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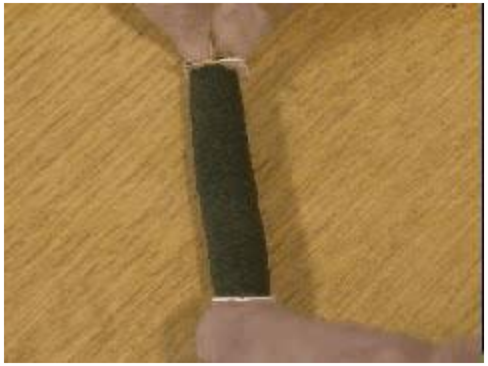
Auxetic polymers for medical device technology

“Medical and stretchy”



Andy Alderson
Professor of Smart Materials and Structures
Director Industry & Innovation Research Institute
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+44 114 225 3523
http://www.linkedin.com/pub/andrew-alderson/15/123/625

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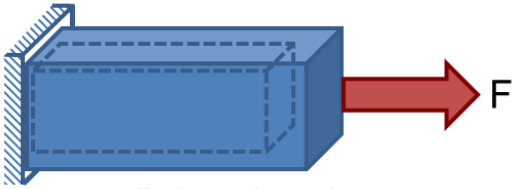


Auxetic Materials

Naturally-occurring auxetic materials

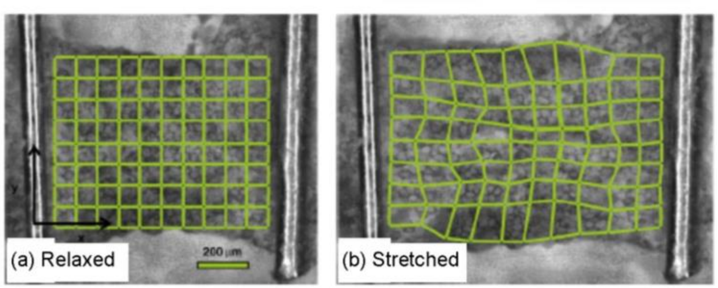
Biomaterials

- Cat skin
- Cow teat skin
- Carotid arteries
- Achilles tendon
- Stem cell nuclei
- Amphibian embryo tissue
- Annulus fibrosus

Minerals & polymers

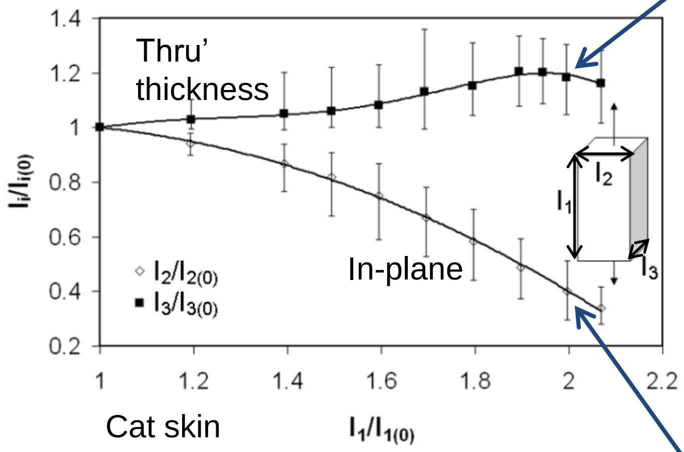
- α-quartz
- α-cristobalite
- Mother-of-pearl
- Zeolites
- Talc
- Cellulose

Auxetic soft tissue (early-stage amphibian (axolotl) epithelium)

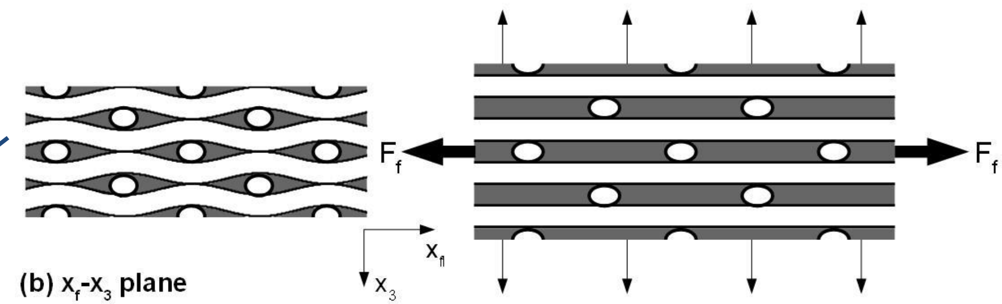


(Chen & Brodland, Journal of the Mechanical Behaviour of Biomedical Materials 2 (2009) 494-501)

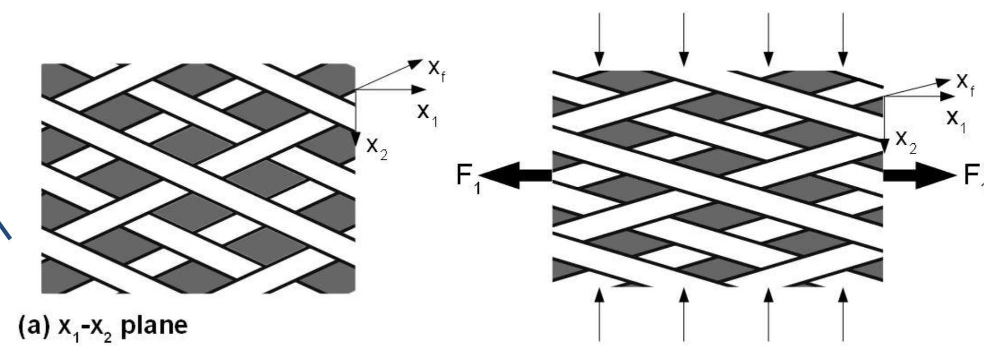
Auxetic cat skin



Veronda & Westmann, J. Biomechanics (1970)

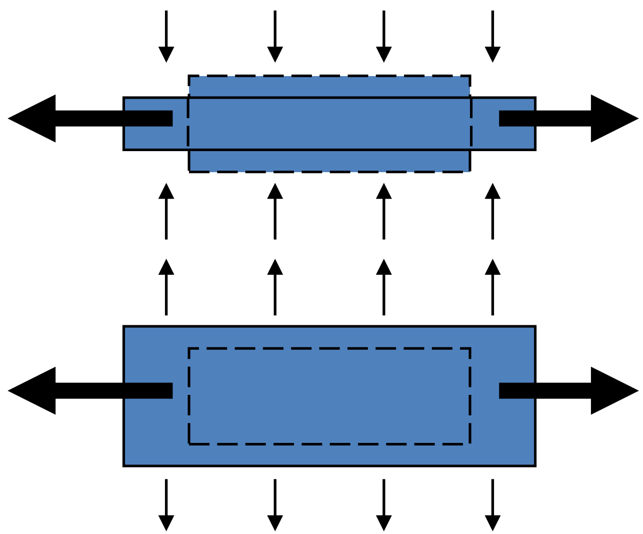


Veronda & Westmann, J. Biomechanics (1970)



Frohlich et al, J. Zool. Lond. (1994)

Poisson's ratio: $\nu_{xy} = -(\varepsilon_y/\varepsilon_x)$



+*ve* ν_{xy}

-*ve* ν_{xy}

Auxetic Material: Material with a negative Poisson's ratio

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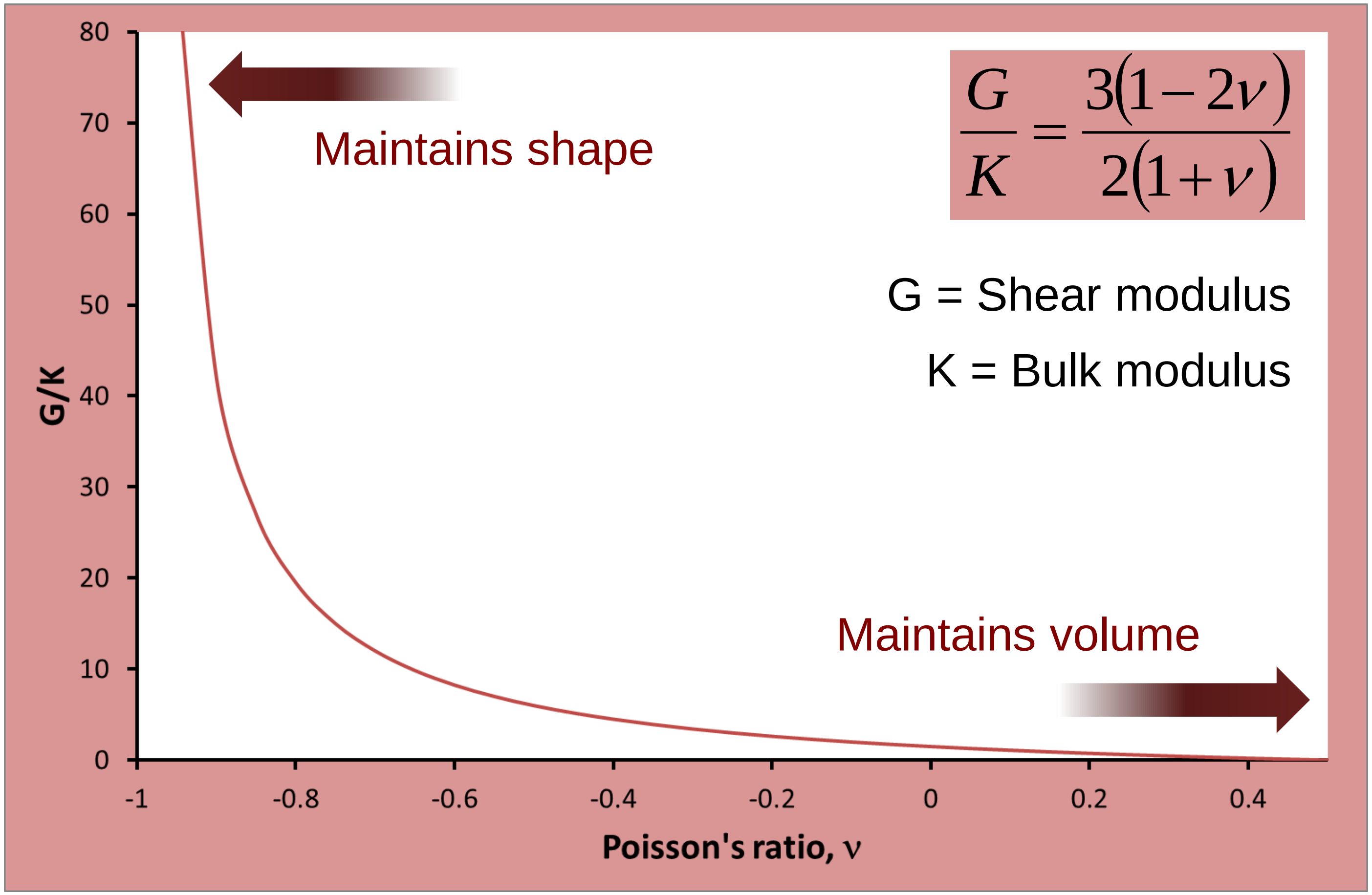
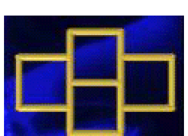
Auxetics: a route to enhancing other properties



