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Prediction and measurement of structural behaviour of porous solids by 3D X-ray tomography and microstructural FE modelling

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Outline of the Work

- Laboratory X-ray microtomography has been used to observe the structural evolution of porous microstructures in 3D
- To understand the deformation mechanisms that are responsible for the auxetic behaviour of polymeric foam
- To map the displacements of a granular material within a die during powder compaction, and effects of features within
- Analysis tools available to monitor structural evolution
  - *Digital Image Correlation, Digital Volume Correlation*
  - *Microstructurally faithful modelling*
- *In situ* investigations require use of external apparatus/rigs
  - *Map displacements during uniaxial tensile loading of foam*
  - *Map flow of powder during transfer and compaction*

Auxetic Foam

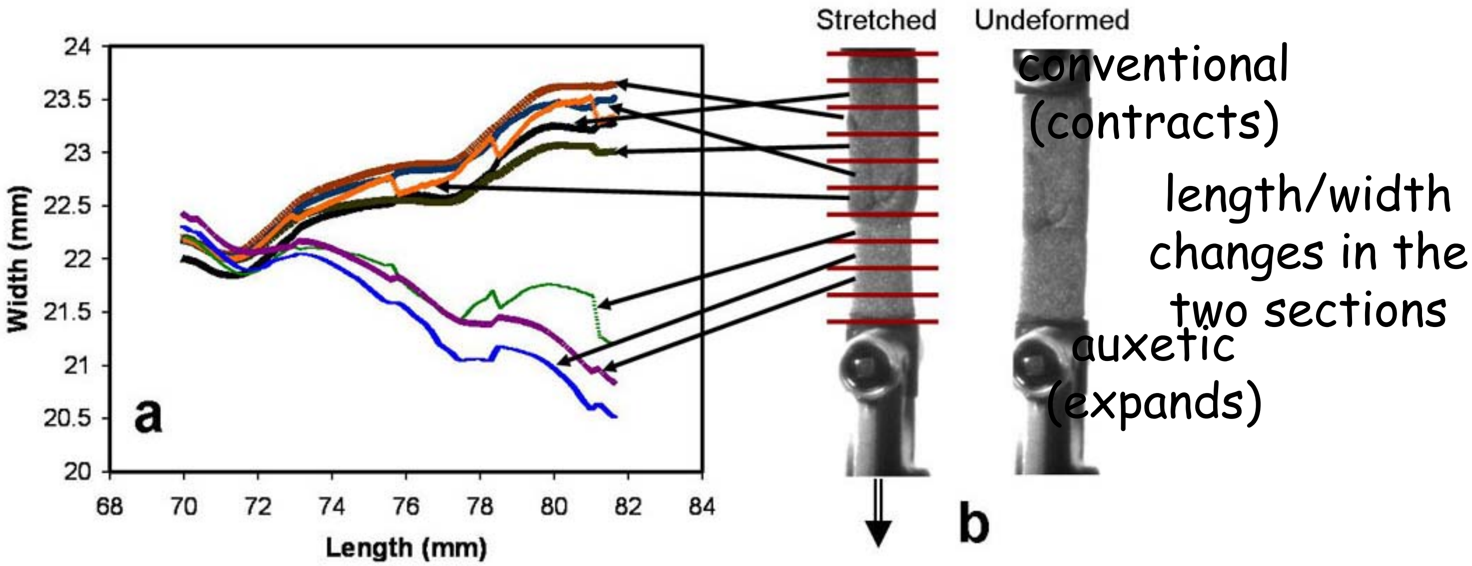
- The three-dimensional nature of auxetic foams makes it difficult to accurately observe the microstructure from quasi-2D microscopy investigations
- Current understanding of the auxetic behaviour of foam materials has been hampered by the difficulty in observing the deformation mechanisms in three-dimensions

X-ray Tomography

- Identify the predominant deformation mechanisms responsible for the auxetic response of polymeric foams
- Perform *in situ* investigations comparing both an auxetic and a conventional low-density polyurethane foam subjected to incremental uniaxial tensile loading
- Map the displacements of the foams during loading, and individual microstructural features, using image correlation

Auxetic Foam

- **Displays negative Poisson's ratio behaviour**
  - *namely a tendency to expand laterally when stretched and contract laterally when compressed*
  - *example of gradient foam shown below, showing conventional and auxetic behaviour: (a) unstressed; (b) after gripping (unstressed); (c) extension applied along length*



Auxetic Foam Fabrication

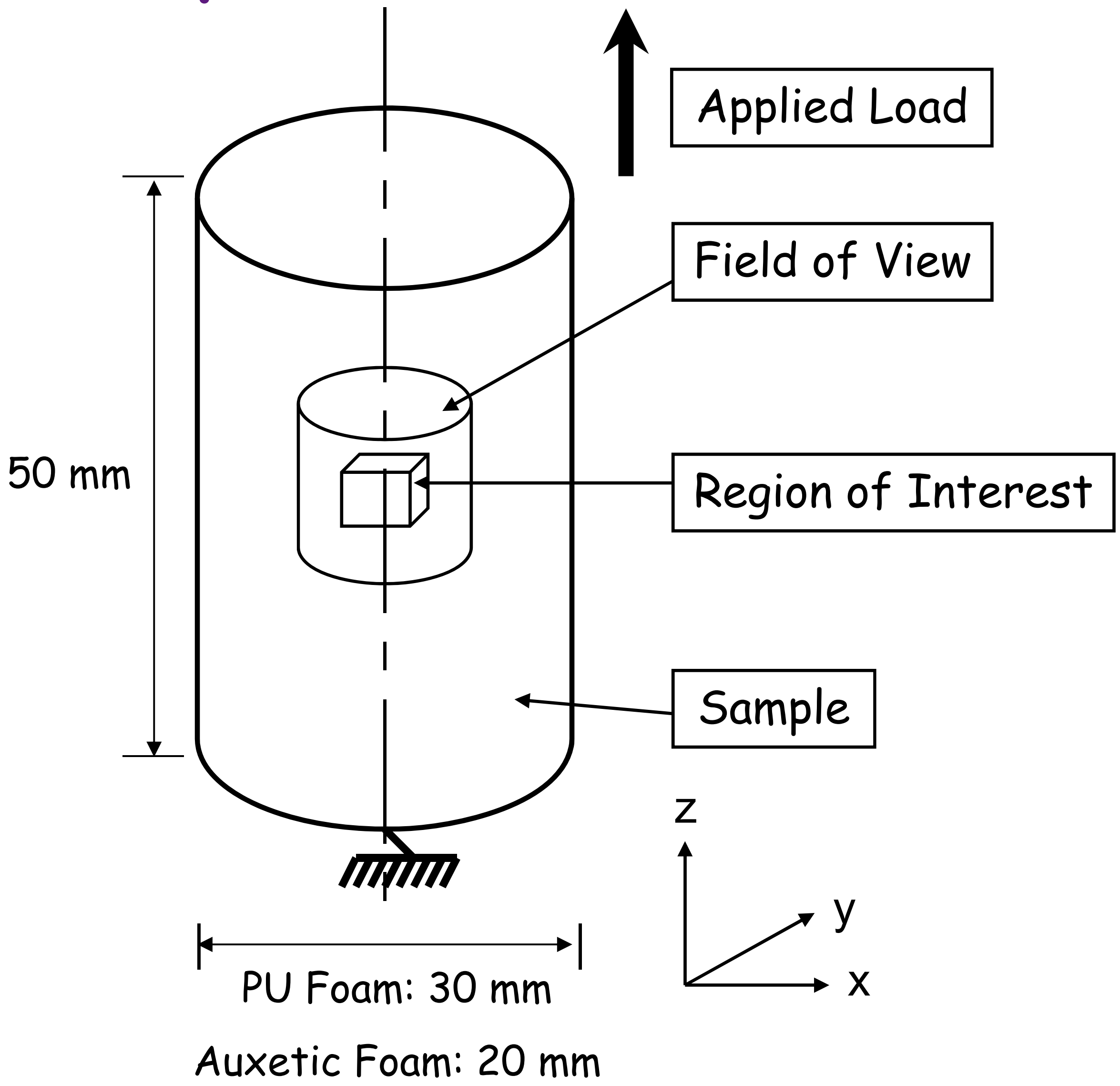
- Low-density polyurethane (PU) foam (density 26-32 kg m^{-3})
- Unconverted foam in cylindrical form of length 150 mm and diameter 30 mm, inserted into metallic tube of length 100 mm and diameter 20 mm
- Linear compression ratio of 0.67, corresponding to volumetric compression ratio of 0.3
- Mould and foam placed in oven at 190°C for 15 min
- Foam removed and relaxed to avoid adhesion of ribs and to minimise surface creasing
- Foam reinserted into mould at 190°C for 10 min, followed by 20 min at 100°C

PU Foam

Auxetic Foam

Experimental Description

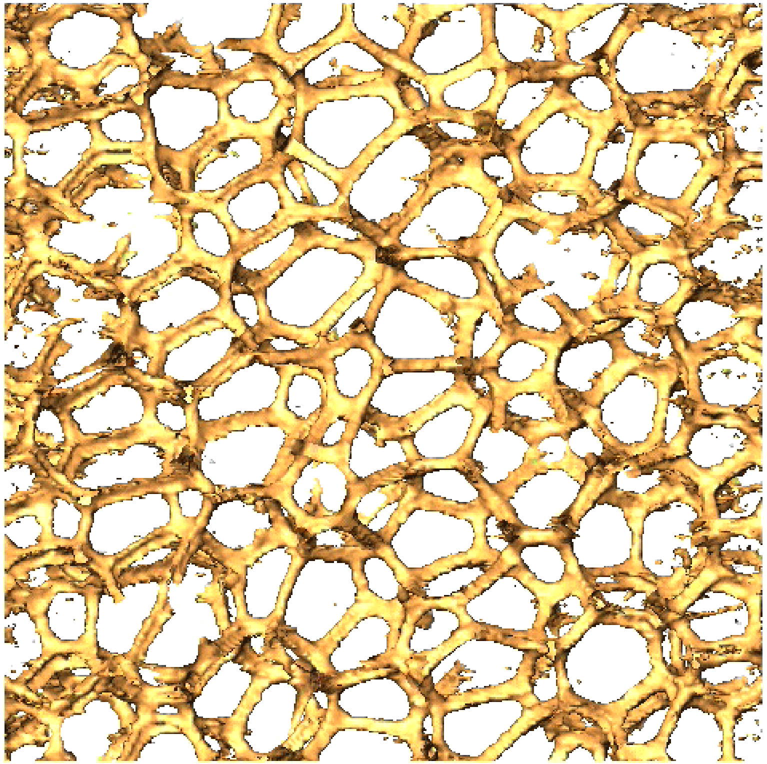
- Small region-of-interest scanned within the sample (~ 10 × 10 mm)
- Pixel size of reconstruction: 15 μm
- Incremental load applied to sample in tension
- Slices (~ 1 mm thick) extracted from virtual 3D isosurfaces for image correlation

