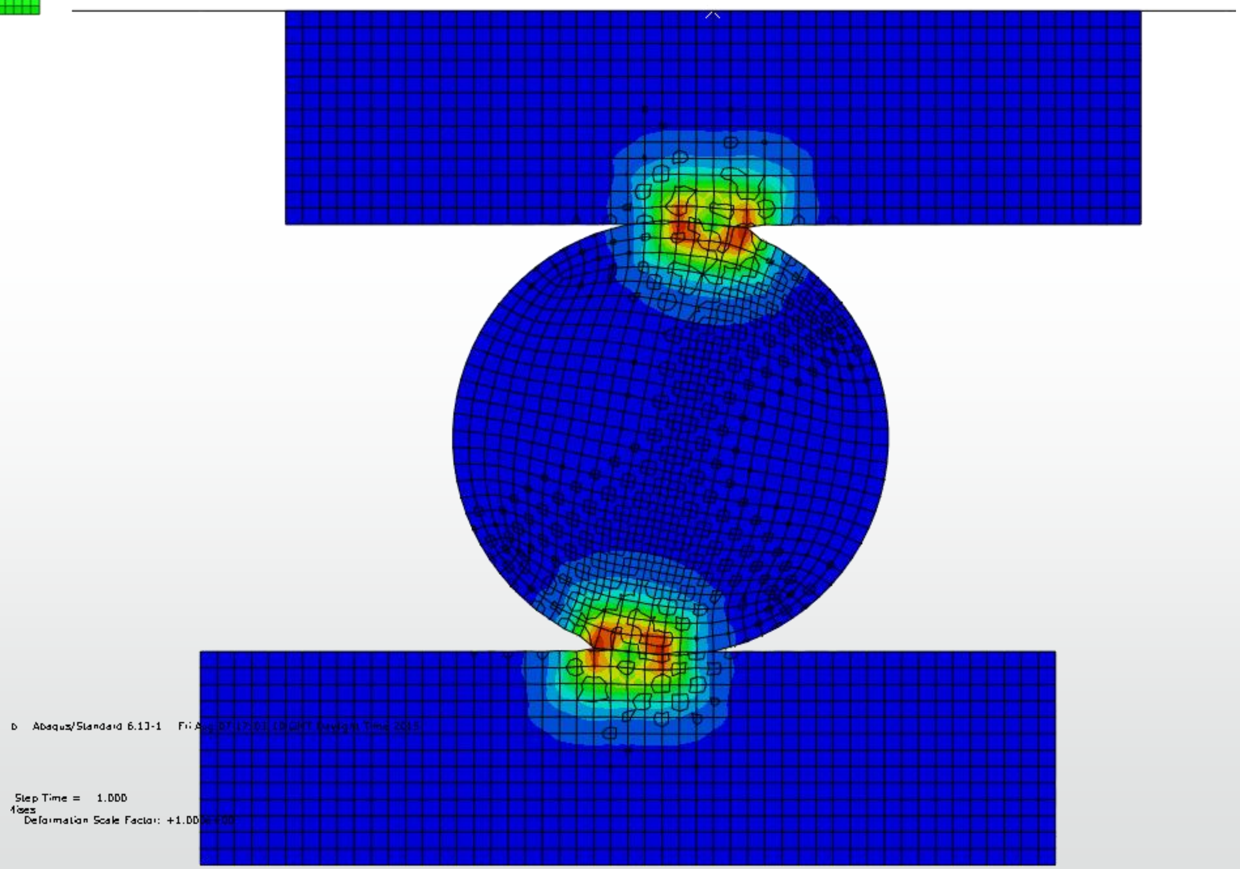






$$\gamma = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}$$




Abaqus/Standard 6.13-1
Step Time = 1.000

Ongoing work & future directions…

-***Functionally graded*** 3D-printed implants using medical polymers
-Novel methods of ***micro-texturing*** 3D-printed polymeric biostructures
-***Patents*** (novel polymeric stent architectures, novel 3d printing processes, novel components (more generic – polymer FDM, ceramic greens, etc.)
-Commercialisation?

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Thanks!

- ❖To you - for listening
- ❖To my PhD students - for doing the work ☺
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