For *isotropic* materials: $-1 < \nu < +0.5$



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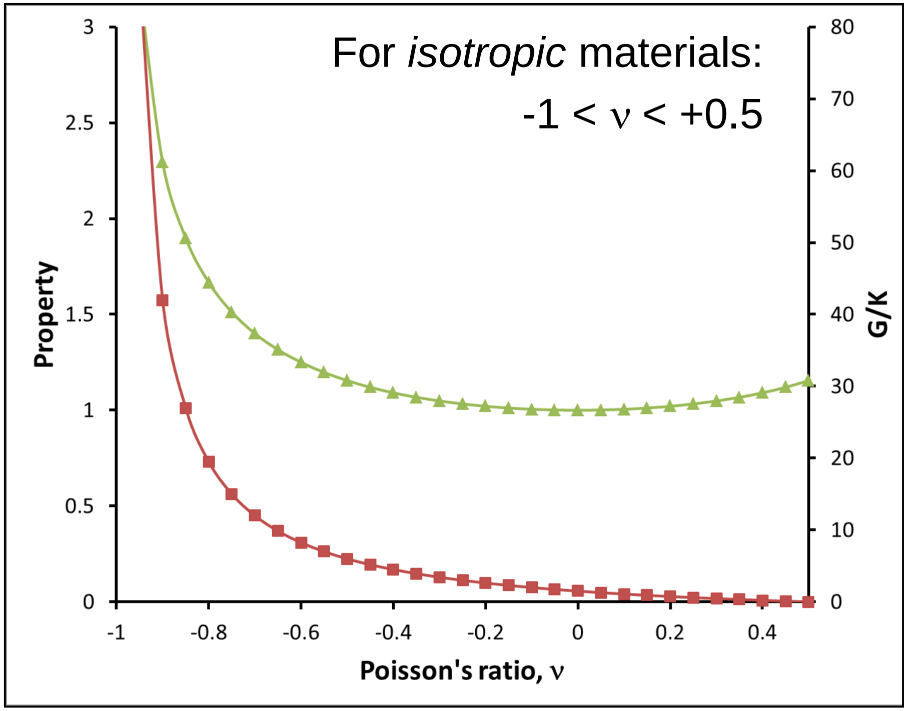
Auxetics: a route to enhancing other properties



$$\frac{G}{K} = \frac{3(1-2\nu)}{2(1+\nu)}$$ Shear rigidity

$$\sigma = \sqrt{\frac{\pi E T}{2r(1-\nu^2)}}$$ Fracture toughness

For *isotropic* materials: -1 < ν < +0.5

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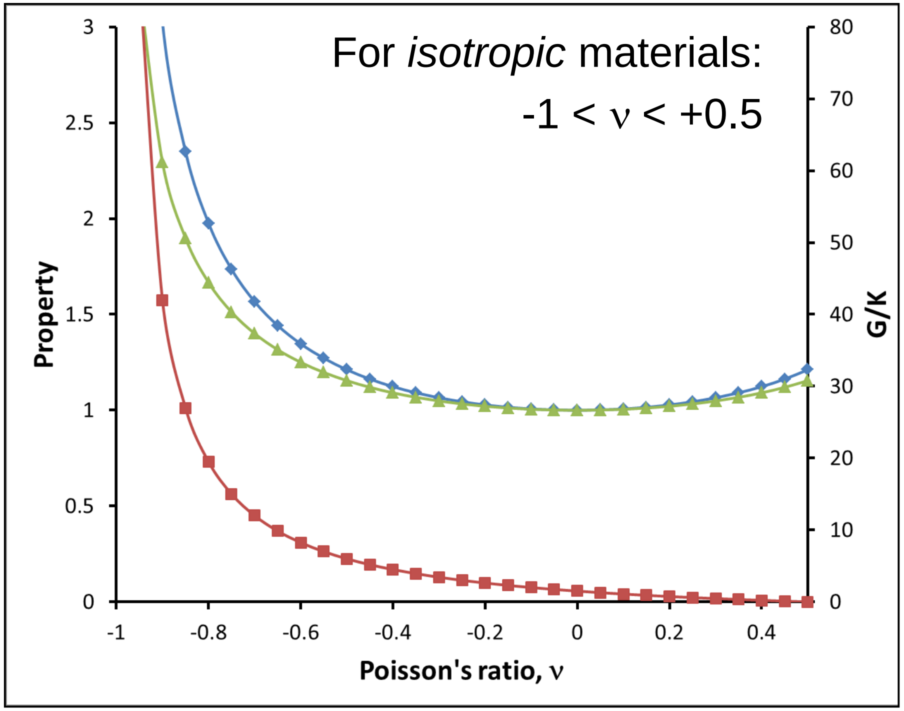
Auxetics: a route to enhancing other properties



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Shear rigidity

$$\sigma = \sqrt{\frac{\pi E T}{2r(1-\nu^2)}}$$

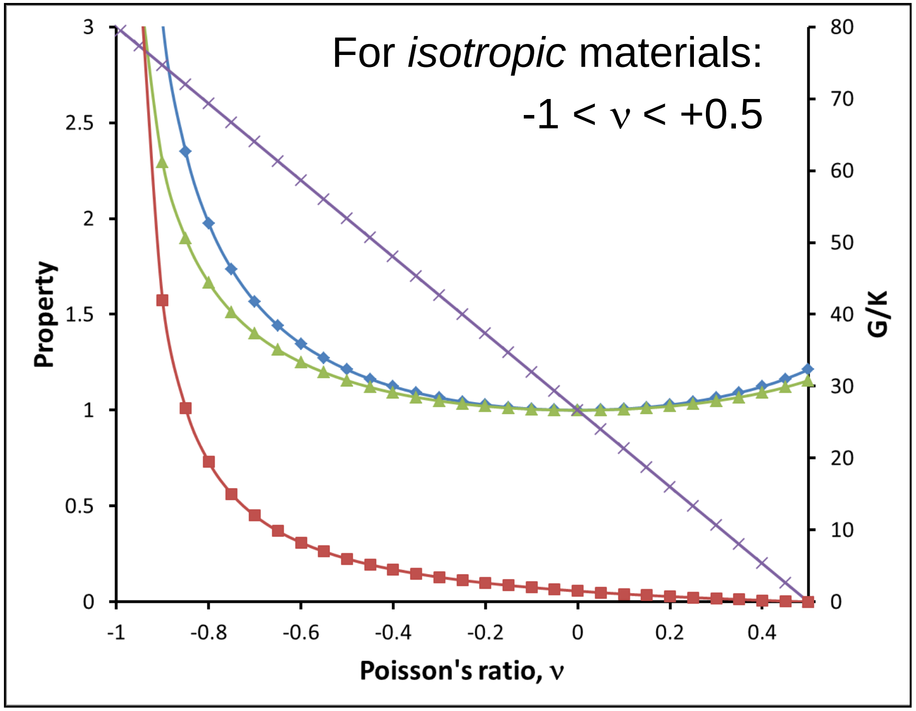
Fracture toughness

$$H \propto \left[\frac{E}{1-\nu^2}\right]^{2/3}$$

Indentation resistance

For *isotropic* materials: -1 < ν < +0.5

Auxetics: a route to enhancing other properties



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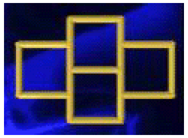
$$H \propto \left[\frac{E}{1-\nu^2}\right]^{2/3}$$ Indentation resistance

$$U_\nu = \frac{(1-2\nu)\sigma^2}{6E}$$ Volumetric strain energy dissipation



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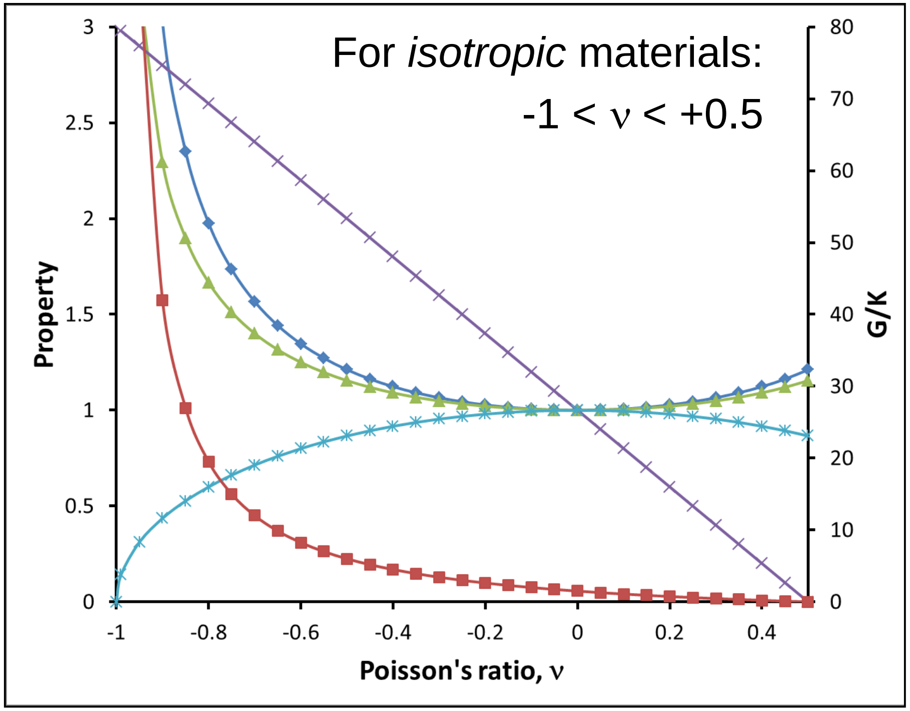
Auxetics: a route to enhancing other properties



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$$f_c \propto (1-\nu^2)^{1/2}$$ Critical resonance frequency

For *isotropic* materials: -1 < ν < +0.5

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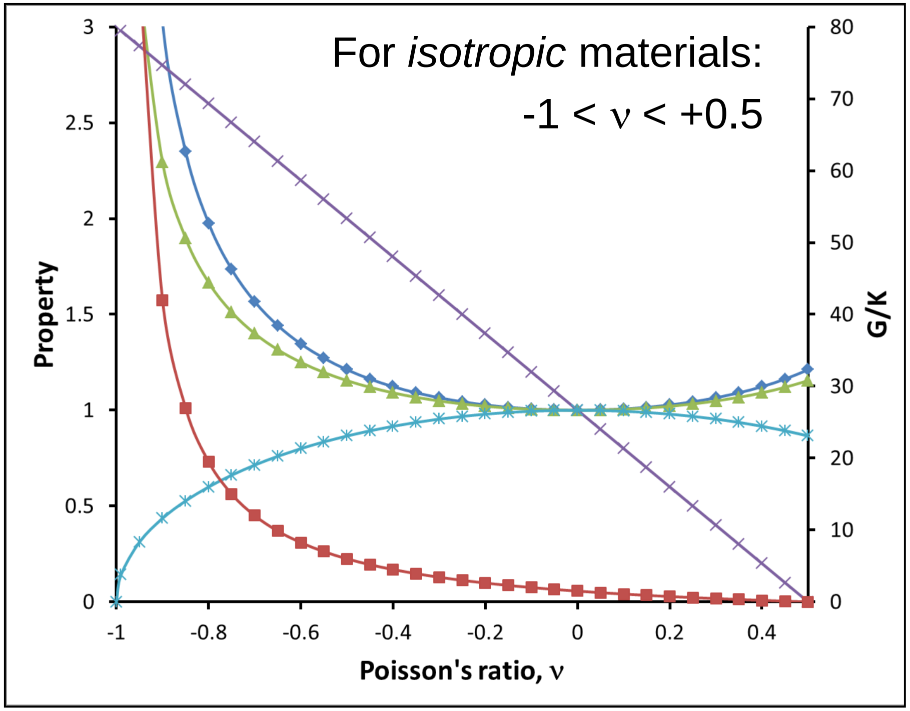
Auxetics: a route to enhancing other properties