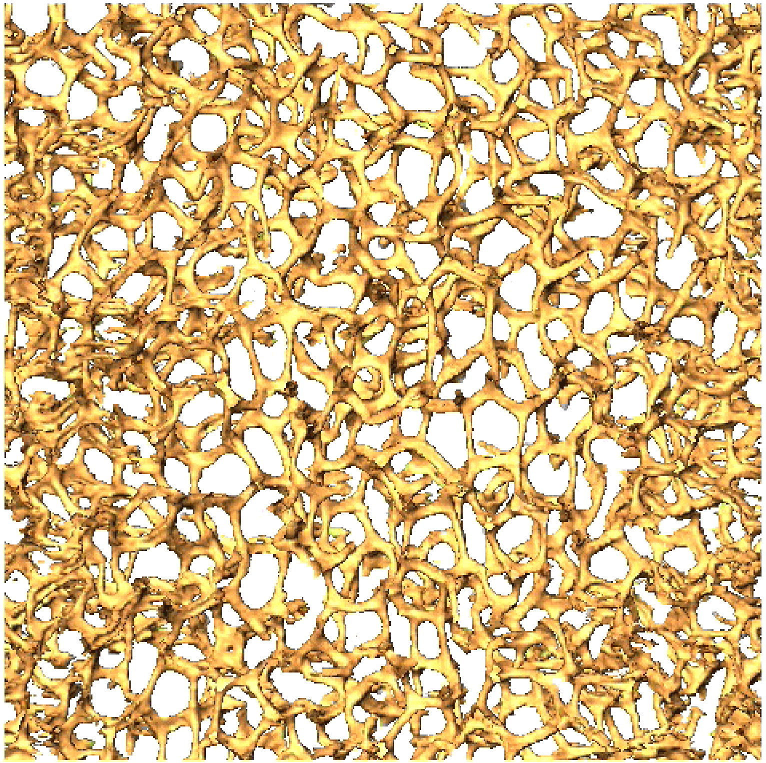


Foam Microstructure - 3D Isosurfaces

CONVENTIONAL FOAM

AUXETIC FOAM

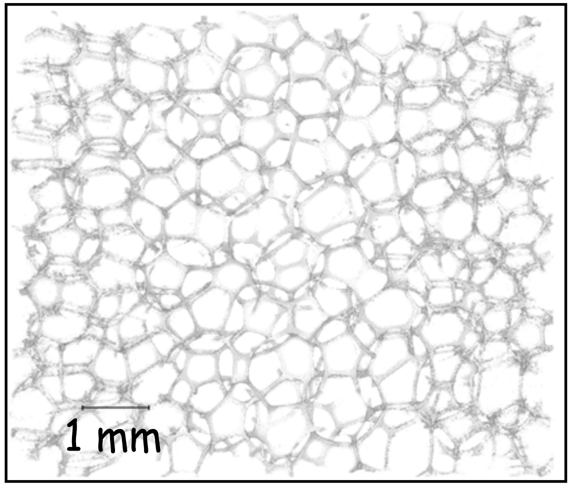




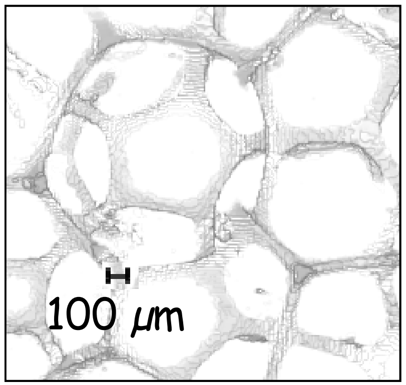
3.0 % Relative Density 6.2 %

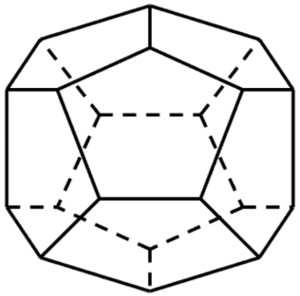
Microstructural Observations

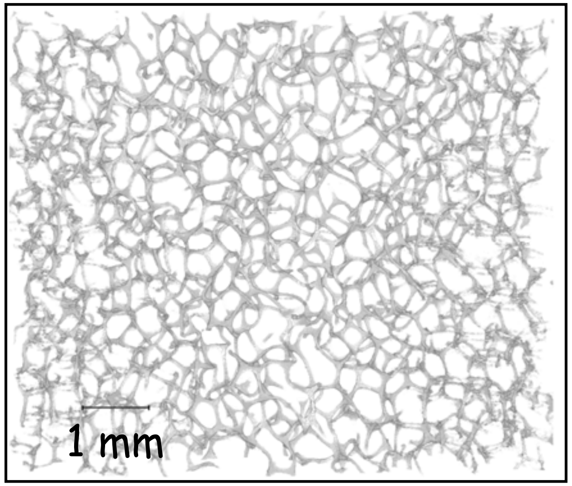
CONVENTIONAL FOAM	AUXETIC FOAM



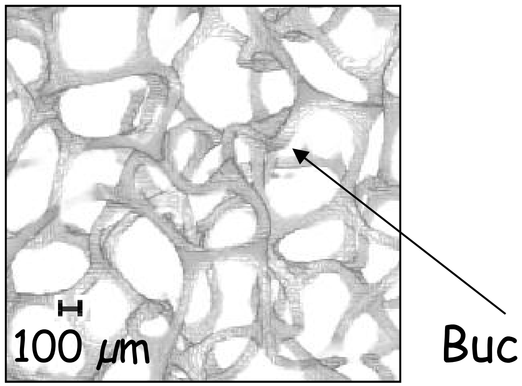
Regular open-cell network

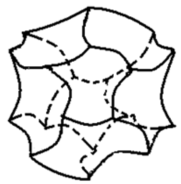




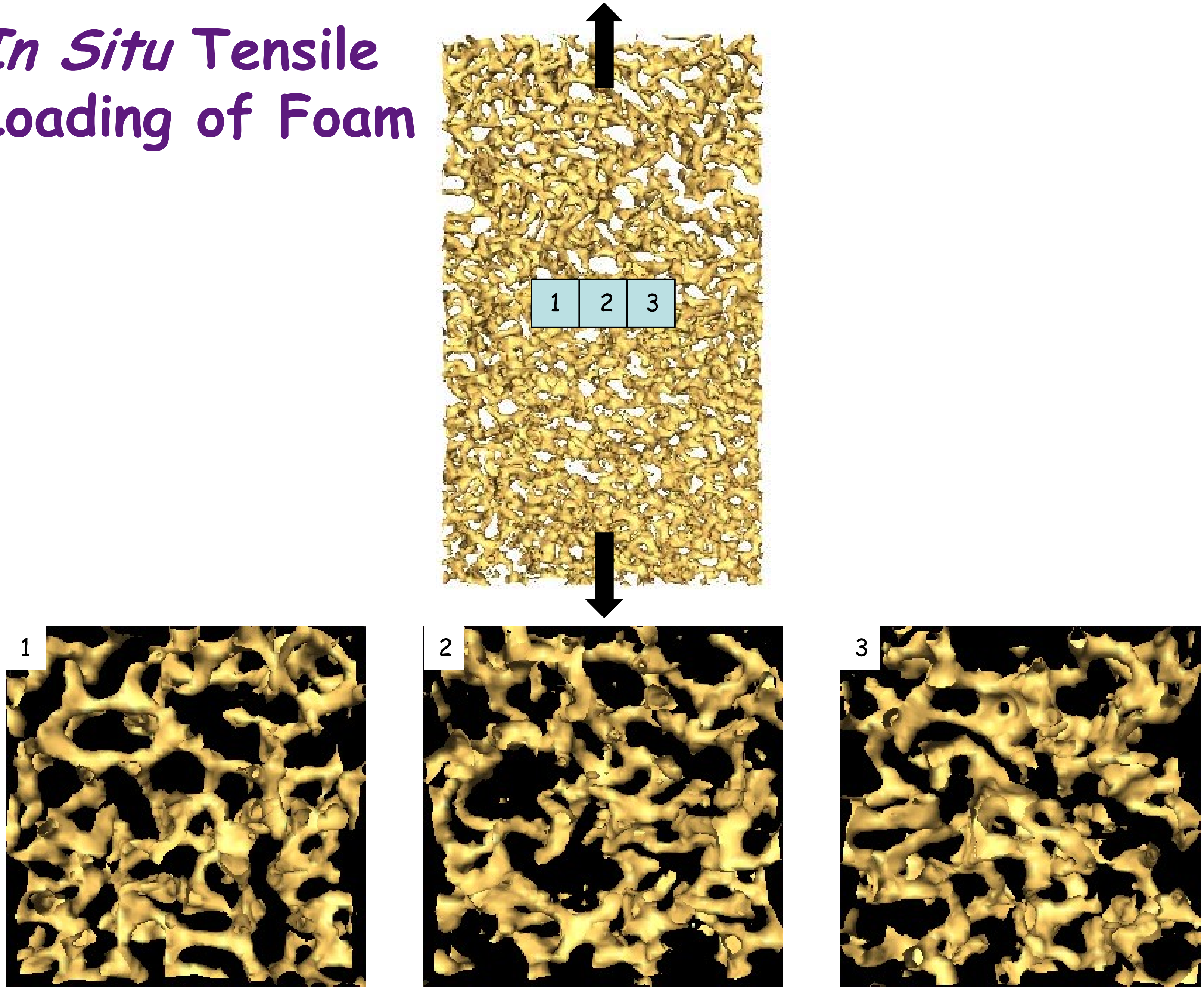


