Auxetics: From Foams to Composites and Beyond

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Acknowledgements

Special thanks for their contribution to:

Introduction

- From the Greek *auxetos*: “that can expand”
- Indicates Negative Poisson’s ratio (NPR) materials

\[-1 < \nu < 0.5\]  
Homogeneous, isotropic solid

\[E_1\nu_{21} = E_2\nu_{12}\]  
Special orthotropic solid

\[\delta = \frac{3FR^2(1-\nu^2)}{16Et^3}\]
Central deflection of a clamped circular plate

\[H \propto \frac{1}{(1-\nu^2)^{2/3}}\]
Hardness – increase with NPR – the material wraps around the indenter

Synclastic curvature – easy manufacturing of dome-shaped structures

(University of Bolton, 2008)
Introduction

Fibril Hinging
(microporous UHMWPE and PFTE - GoreTex®)


(courtesy of Azon.com™)
Introduction

Rotating rectangles

Used to prototype “smart” filters for chemical processes.
Possible explanation of auxetic behaviour in some forms of \(a\)-crystobalite.

A. Alderson \textit{et al}.

(Courtesy of Professor Joseph Grima, http://home.um.edu.mt/auxetic/properties.htm)
Introduction


\[ \theta = 30^\circ \quad \alpha = L/r \quad \beta = t/r \quad \chi = b/L \]

- Rotations of the nodes induce bending of the ligaments
- Isotropic in-plane properties \((\nu = -1)\)
Foams

Strain dependent tensile Poisson’s ratio

Foams

1. Multiaxial compression

2. Annealing

3. Cooling

4. Relaxation of the sample
Foams

Conventional PU foam

Non-auxetic iso-density

Auxetic (ψ = -0.26)
Foams

Compression is the most significant manufacturing parameter for auxetic foams.

(M. Bianchi, F Scarpa, C W Smith. J. Mat. Sci. 43(17), 5851)

University of Bristol

ACCIS
ADVANCED COMPOSITES CENTRE FOR INNOVATION & SCIENCE
Foams

- Conventional
- Iso density
- Auxetic

Energy $U$ [mj/cm$^3$] vs. Number of cycles $N$

$N = 0, 25000, 50000, 75000, 100000$

$U = 0, 25000, 50000, 75000, 100000$

Loading level $r$ vs. Number of cycles $N$

$r = 1.225 - 0.036 \ln(N_R)$

$R^2 = 0.9575$

$r = 1.034 - 0.03 \ln(N_R)$

$R^2 = 0.9447$
Smart auxetic foams


Doping auxetic foams with magnetorheological fluids can provide a tuned acoustic absorber with shift peak varying with the intensity of an external magnet.
Shape Memory effect

Auxetic Sample

Returned Sample
Shape Memory effect

SEM images of (a) conventional, (b) 1st auxetic, (c) returned from auxetic and (d) 2nd auxetic open-cell PU based foam

Foams – New manufacturing process

New manufacturing process for Auxetic foams

Foams – Vibration transmissibility
Centre-symmetric honeycombs

Flexible topology to enhance the mechanical and thermal conductivity performance

\[ \frac{\rho}{\rho_c} = \beta \frac{4\gamma + 2 + \alpha}{2(2\gamma \cos \varphi + \cos \theta)(\alpha + \sin \theta + 2\gamma \sin \varphi)} \]
Centre-symmetric honeycombs

INCONEL 617 core
Conduction – radiation problem

Time 0 s – uniform 273 K
Time 20 s – 1400 K at upper face

In upper surfaces, temperatures are lower for auxetic configurations

Innocenti P., Scarpa F, 2009. J. Comp. Mat. 43(21), 2419
Centre-symmetric honeycombs

Shape memory alloy honeycombs
Centre-symmetric honeycombs

Nonlinear in-plane properties – SMA honeycombs

![Graph showing stress-strain relationship for Centre-symmetric honeycombs.]

**Auxetic centresymmetric honeycomb**

4 x 4 cells, $\alpha = 2$, $\beta = -15$, $\gamma = 0.02$

At 2% tensile strain:

<table>
<thead>
<tr>
<th></th>
<th>CMT (linear)</th>
<th>FE</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu'_{yx}$</td>
<td>-2.76</td>
<td>-2.8</td>
<td>-2.0</td>
</tr>
</tbody>
</table>

![Graph showing stress-strain relationship for Auxetic centresymmetric honeycomb with different parameters.]