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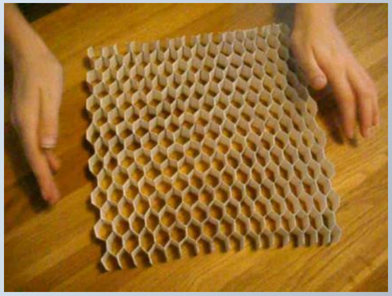
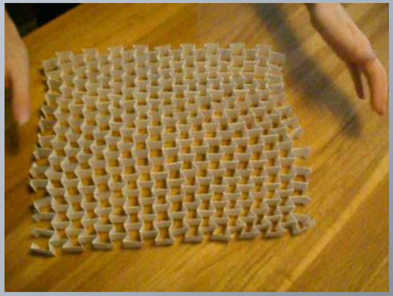
Curvature



Non-auxetic



Auxetic

$$R_2 = -\frac{R_1}{\nu_{12}}$$ Ability to naturally adopt dome shape when bent out of plane

For *isotropic* materials: -1 < ν < +0.5

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The 7-pad system fits most ground combat helmets. Each helmet pad in this replacement/upgrade system features a unique geometry that allows the pad to fit the shape of the head and offers superior deceleration under blunt impact tests vs. market leading competitors.

PRODUCT FEATURES

- High Performing
- Patented D3O® technology
- Comopsite Solution
- Unique auxetic geometry when stretched becomes thicker perpendicular to the applied force

WaveCel - Bontrager

https://wavecel.trekbikes.com/us/en_US/

https://www.d3o.com/wp-content/uploads/2016/09/D3O-TRUST-Helmet-pad-system.pdf

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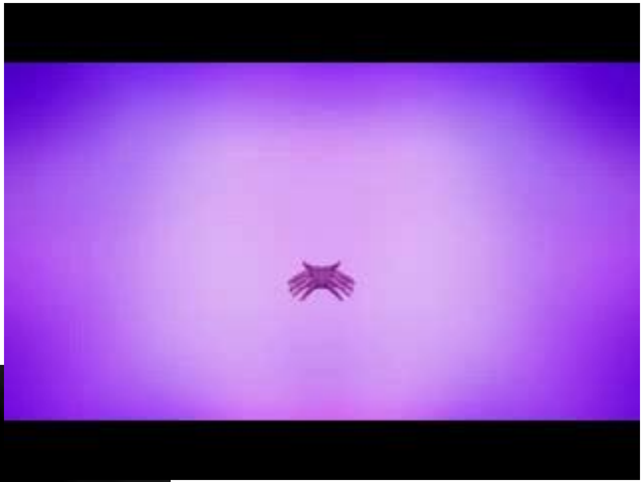
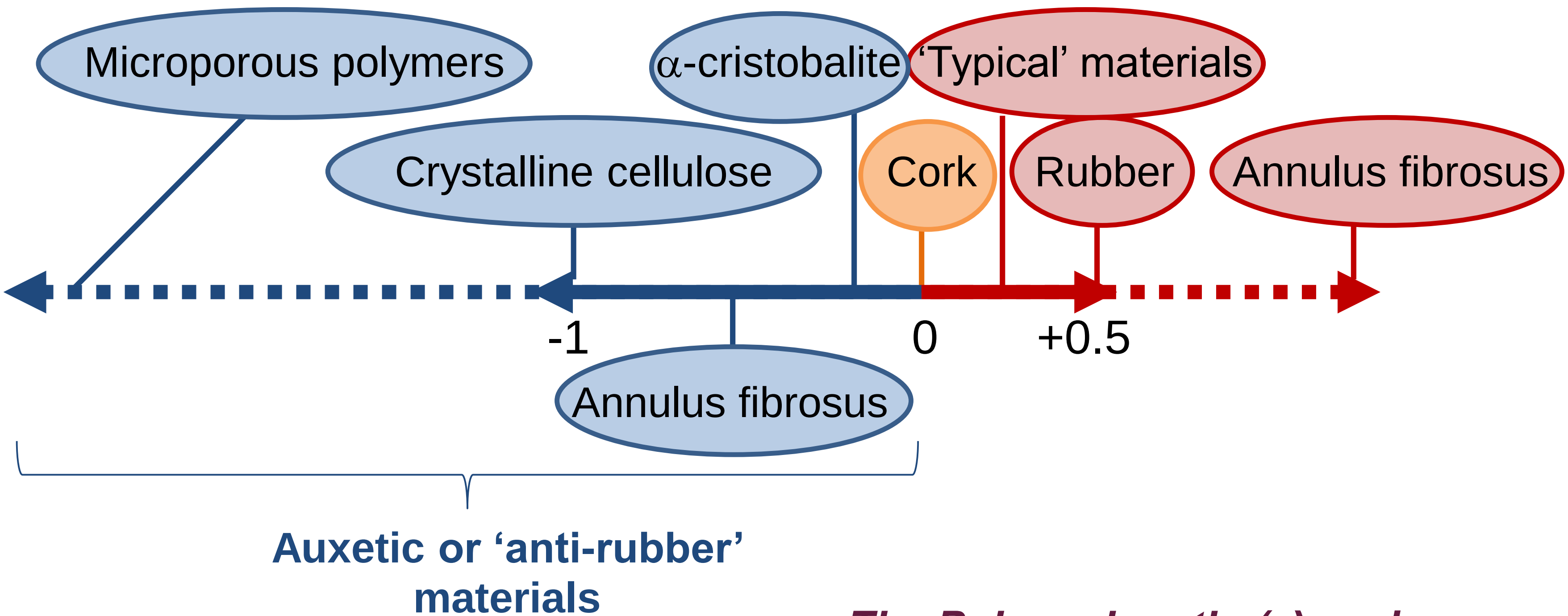


Nike Womens Free Run Flyknit
https://www.youtube.com/watch?v=3M5jEB4-H0M

PUMA Calibrate Runner
https://www.youtube.com/watch?v=K8pahZAmAV0&feature=youtu.be

Under Armour 3D-printed sports shoes
UA Architech - latticed upper made from Clutchfit Auxetic materials
https://www.youtube.com/watch?v=3fH9UVEfLyo

Am I in the right place?



The Poisson's ratio (ν) scale

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Auxetic elastomer developments

- Auxetic fabrics containing elastomeric fibres
- Auxetic fibre-reinforced elastomer composites
- Auxetic Liquid Crystal Elastomers

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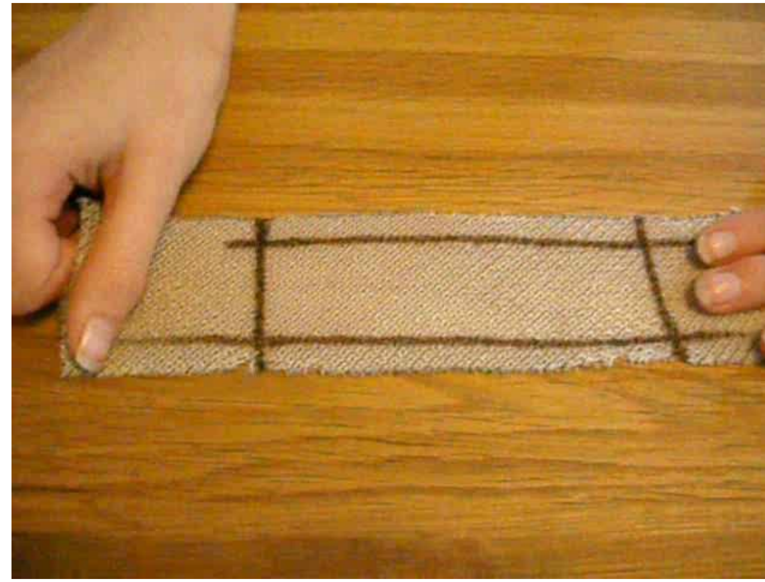
Fabrics:
Auxetic fabric structure



- Made on commercial warp knitting machine
- Commercially-available, conventional yarns
  - 480dtex Dorlastan V500
  - Polyester monofilament of 0.15 and 0.25mm diameters
- Apparel applications
  - Comfort, fit, breathable garments
- Healthcare applications
  - Breathable wound-healing bandages

Sara Lee Branded Apparel/Hanes Brands Inc/Global Composites Group
PCT Patent Publication Nos. WO2008/016690; WO2010/125397

Phys. Status Solidi B **249**, No. 7, 1322–1329 (2012) / **DOI** 10.1002/pssb.201084216

physica status solidi b
www.pss-b.com
basic solid state physics

Auxetic warp knit textile structures

Kim Alderson*, Andrew Alderson, Subhash Anand, Virginia Simkins, Shonali Nazare, and Naveen Ravirala