Microstructure more compact and random

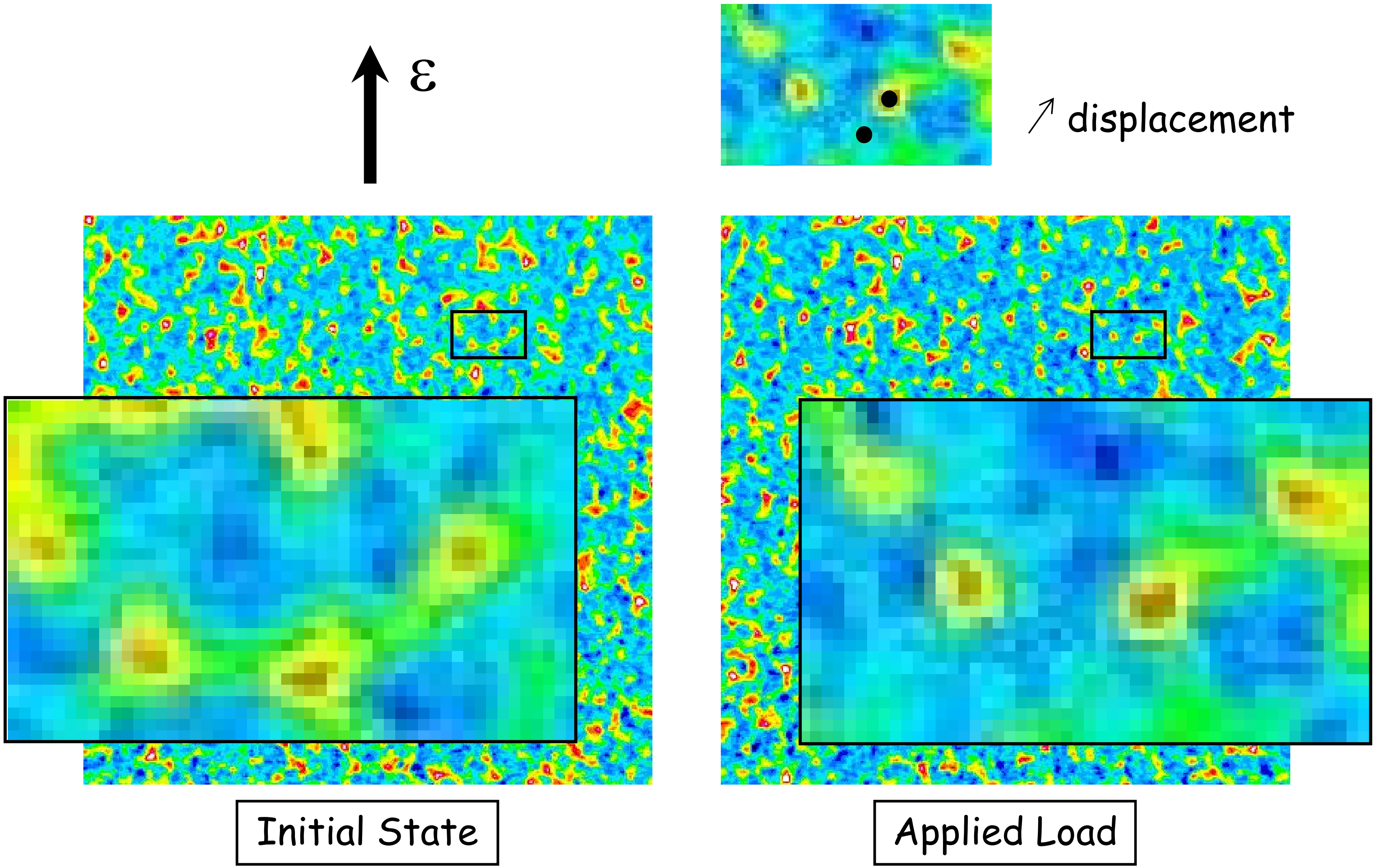




In Situ Tensile Loading of Foam

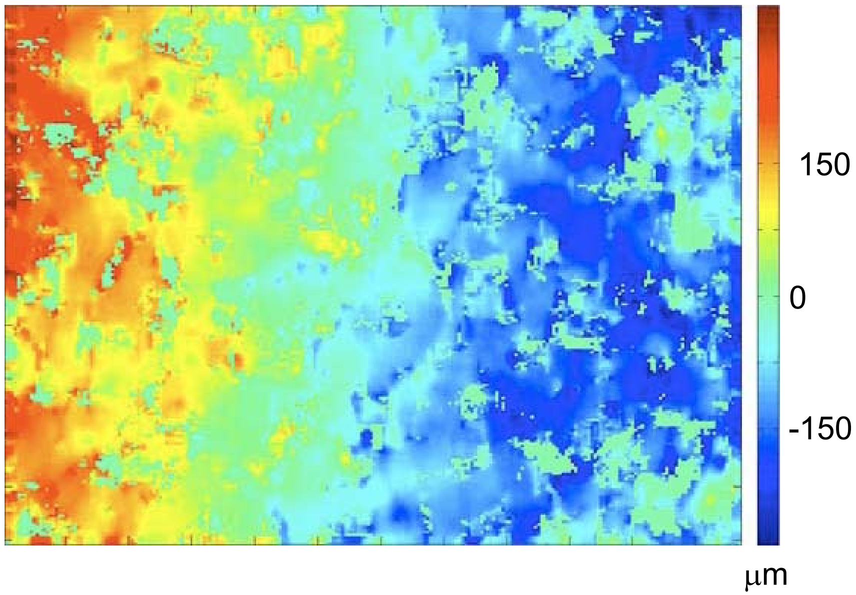


Digital Image Correlation

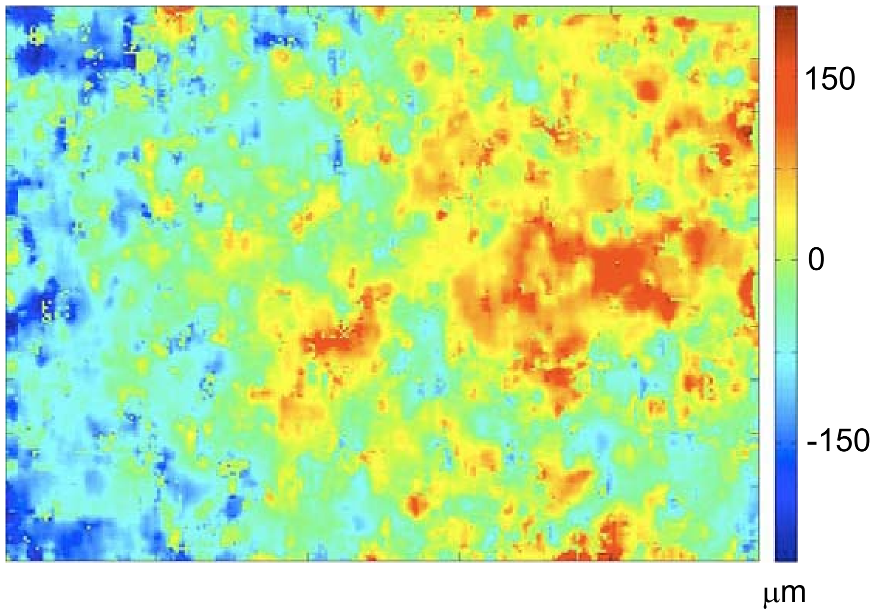


Lateral 2-D Displacement Maps

CONVENTIONAL POLYURETHANE FOAM



AUXETIC FOAM



Poisson's Ratio ~ 0.30

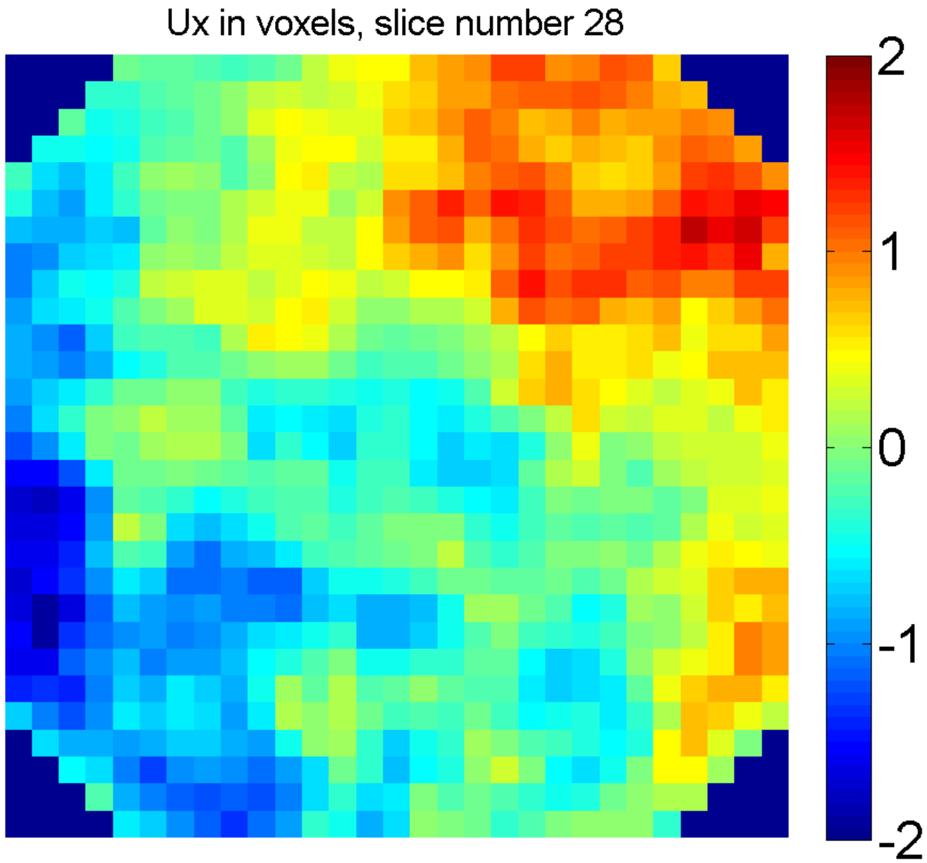
(from Videoextensometry -> 0.31)

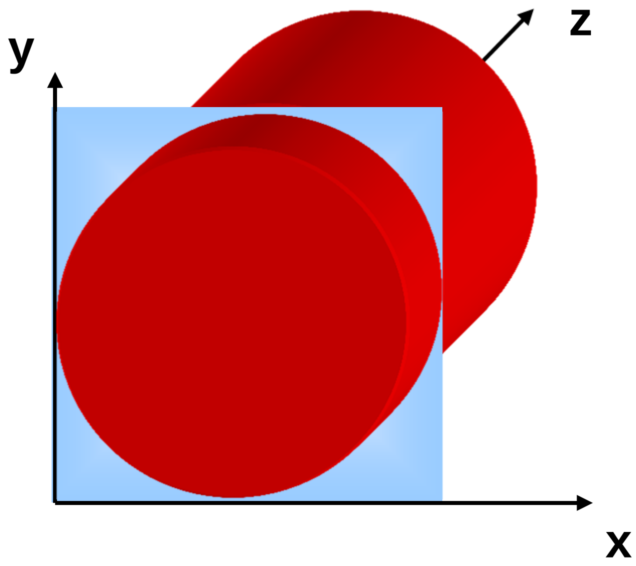
Poisson's Ratio ~ -0.22

(from Videoextensometry -> -0.21)