**Auxetic centresymmetric honeycomb**

4 x 4 cells, $\alpha = 2$, $\beta = 40$, $\gamma = 0.02$

At 2% tensile strain:

<table>
<thead>
<tr>
<th></th>
<th>CMT (linear)</th>
<th>FE</th>
<th>Exp.</th>
</tr>
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<tr>
<td>$\nu'_{yx}$</td>
<td>2.59</td>
<td>2.48</td>
<td>2.2</td>
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</table>

(Hassan MR, Scarpa F, Mohamed NA. Journal of Intelligent Material Systems and Structures 2009 **20**: 897-905)
Zero \( \nu \) honeycombs (SILICOMB)

Gradient honeycombs

Kirigami/Origami honeycombs

(Saito K., Neville R. Scapa F., ICCS16 Porto, 28-30 June 2011)
Chiral structures

- Developed using RTM techniques for maritime sandwich applications
- Core with polyester/glass fibre
- Superior specific compressive and shear strength compared to analogous cores in marine constructions
- Possibility of embedding sensors (PZT, MFCs) for SHM or other monitoring applications
- Flat or curved panels easily manufactured with no in-plane buckling stresses
- Developed and commercialised by CHISMATECH (Catania, I)

(Scarpa F., 2010. *Comp. Sci. Tech.* 70. CHISMACOMB Special Issue)
Chiral structures

Truss-core beam

Deformed configurations for excitation at resonant frequencies:

Localized deformations

Numerical

1120 Hz

Localized deformations

Experimental

1150 Hz

(Spadoni A., Ruzzene M., Scarpa F, 2006. *J. Int. Mat. Syst. Struct.* 17(11), 941)
Chiral structures

**Eppler420 for racecar wing design**


Chiral wingbox provides continuous camber variation with a stiff bending airfoil
Deployable SMA antenna demonstrator

Packed to Deployed Area Ratio

Weight to Area Ratio

University of BRISTOL
Auxetic composite laminates

\[ \nu = -0.156 \]

\[ \nu = 0.086 \]

<table>
<thead>
<tr>
<th>Name</th>
<th>Stacking sequence</th>
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<th>Name</th>
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<td>[± 33 /± 0]s</td>
<td>ST 21</td>
<td>[± 10 /± 0]s</td>
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<td>[0_2/± 0]s</td>
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<td>[± 35 /± 0]s</td>
<td>ST 22</td>
<td>[± 15 /± 0]s</td>
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<td>ST 3</td>
<td>[90_2/± 0]s</td>
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<td>[± 24 /± 0]s</td>
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Auxetic composite laminates

3-point bending (T300-914 prepreg)

Auxetic composite laminates

3-point bending (T300-914 prepreg)

Nano-auxetics in carbon structures

- Weakening of C-C bonds strength → NPR in SWCNTs
  

- NPR effect when bond angle variation dominant
deformation mechanism modification of force constants and bond length equilibrium


- Evidence of in-plane NPR in buckypapers when mixing SWCNTs and MWCNTs


Other possible mechanisms?
Nano-auxetics in carbon structures

Missing rib model (MRM) to explain NPR in open cell foams


Vacancy defects induced by electronic or ion irradiation


Uniaxial mechanical properties depending on % of vacant atoms

CNT and graphene mechanical properties

(Scarpa F., Adhikari S., Phani A S, 2009. Nanotechnology 20 065709)
Nano-auxetics in carbon structures

- FE nonlinear tensile loading simulations – applied strain 1.e-3
- Random generation for vacancies
- Elements attached to vacant atoms desactivated (ekill utility)
- Combinations of SWCNT aspect ratio, radius and % of vacant atoms considered
- 12800 MC simulations

Nano-auxetics in carbon structures

Mean Young’s modulus ratio and standard deviation Young’s modulus ratio for armchair (n,n). ● = 2 % NRV; ■ = 1.5 % NRV; ▲ = 1 % NRV; ◊ = 0.5 % NRV

Nano-auxetics in carbon structures

Probability density functions for $n_{rz}$ in (n,n) tubes ($R = 0.426$ nm, AR=5)

Distribution of the standard deviations for (n,n) configurations (pristine $n_{rz}$ between 0.29 and 0.16)

Nano-auxetics in carbon structures


Evidence on NPR in defective CNTs found in NI-CNT systems

(6,0) $\nu_{rz} = -0.41$

(Smolyanitsky A, Twari V K, 2011. Nanotechnology 22 085703)
Nano-auxetics in carbon structures

Nano-auxetics in carbon structures

Conclusions

- Auxetics and NPR can be engineered at different scales

- Use of auxetic materials and structures needs lateral thinking → multidisciplinary research

- There is scope for R&D activities at different TRLs – from blue sky to manufacturing of commercial prototypes
Thank you for your attention!