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WARP KNIT STRUCTURES BASED ON TRIANGULAR LATTICE GEOMETRY

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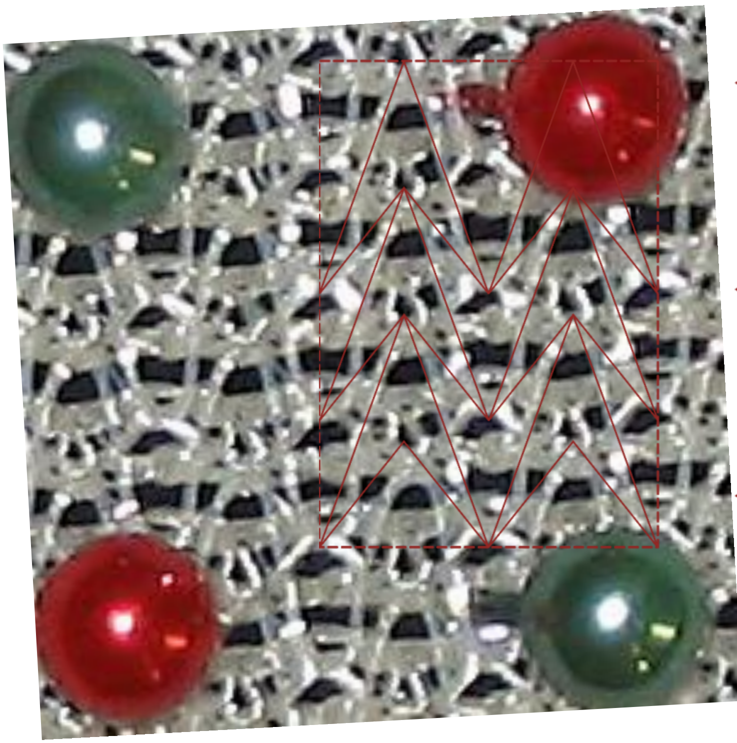
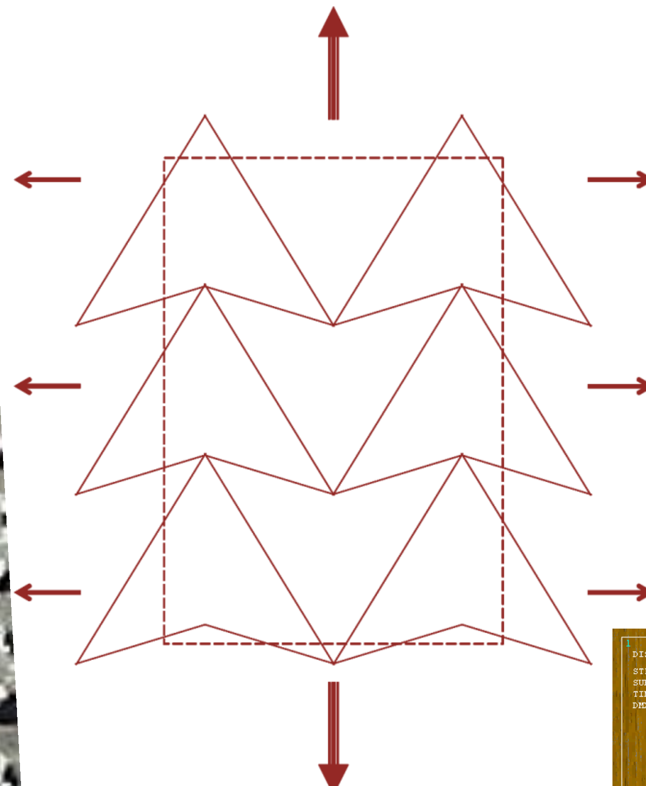
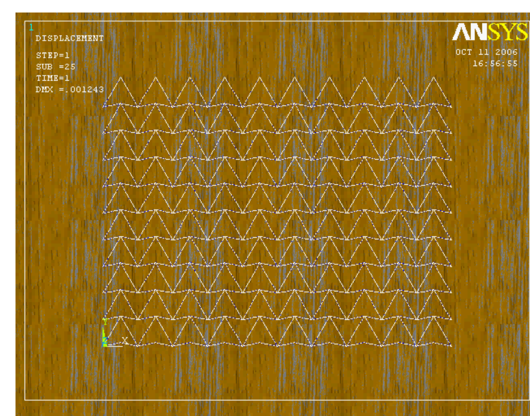
WARP KNIT STRUCTURES BASED ON TRIANGULAR LATTICE GEOMETRY







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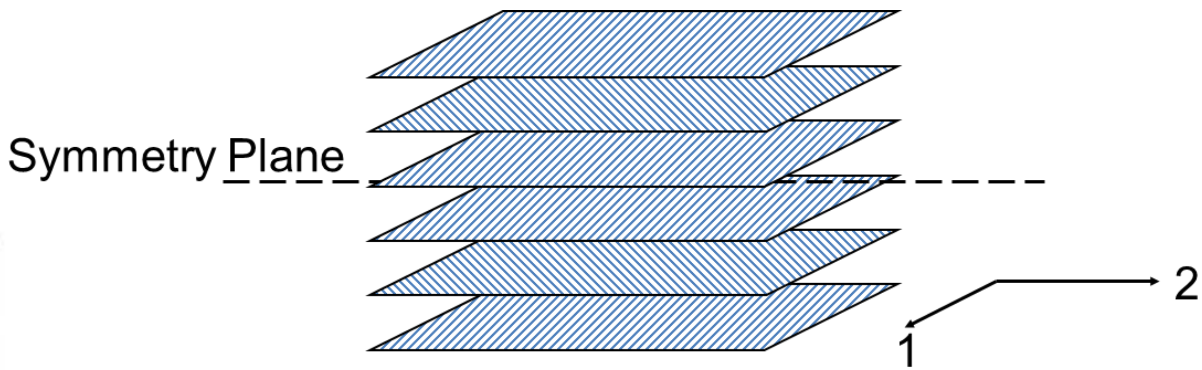
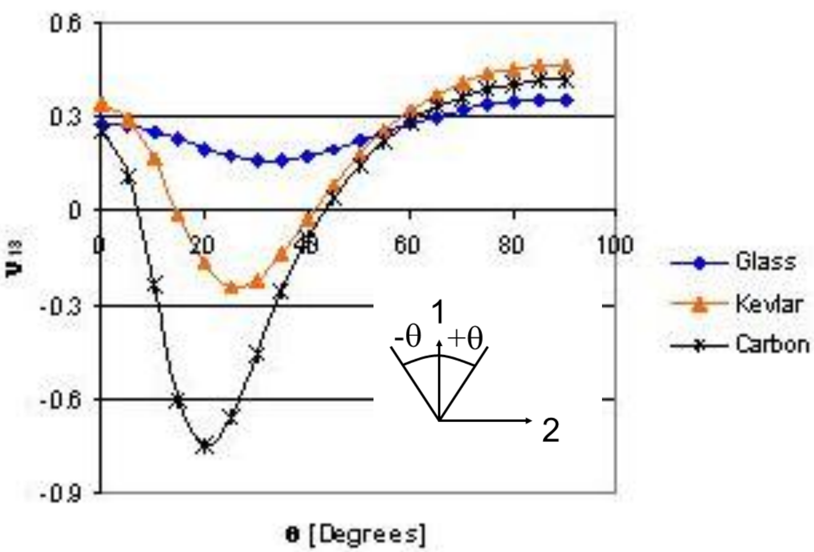
Auxetic composites: *Angle-ply laminates*

•Negative in-plane or out-of-plane Poisson's ratios possible for certain lay-up sequences





phys. stat. sol. (b) **244**, No. 3, 883 – 892 (2007) / **DOI** 10.1002/pssb.200572707

Modelling the influence of the orientation and fibre reinforcement on the Negative Poisson's ratio in composite laminates

El Hadi Harkati[***, 1], Abderrezak Bezazi[*, **, 2], Fabrizio Scarpa[2], Kim Alderson[3], and Andrew Alderson[3]

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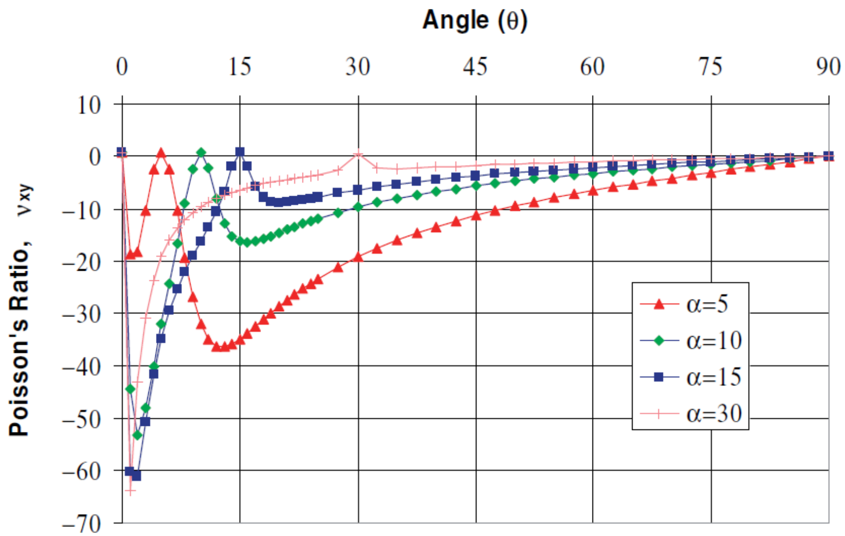
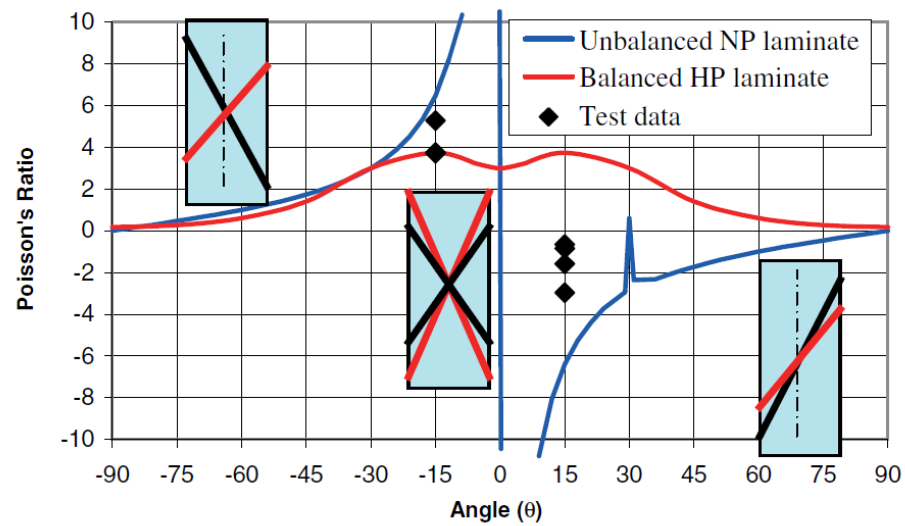
Auxetic fibre-reinforced elastomer composites



CLT predictions for in-plane Poisson's ratio ν_{xy} as a function of angle θ for various fixed angle α values in an unbalanced graphite/polyurethane laminate with a lay-up of $[\theta/\alpha]_s$



CLT predictions vs experiment as a function of angle θ for unbalanced $[\theta_2/30_2]_s$ and balanced angle-ply $[\pm\theta/\pm30]_s$ graphite/polyurethane laminates

L. D. Peel, Phys. Stat. Sol. B 244(3) (2007) 988

Auxetic Liquid Crystal Elastomers

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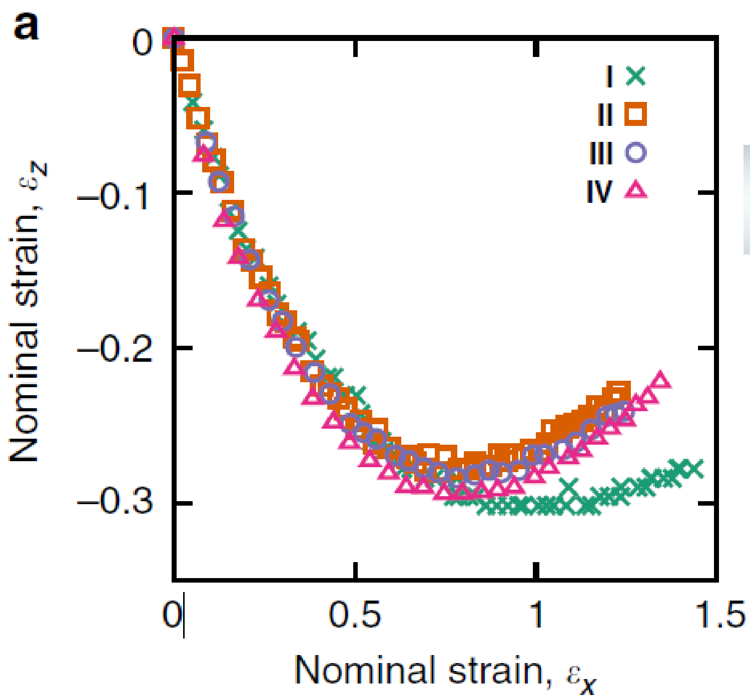