3-D Displacement Mapping

Displacements: Ux



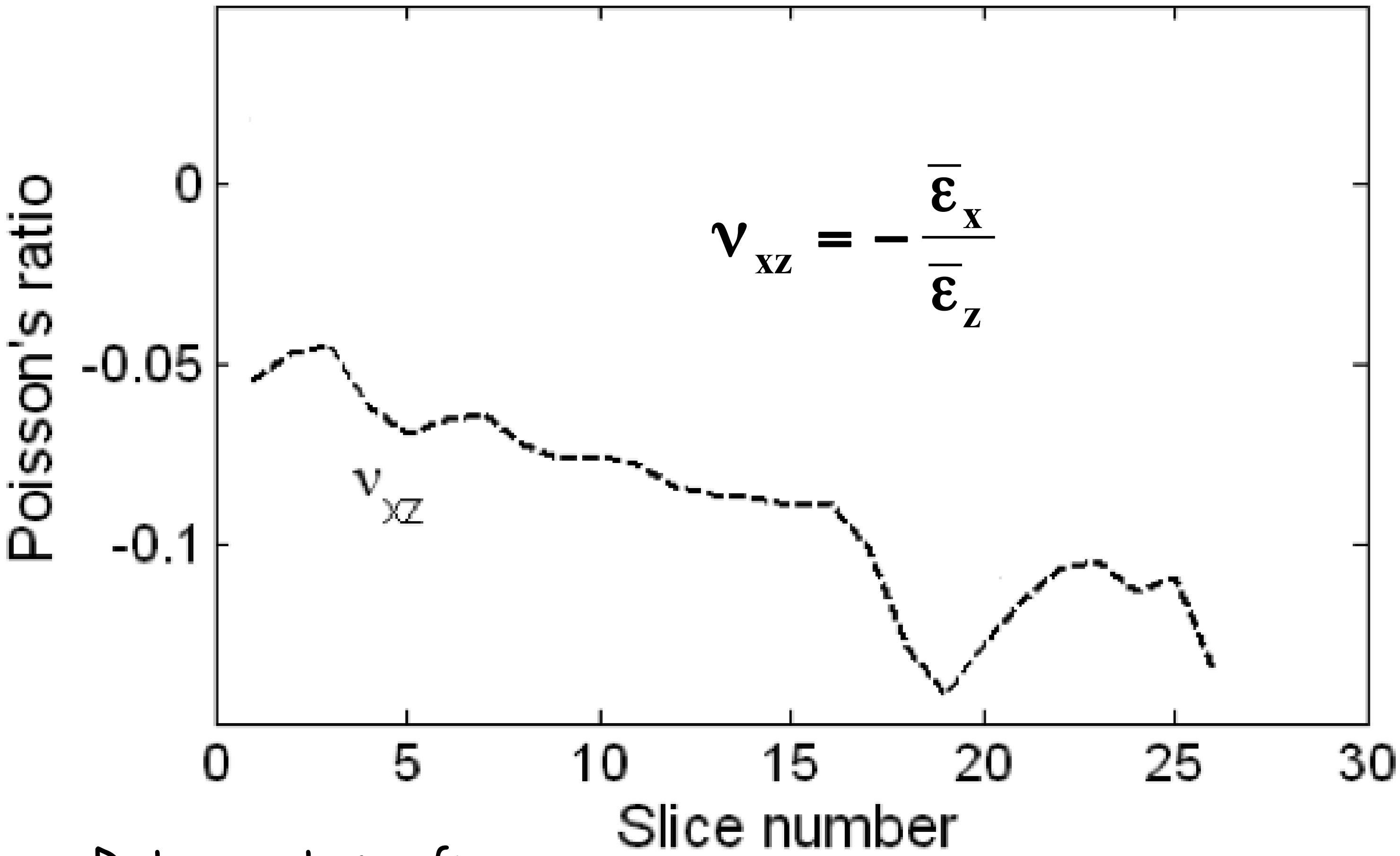


Small gradient of Ux with respect to z (ε_{xz} shear)

Data courtesy of:
Fabrice Pierron, Arts et Métiers Paris Tech
Dave Hollis, LaVision

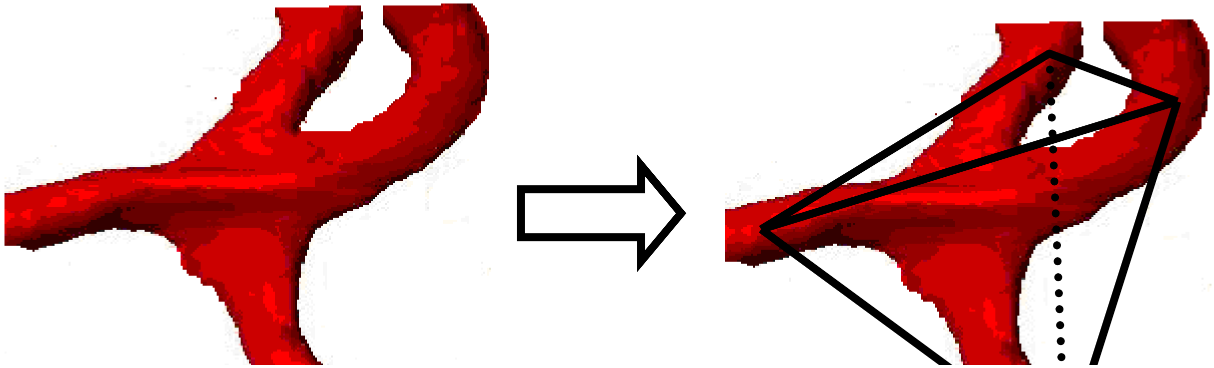
3-D Displacement Mapping

Poisson's ratio estimation



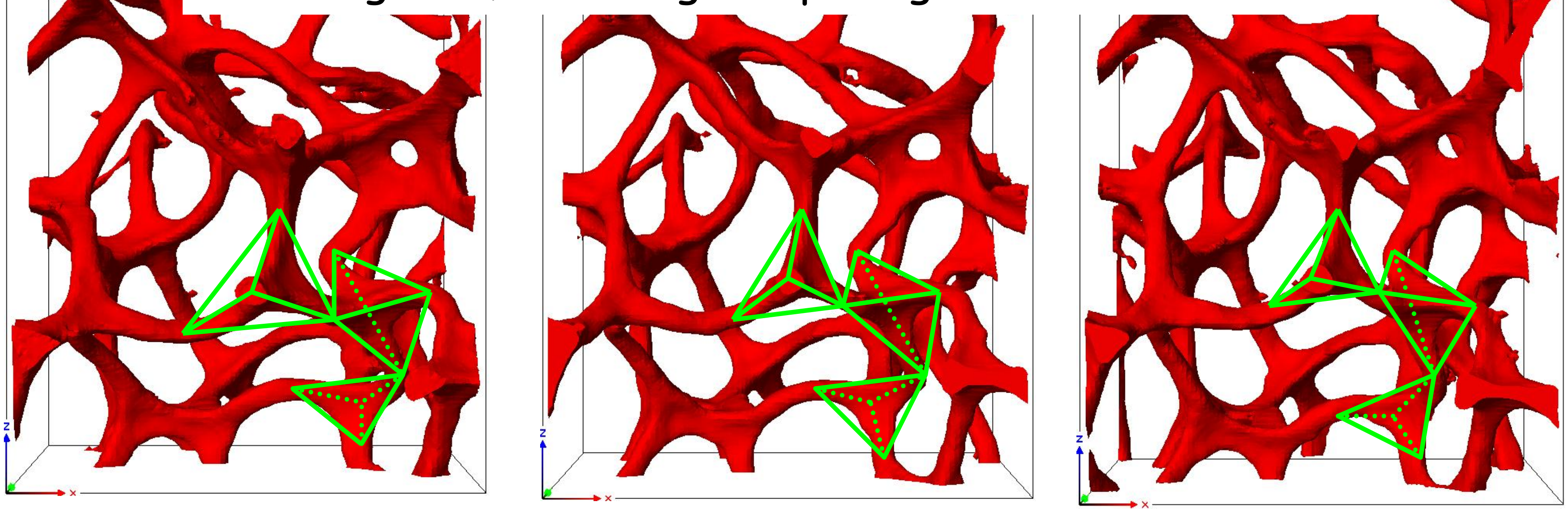
Data courtesy of:
Fabrice Pierron, Arts et Métiers Paris Tech
Dave Hollis, LaVision

Behaviour of Foam Microstructure

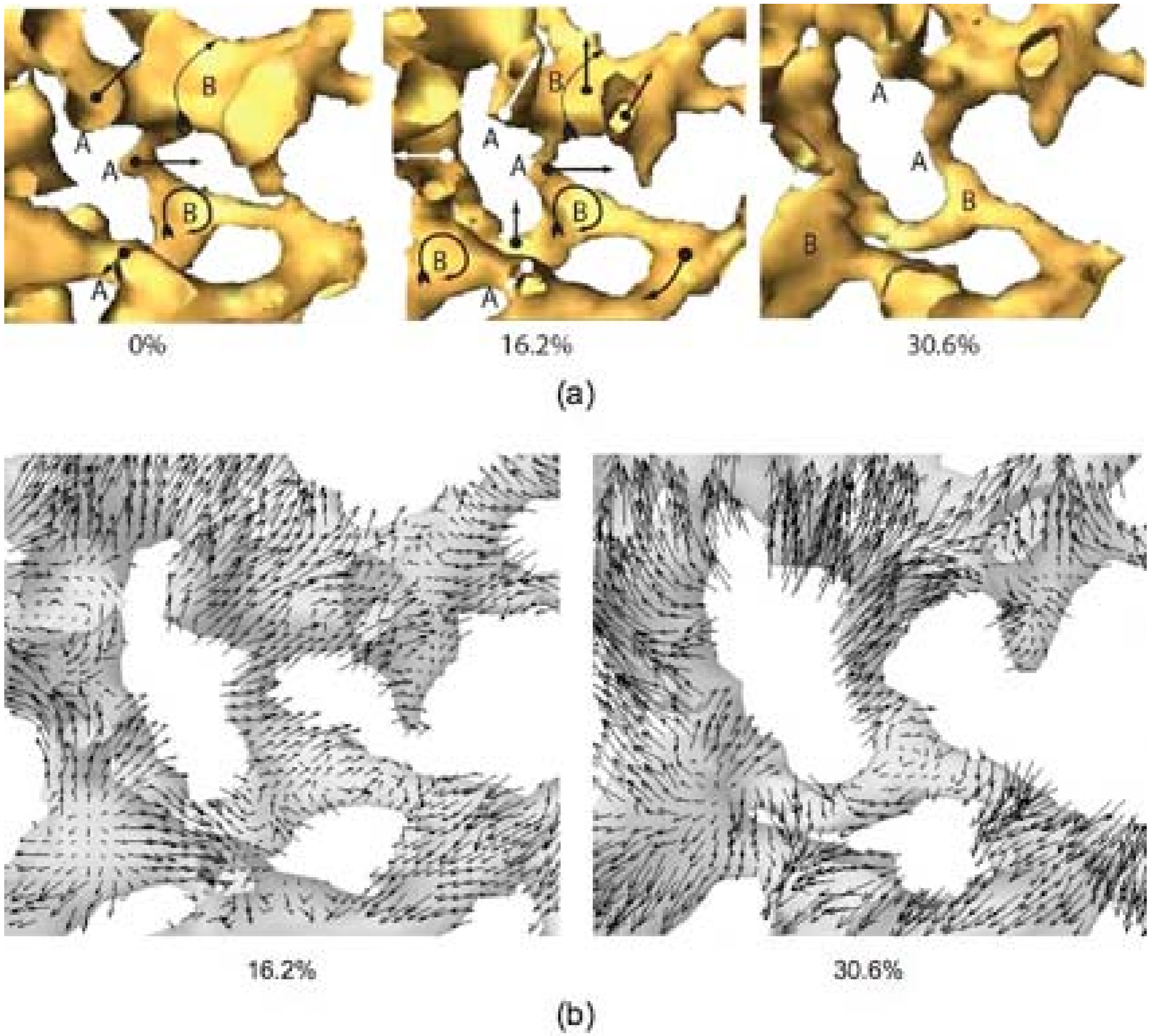


Joint represented by "rigid pyramid"