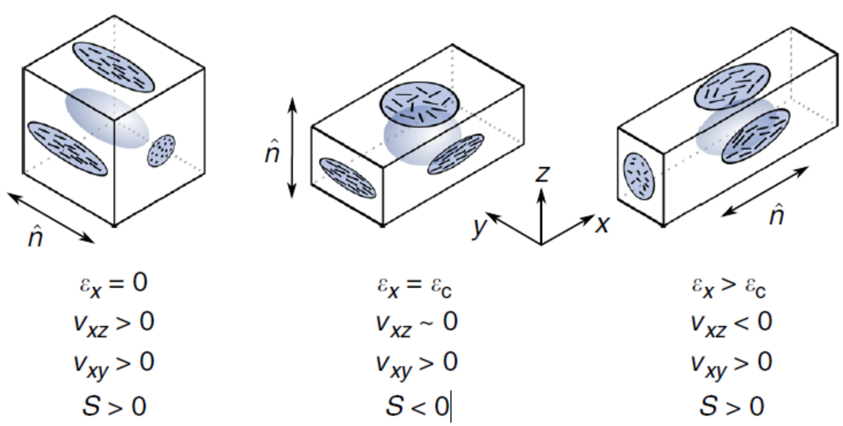
nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-018-07587-y OPEN

Coincident molecular auxeticity and negative order parameter in a liquid crystal elastomer

D. Mistry[1], S.D. Connell[1], S.L. Mickthwaite[2], P.B. Morgan[3], J.H. Clamp[4] & H.F. Gleeson[1]



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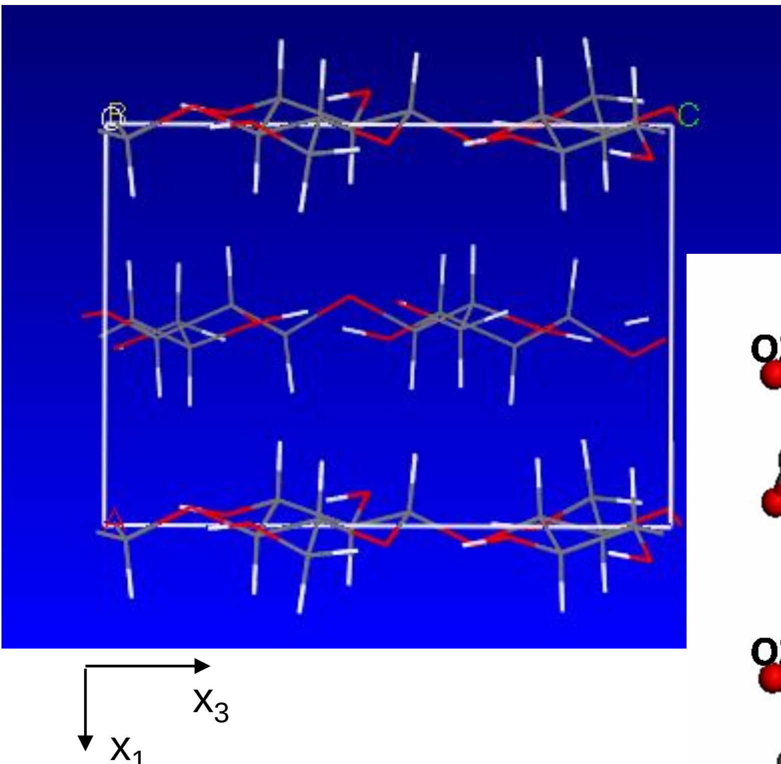
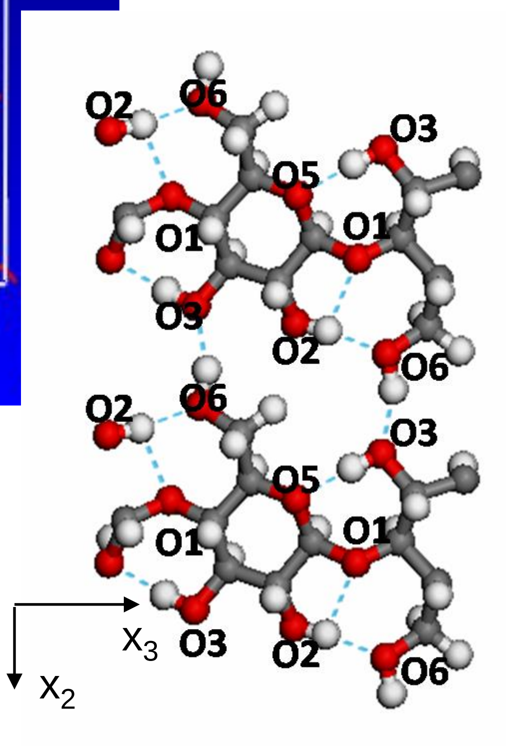
Crystalline cellulose – Kraft cooked spruce





Experimental data		
Tc [min]	Poisson’s ratios	
	ν_{31} (before yield)	ν_{31} (after yield)
120	-1.06±0.53	-0.98±0.46
150	-0.91±0.25	-1.00±0.25
180	-0.76±0.3	-0.86±0.25
210	-1.17±0.26	-1.05±0.26
240	-0.26±0.15	N/A

M. Peura, et al (2006), Biomacromolecules, 7, 1521-1528

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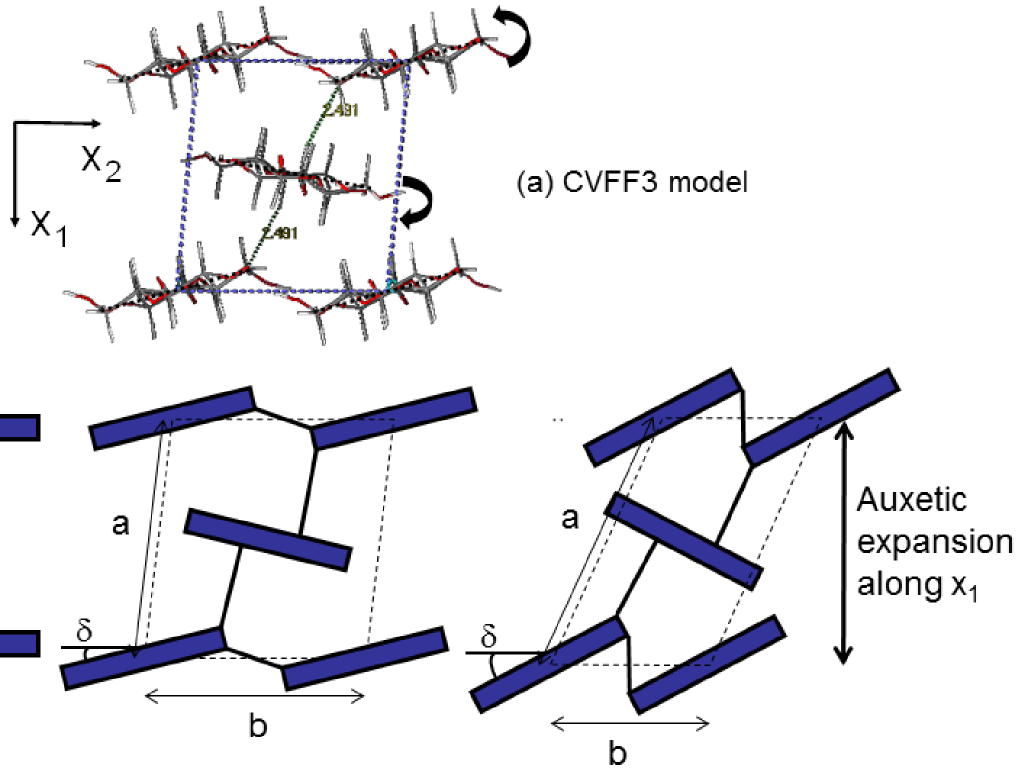
Cellulose (2016) 23:3429–3448
DOI 10.1007/s10570-016-1069-9

CrossMark

ORIGINAL PAPER

Modeling of negative Poisson's ratio (auxetic) crystalline cellulose I_β

Yong T. Yao · Kim L. Alderson · Andrew Alderson



(b) Zero tilt ($\delta = 0$; $\sigma_3 < 0$)

(c) Intermediate tilt ($\delta > 0$; $\sigma_3 = 0$)

(d) High tilt ($\delta >> 0$; $\sigma_3 > 0$)

- σ_3 (ε_3) > 0
- $\varepsilon_1 > 0 \rightarrow \nu_{31} < 0$
- $\varepsilon_2 < 0 \rightarrow \nu_{32} > 0$

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Applying the cellulose chain model to mesogen rotation in auxetic LCEs

Shruti Mandhani

MPG / RIEG Webinar - Elastomers and Polymers - Can the demand for improved sustainability be satisfied?

16th November 2020

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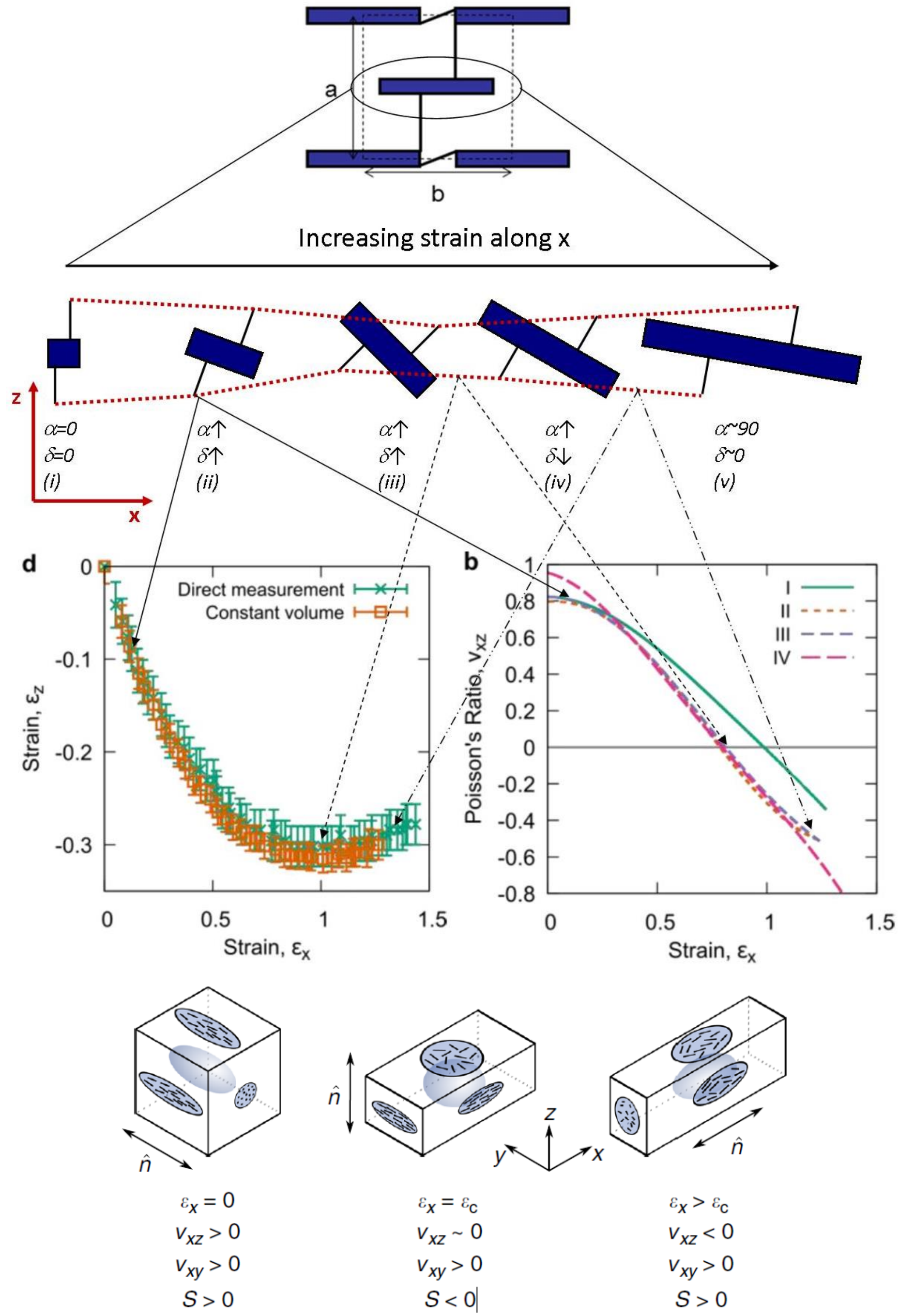
MICHELIN A BETTER WAY FORWARD

An ‘anti-rubber’ Elastomer

Shruti Mandhani
PhD Researcher
Sheffield Hallam University

Supervisors:
Prof. Andy Alderson
Prof. Doug Cleaver



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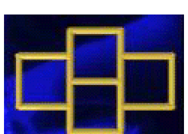
Sheffield Children's NHS Foundation Trust

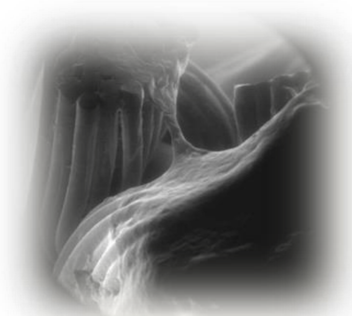
MERI-BMRC-SCH collaboration: Auxetic scaffolds for tissue engineering



Cell growth & proliferation #1
1yr u/g placement student: Jordan Roe
Supervisors:
C. Le Maitre (BMRC), AA, N. Jordan-Mahy (BMRC) & P. Godbole (SCH)
2015-2016

Cell growth & proliferation #2
1yr RA: Paul Mardling
Supervisors:
C. Le Maitre (BMRC), AA, N. Jordan-Mahy (BMRC) & P. Godbole (SCH)
2017

Tissue Engineering
VCS PhD student: Paul Mardling
Supervisors:
C. Le Maitre (BMRC), AA, N. Jordan-Mahy (BMRC)
Advisor: P. Godbole (SCH)
2018-2021



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Why auxetic scaffolds?

- Increasing number of natural soft biological tissues reported to display auxetic behaviour

- Preliminary report (Park 2013) that auxetic PU foam scaffold under compression leads to enhanced physical stimulation for cellular proliferation during cell cultivation
  - 1.3 times higher cellular proliferation rate 3 days after cell seeding
  - 1.5 times higher amount of collagen produced by the cells after 3 and 5 days in culture

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PhD: Investigating the Use of Auxetic Materials Within Tissue Engineering

Aim/Objectives	Methodology
Create auxetic scaffolds	Thermomechanical triaxial compression
Assessment of mechanical properties	3D Digital image correlation
Culture human cells within auxetic scaffolds	Various primary cell types seeded within auxetic scaffolds and cultured for up to 4 weeks.
Assessment of cell culture	Histology: • Haematoxylin and Eosin : Cell morphology • Masson's trichrome : Extracellular matrix • Immunohistochemistry: Cell markers
Culture human cells within auxetic scaffolds under physiological load	Using a bioreactor to grow cell seeded scaffolds under cyclic physiological load.
Assessment of cell culture	Histology: • Haematoxylin and Eosin : Cell morphology • Masson's trichrome : Extracellular matrix • Immunhistochemistry: Cell markers

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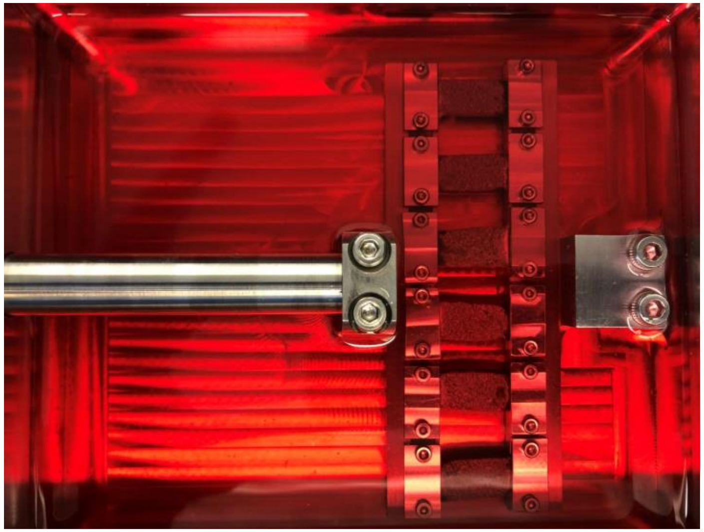
Key results and outcomes/conclusions to date

- Development of auxetic scaffolds successful
  - Another novel scaffold currently in development
- Cell culture of seeded scaffolds for 4 weeks
  - Cells attach
  - Proliferate
  - Currently checking differentiation status
- Cell culture under cyclic physiological load
  - ongoing



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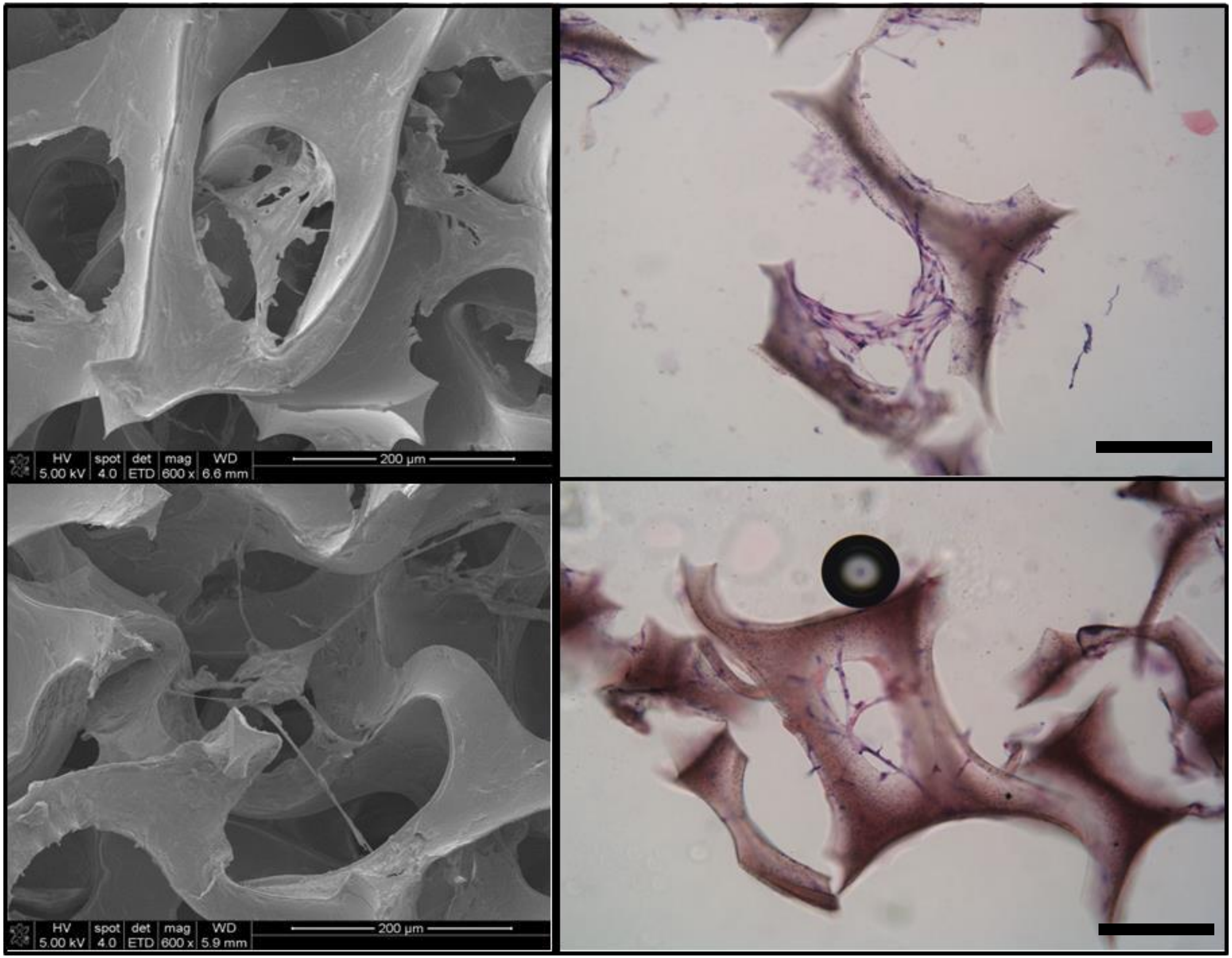
SEM & Histology comparison