Observe rotation of the rigid joints (as solid bodies) relative to one another, with applied load, as the ribs straighten, resulting in 'opening' of the structure



Behaviour of Foam Microstructure



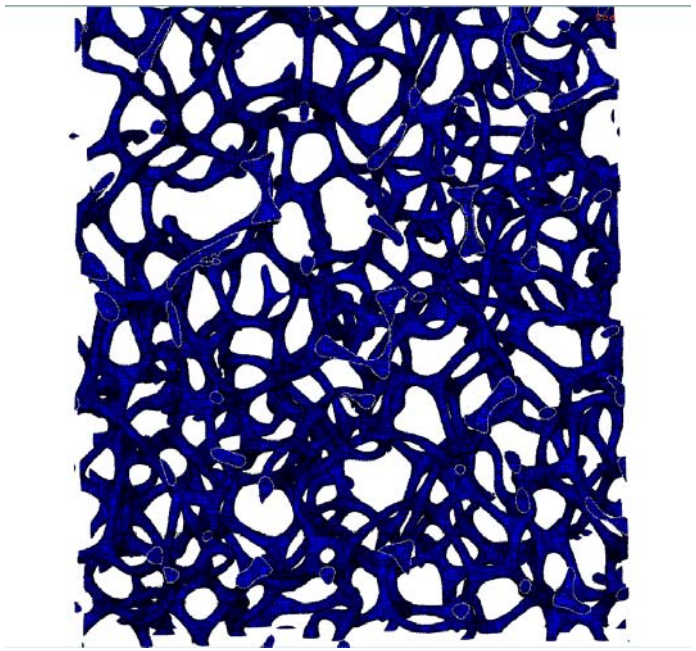
- Local shape changes giving rise to auxetic behavior
- Straightening of bent ribs (A)
- Rotation of rigid junctions (B)

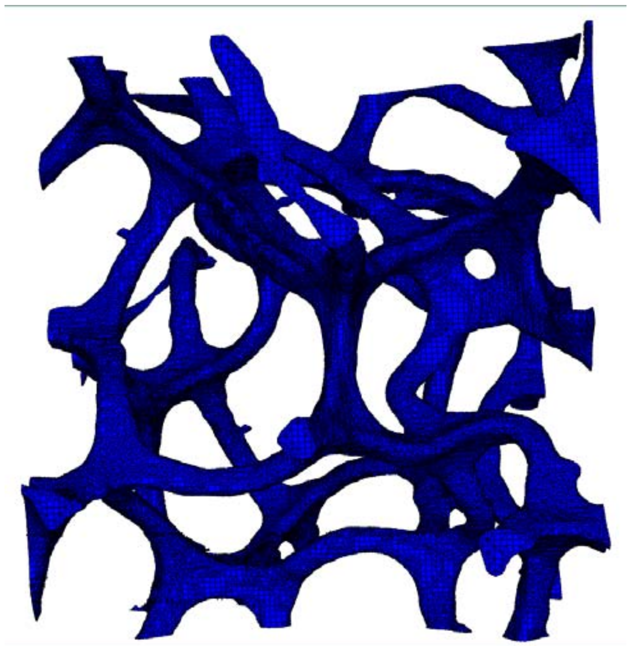
(a) Section from 3D isosurface of foam undergoing extension
(b) Structure overlayed with vector displacements

Microstructurally Faithful Modelling

- Volume meshing software, from Simpleware, converts one voxel of the tomographic dataset into one element
- Apply material properties based on the grey level of a voxel
- Boundary Conditions
  - *Bottom of the ROI fixed, foam edges free to move*
  - *Displacement prescribed to the top of the ROI*

global model



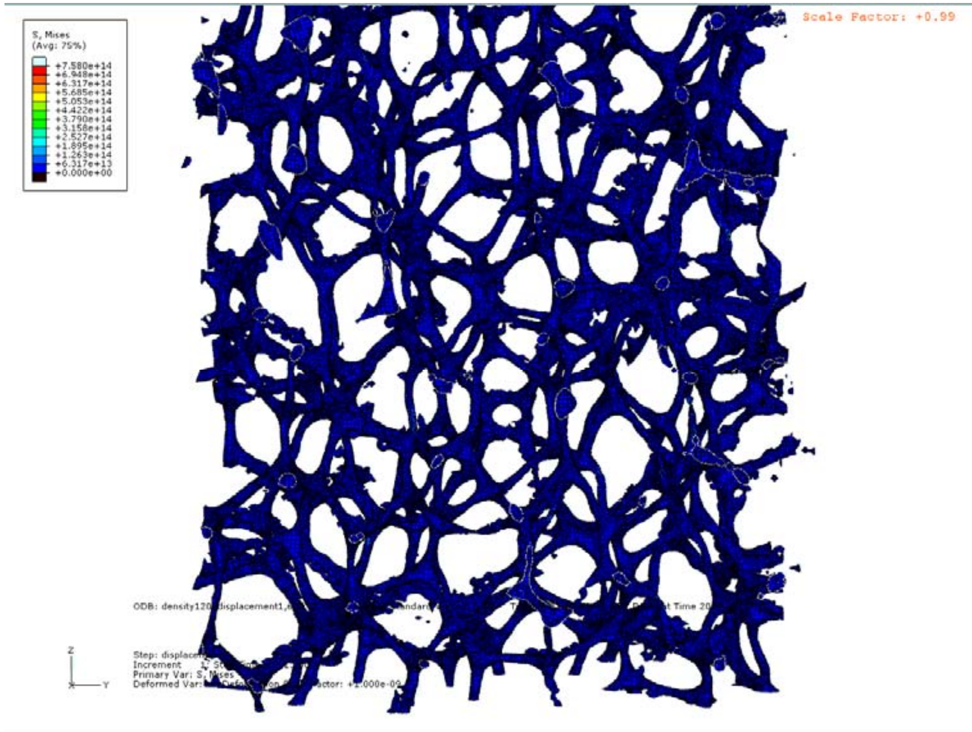


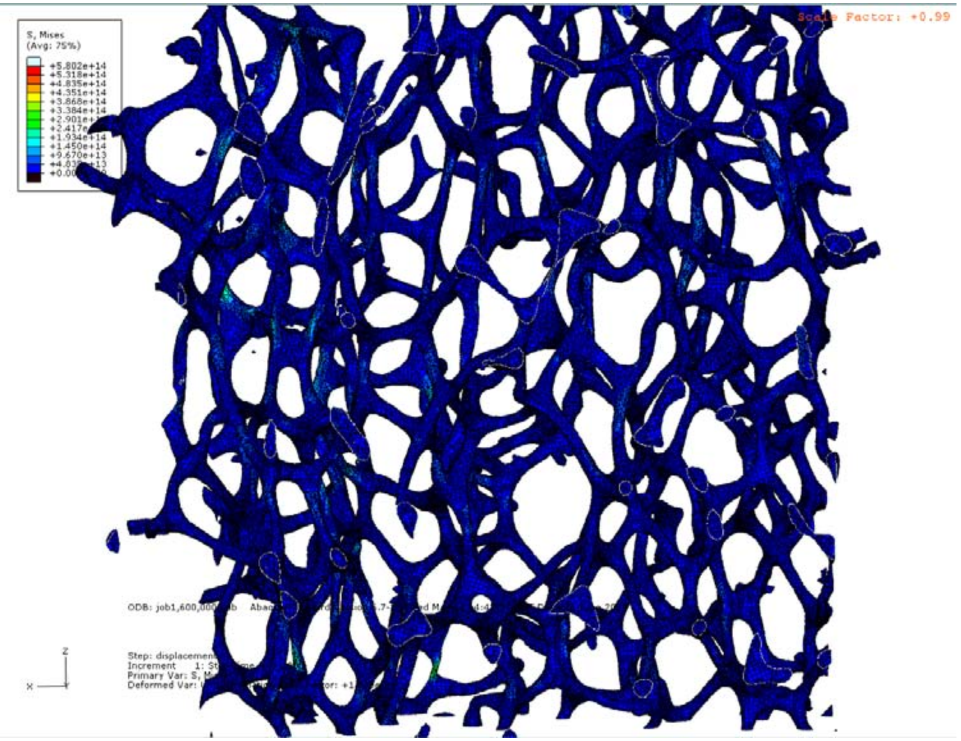
local model

FE Model - Bulk Representation

CONVENTIONAL POLYURETHANE FOAM

AUXETIC FOAM





Sample contracts

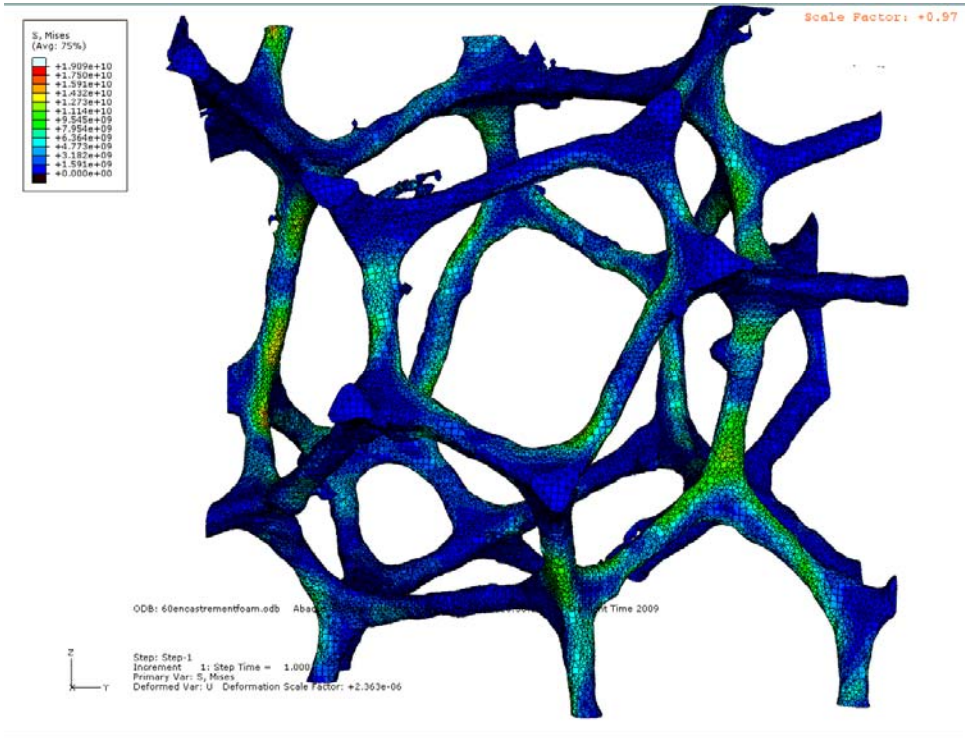
Opening of the foam structure

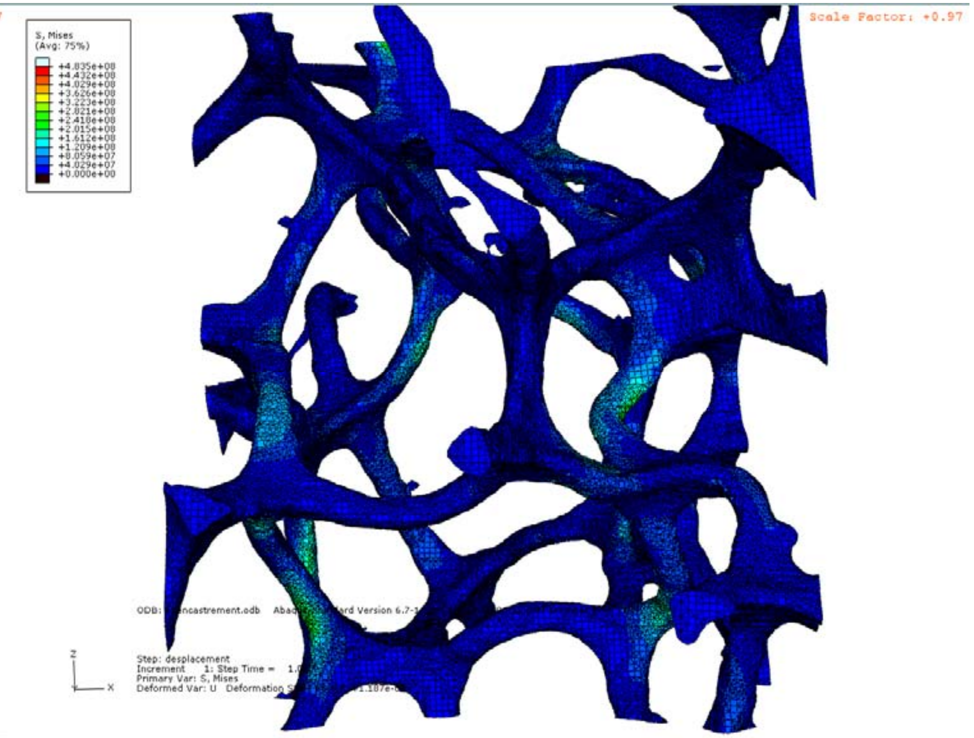
Simulates the auxetic response

FE Model - Local Region of Interest

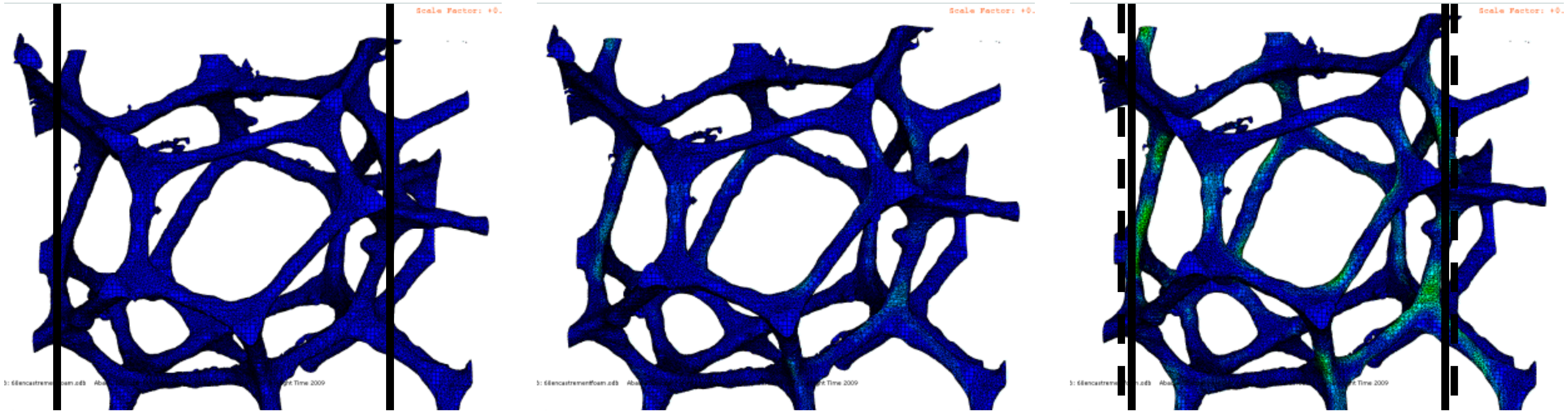
CONVENTIONAL POLYURETHANE FOAM

AUXETIC FOAM

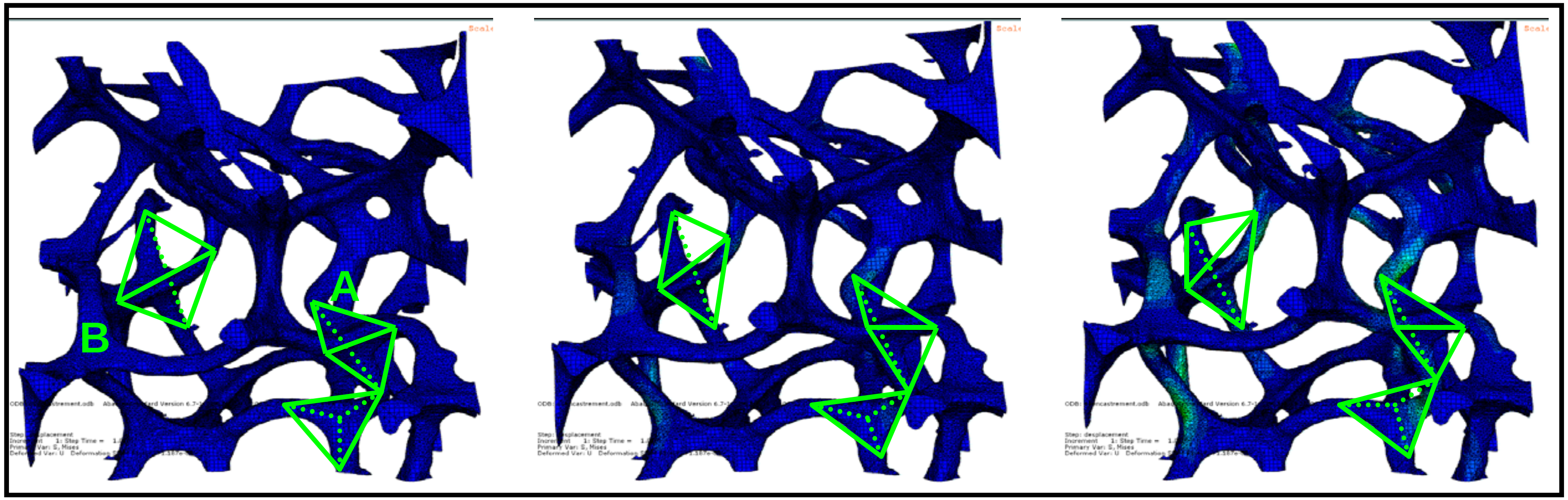




FE Model - Local Region of Interest



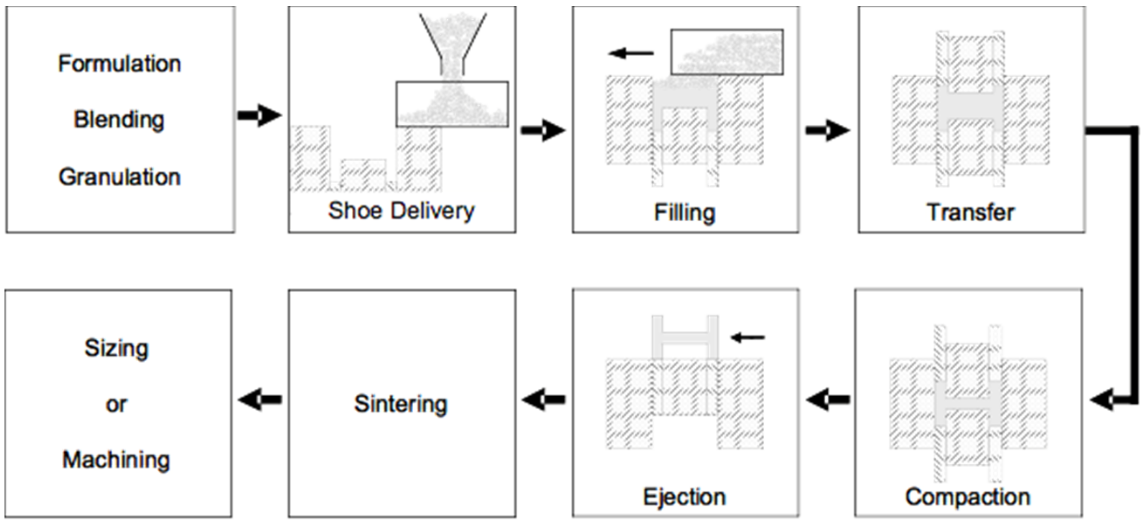
Conventional – contraction of cell in lateral direction (initial state, dashed line)



Auxetic – rotation of joints (opening of structure, A) as buckled ribs straighten

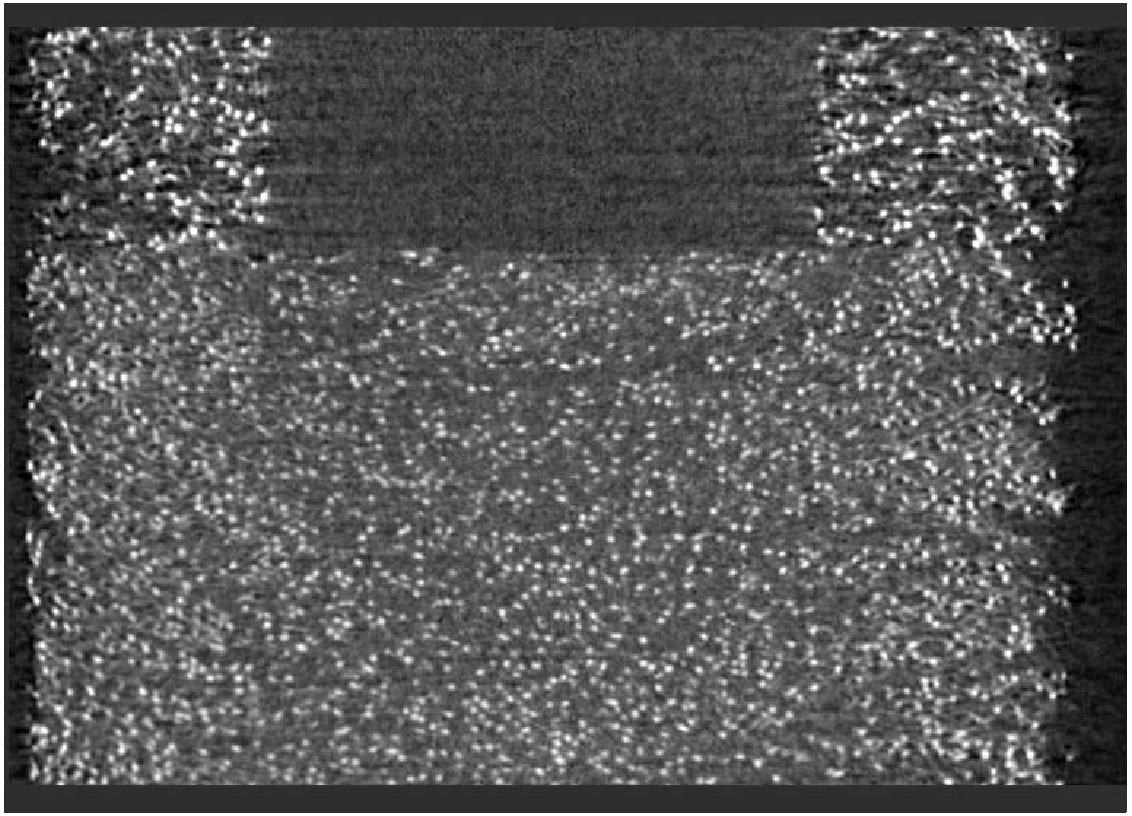
In situ Behaviour of Granular Materials during Powder Transfer and Compaction