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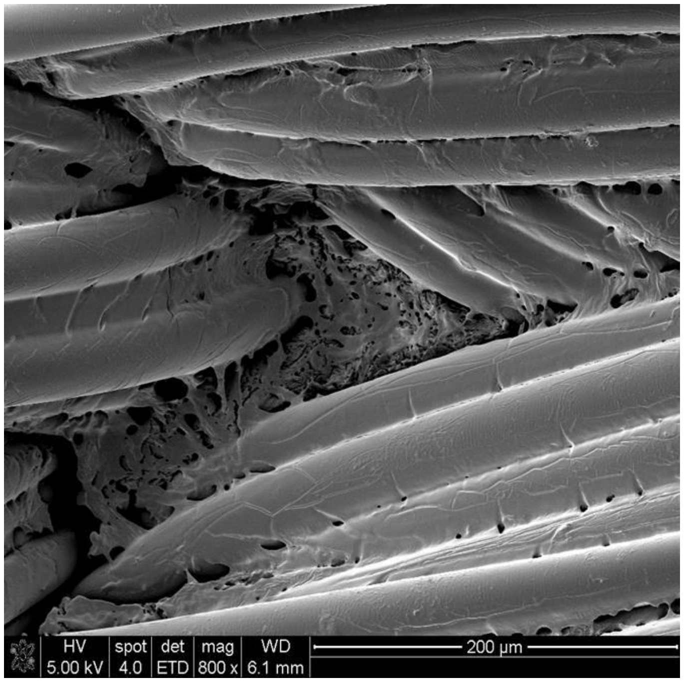

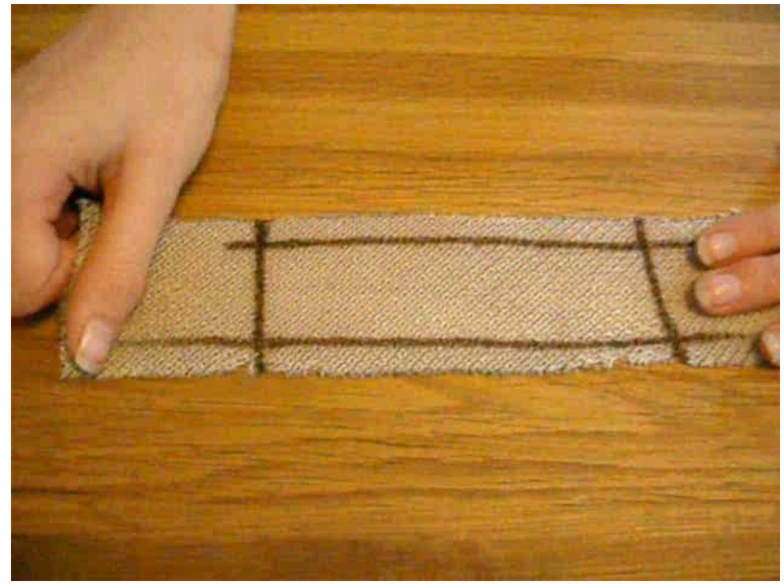

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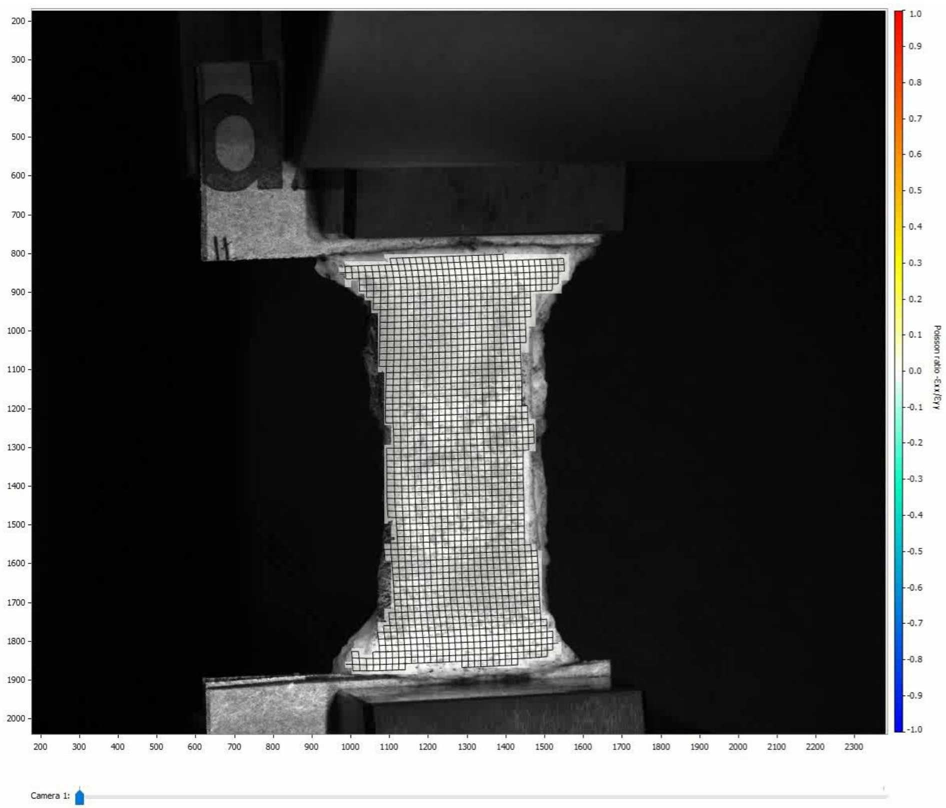
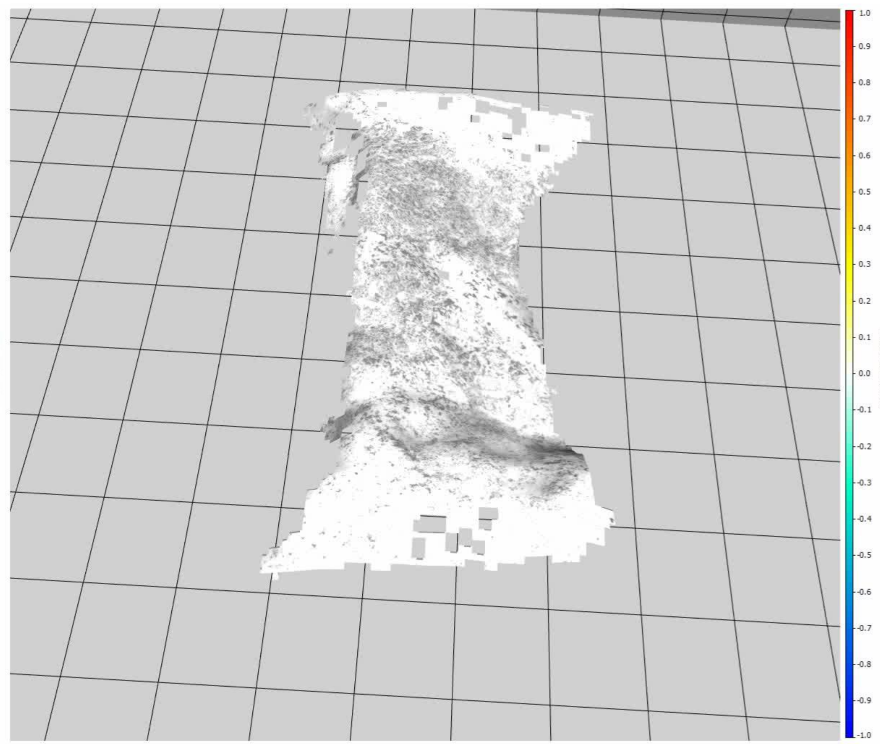
3D DIC Tissue samples





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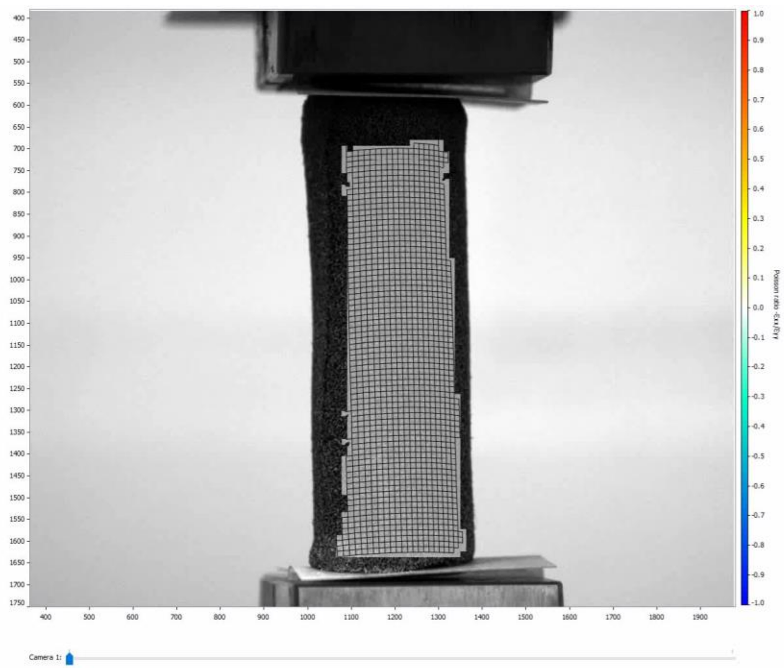
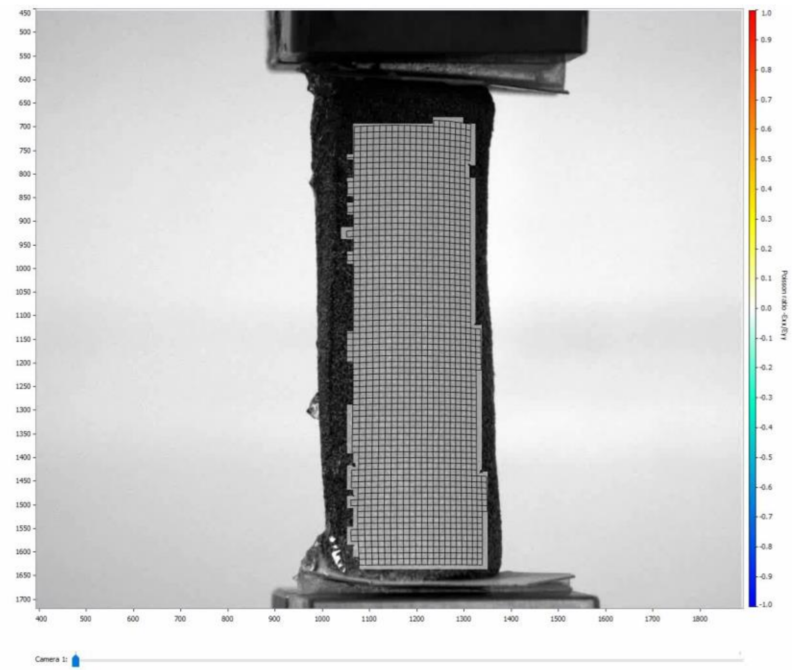
Composite Foam-Hydrogel Scaffold

Converted



Converted containing Hydrogel



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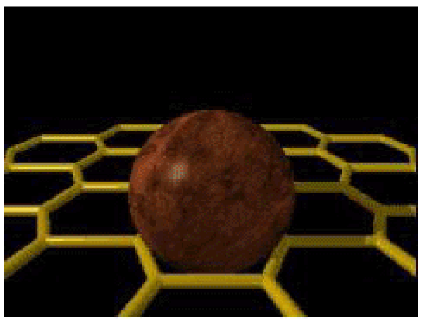
654 Ind. Eng. Chem. Res. 2000, 39, 654–665