- Blocks of material translated past each other after filling to create complex shape
- This can influence the evolution of the density distribution during subsequent stages
- Intense shear deformation of green body can occur during compaction, giving rise to cracks
- X-ray tomography and digital image correlation combined to map displacement during transfer and compaction



Simple Indentation of Loose Powder

0.5 mm steps



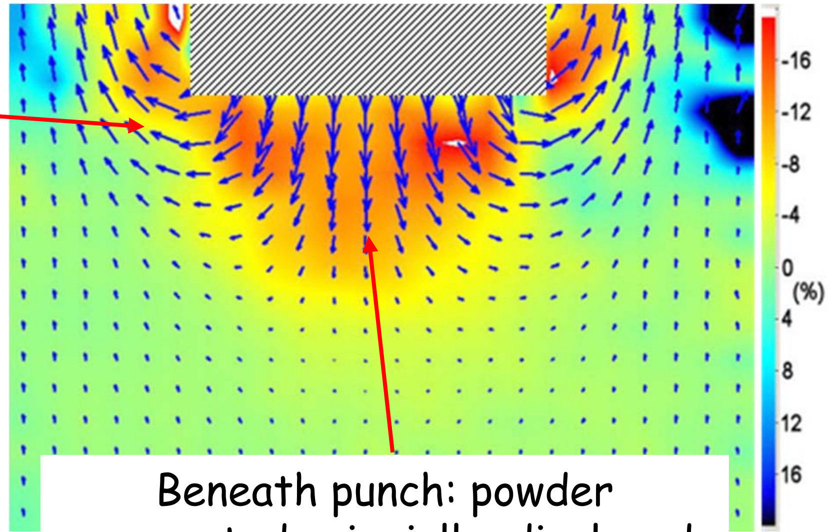
20 mm

Sn particles, 140-200 μm in size and 10 vol. % concentration, randomly dispersed within 45 μm Al matrix powder.

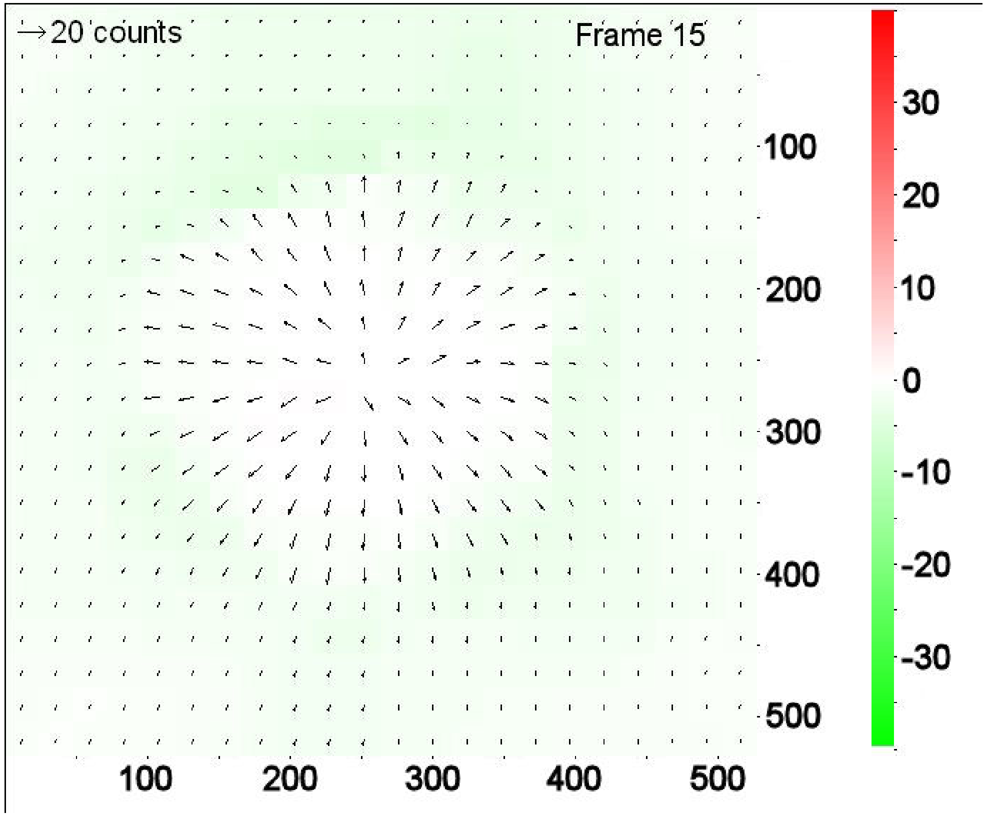
Displacement Maps

Vertical slice from centre of die showing 2D displacements

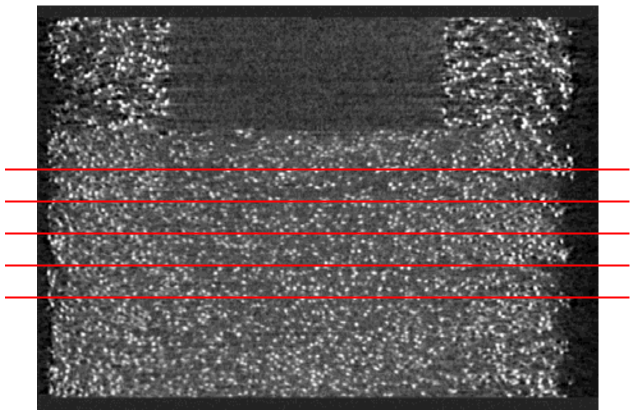
Flow around corners of punch: shear deformation



Beneath punch: powder compacted uniaxially, displaced vertically downwards.

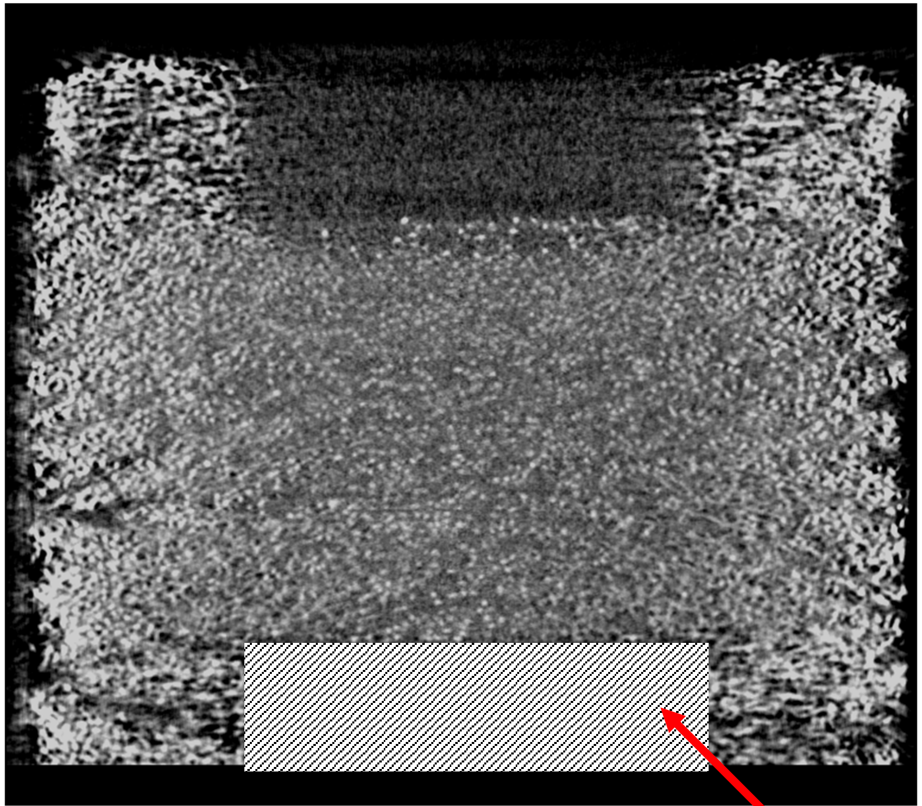


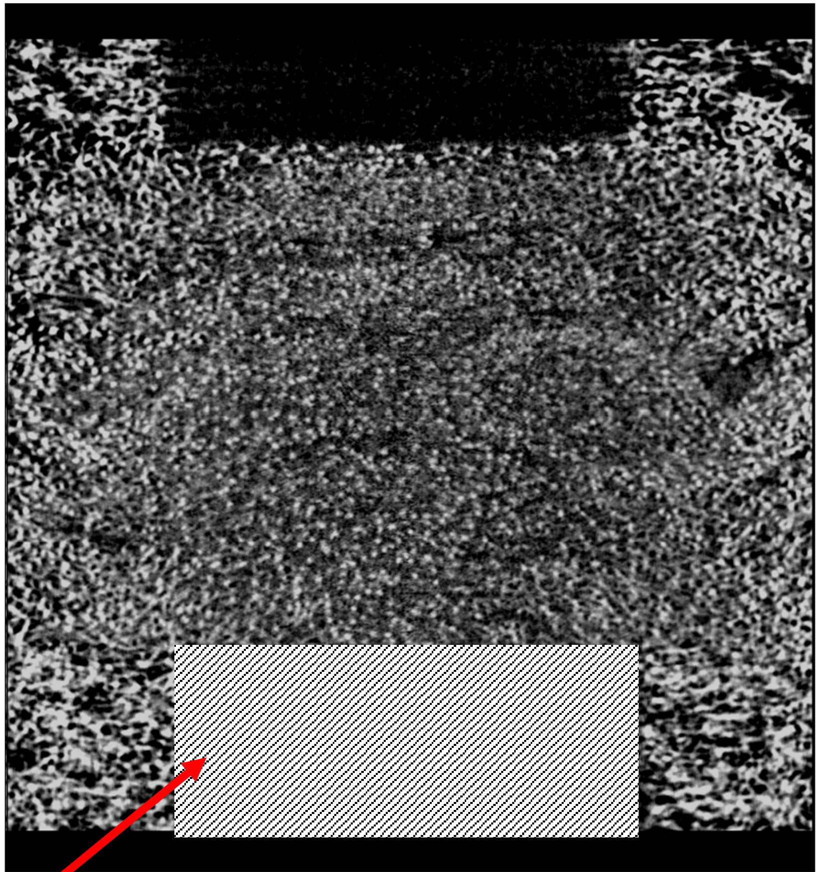
Horizontal slices, calculated using digital volume correlation, taken from postions moving away from punch, as indicated right