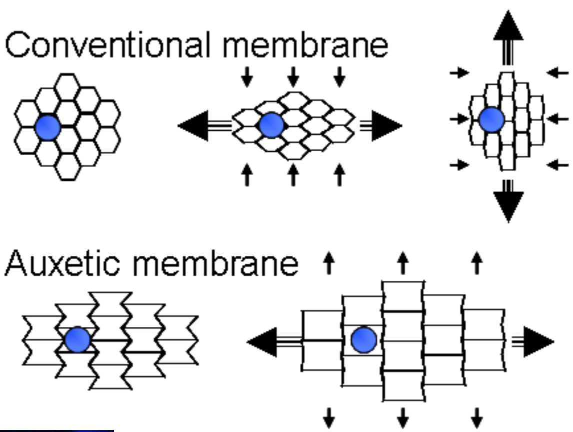
An Auxetic Filter: A Tuneable Filter Displaying Enhanced Size Selectivity or Defouling Properties

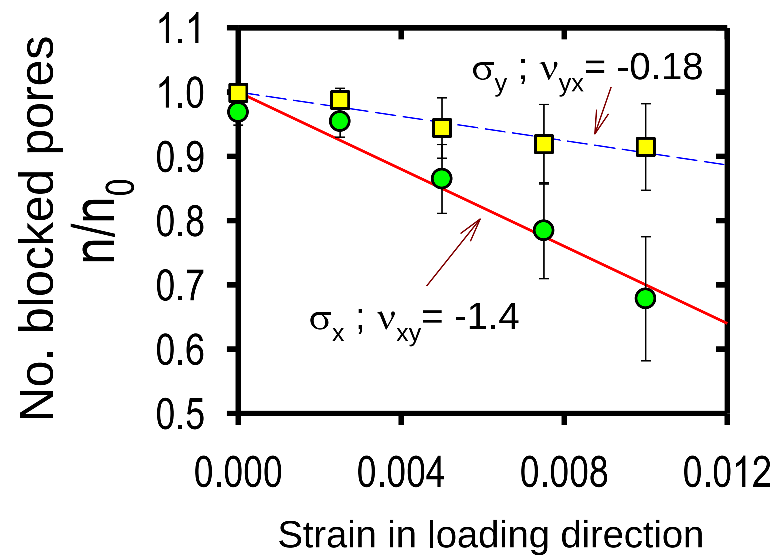
Andrew Alderson,*,† John Rasburn,‡ Simon Ameer-Beg,† Peter G. Mullarkey,‡ Walter Perrie,† and Kenneth E. Evans‡

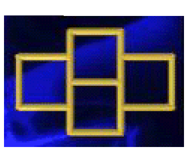
Storage and release of guest material:

High volume change (variable porosity membranes)









Movie courtesy of BNFL (source: BNFL ‘World Beating Science’ CD-ROM)

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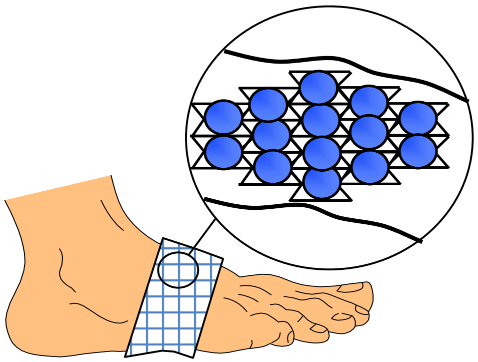
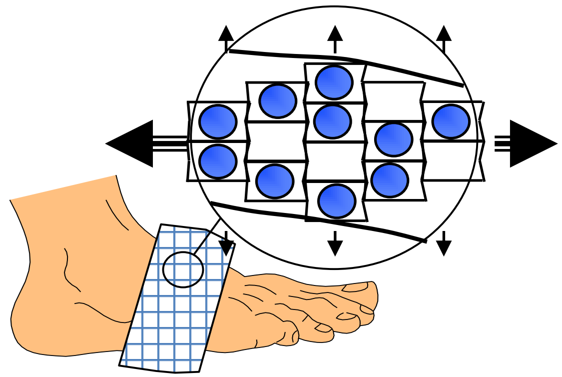
'SMART' BANDAGE: IMPREGNATED AUXETIC FILAMENTS



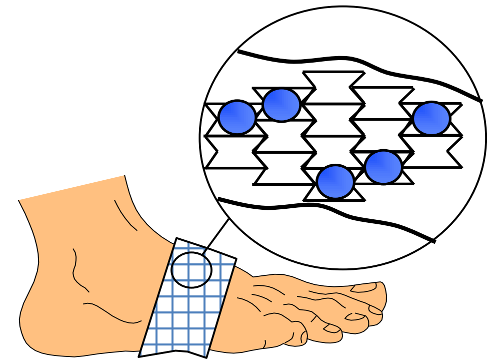
Bandage applied to wound

- bandage consists of auxetic filaments impregnated with wound-healing agent



Infected wound swells

- bandage stretches
- filaments stretch
- filament micropores open (auxetic effect)
- *release of wound-healing agent starts*



Wound heals

- swelling decreases
- bandage relaxes
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- *release of wound-healing agent stops*

A.Alderson, Presentation to Engineering Council 2001
A.Alderson, K.L.Alderson, *Technical Textiles International,* 14(6) (2005) 29.

Healthcare case study: the LaparOsphere™

- 3 million abdominal laparoscopic (key-hole) procedures are undertaken each year
- Expect increasing use of laparoscopic techniques to reduce patient trauma, speed up operations and reduce healthcare costs
- CO_2 insufflation currently used to visualise the area of interest and create a space to operate within. Issues include:
  - Raised abdominal pressure can result in reduced heart and lung function, hypercapnia and hypoxaemia
  - CO_2 losses due to the use of suction devices and leakage
  - Difficulties in using electrosurgical and laser based cutting and sealing devices
  - Requirement for additional and frequent organ retraction

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LaparOsphere™

Innovative new device for space creation and organ retraction in laparoscopic surgery

- Provides improved access and visibility for the surgeon
- Eliminates patient side effects associated with CO_2 insufflation
- Enables use of suction without deflation
- Improved use of thermal cutting systems
- No need for multiple gas tight access ports
- Eliminates recurrent deflation caused by CO_2 leaks
- No requirement for medical grade CO_2
- With its innate retraction function on inflation, reduces need for additional instruments

Potential to contribute to cost savings, reduced lengths of stay, reduced complications and reduced adverse events associated with laparoscopic procedures

(Dr James Corden (TrusTECH), "Auxetic Technology in Improving Healthcare", Materials KTN workshop, 4th September ***2012)***

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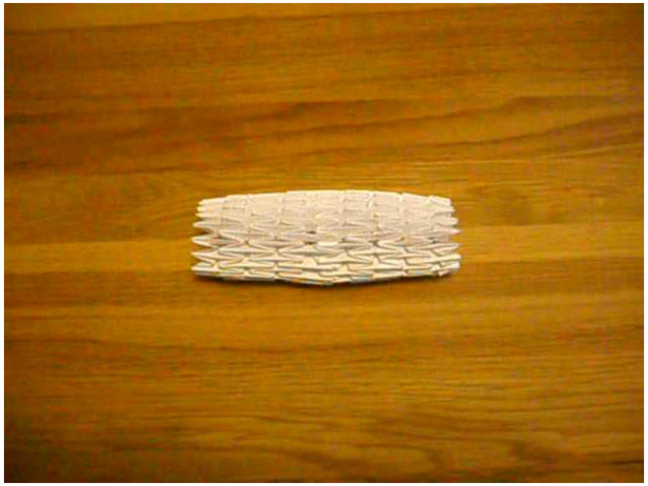
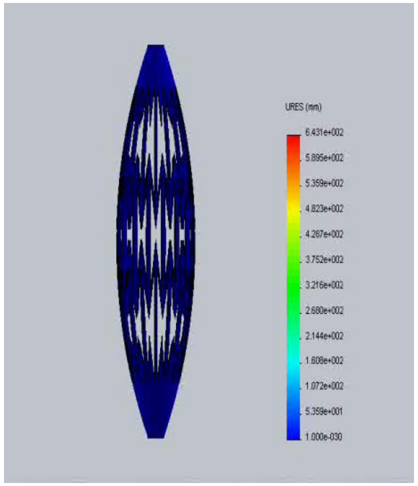
TRUSTECH The North West NHS Innovation Service NHS

EPSRC Engineering and Physical Sciences Research Council

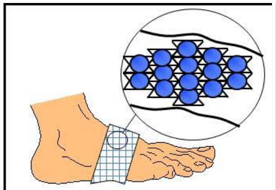
Deployable auxetic cylinders

PhD student: Dignesh Shah





Sector case study: Healthcare



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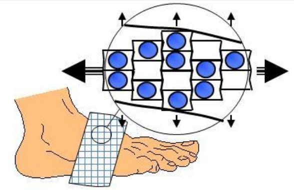

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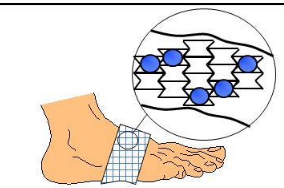

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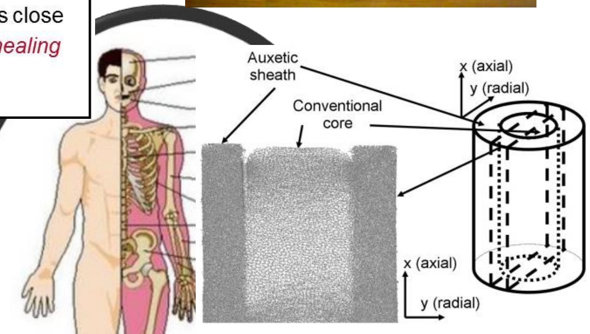
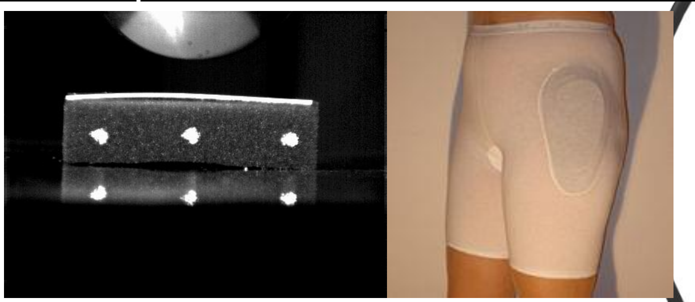
The 'smart bandage' concept delivers controlled drug release from wound dressings in response to swelling of the wound

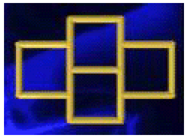
Deployable gradient auxetic structures for space creation and organ retraction in keyhole surgery



Gradient one-piece foams mimic the concentric core-sheath structure of the natural intervertebral disc. The auxetic sheath reduces disc bulge under compression to reduce lower back pain



Auxetic foam pads will improve wearer acceptance and compliance in hip protector devices due to:
- improved comfort/fit (double curvature)
- enhanced energy absorption (impact response)
- lower device weight and/or volume



Hip implants with auxetic mesh stems provide
- improved match to bone mechanical properties
- reduced ‘stress shielding’
- a compensation mechanism for loosening of the stem over time - extending device lifetime and time between implant replacement operations