Extension to Industrially Relevant Cases

Features exist within the die; open and closed dies





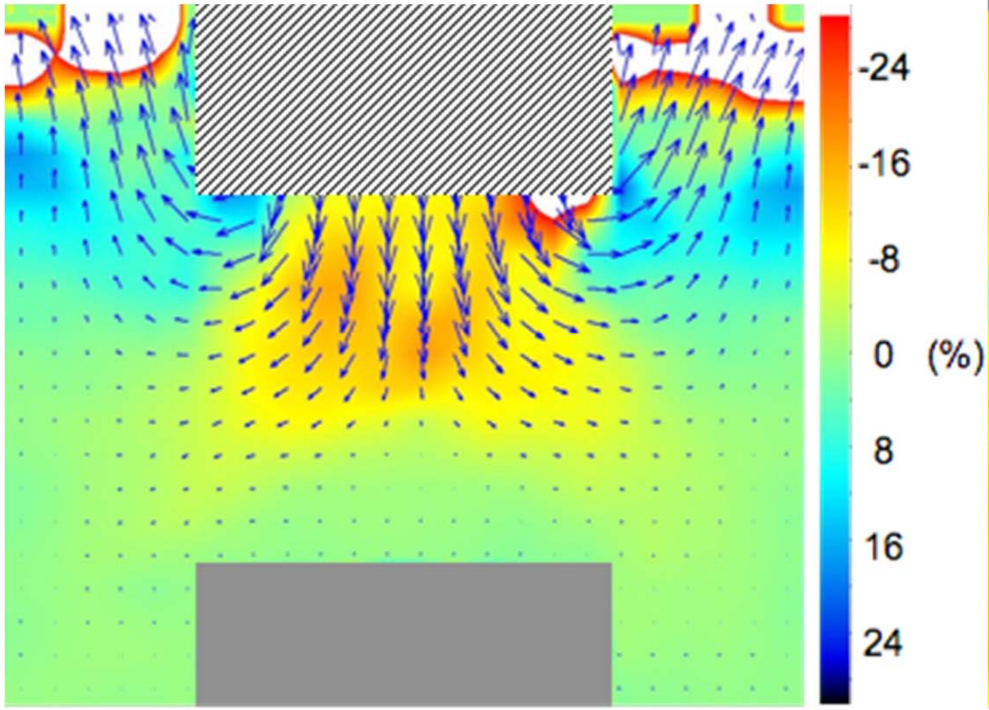
Powder free to move upwards into gap between punch and die wall

stationary insert

Restrictive cap at top of die preventing upwards movement

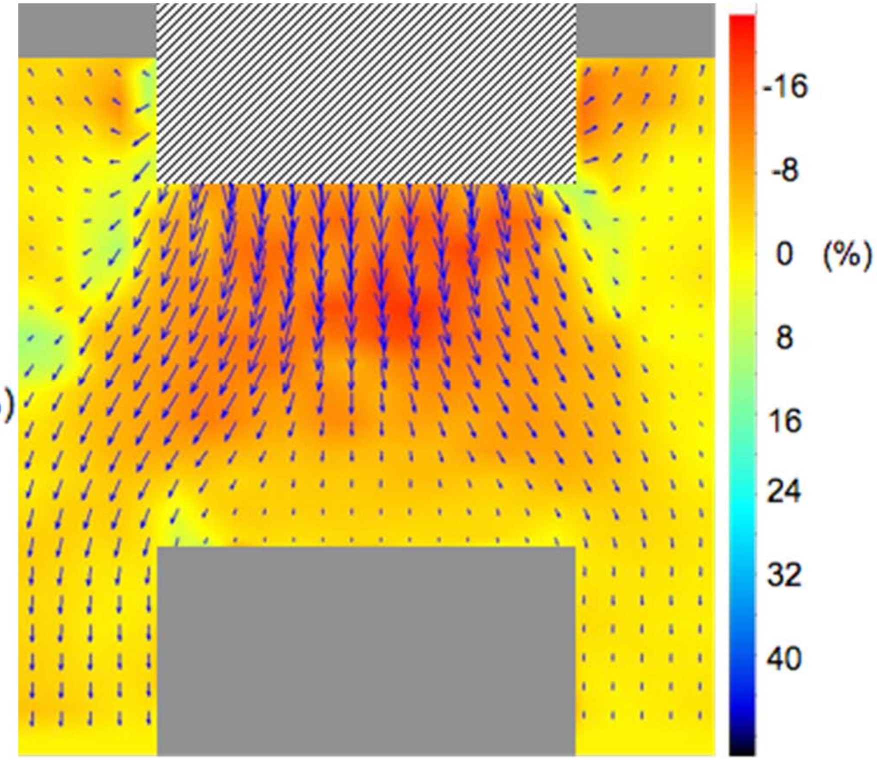
Open and Closed Dies

dilatational strain fields



upwards movement unrestricted

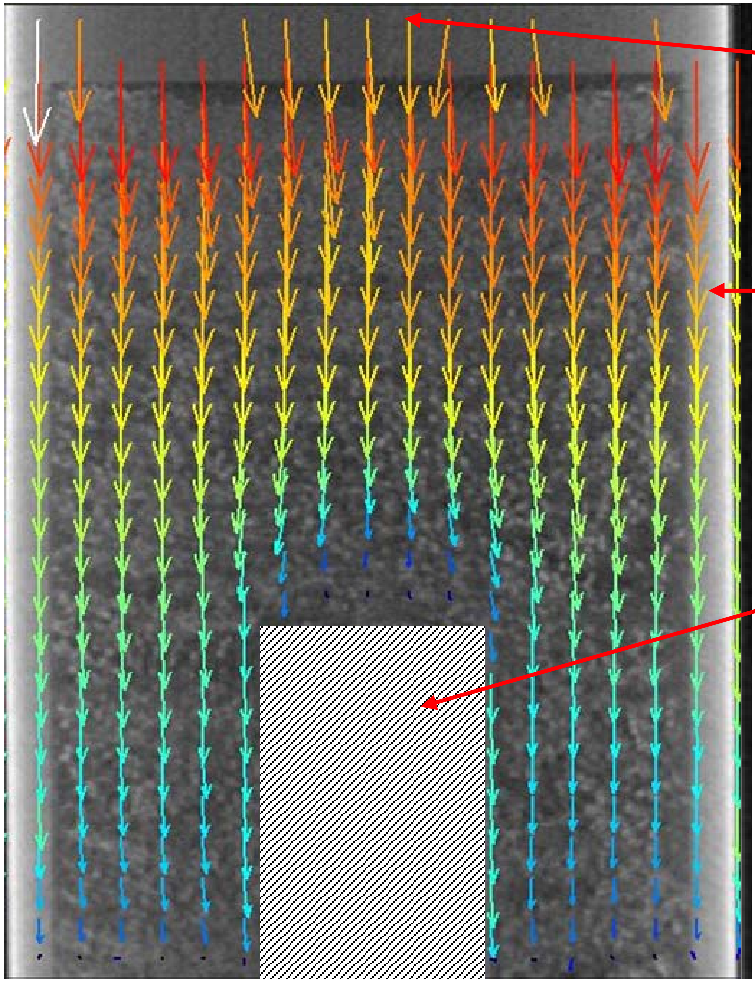
Flow around the downwards moving punch dominates



upwards movement restricted

Downwards flow of powder around the lower insert dominates

Die Compaction



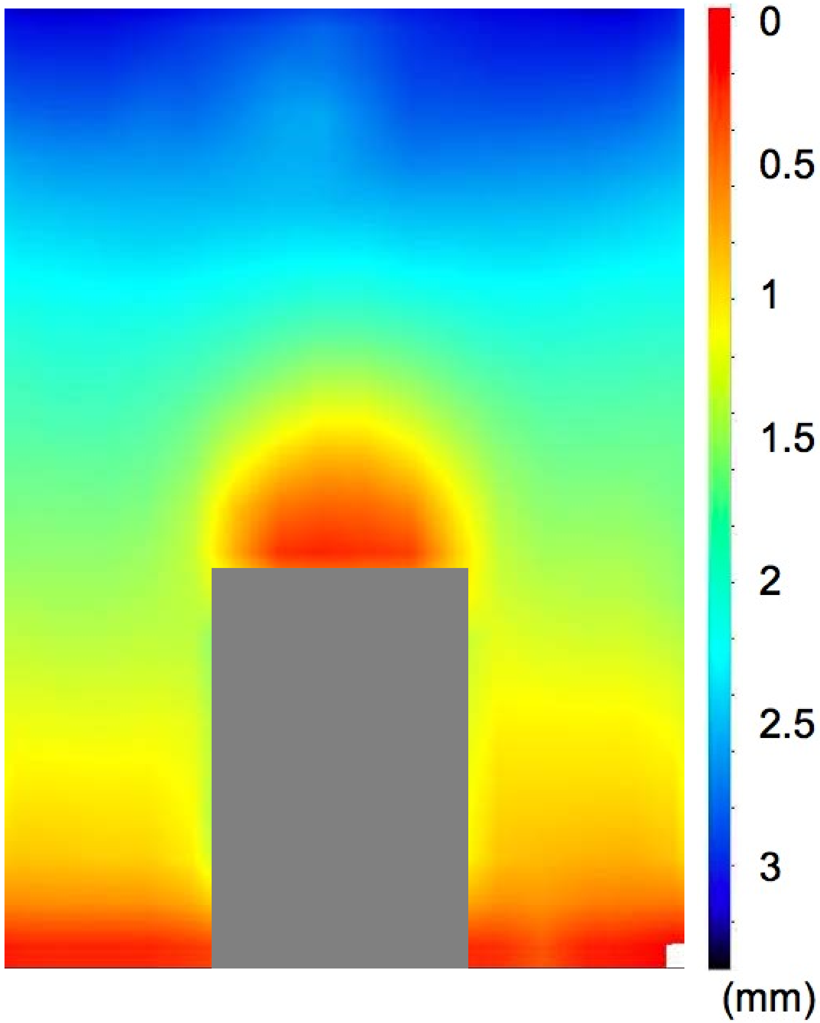
steel punch compacts powder

steel die,
1 mm thick wall,
15 mm diameter

stationary steel pin

Showing vector displacements from sequence of steps during compaction of powder

Die Compaction

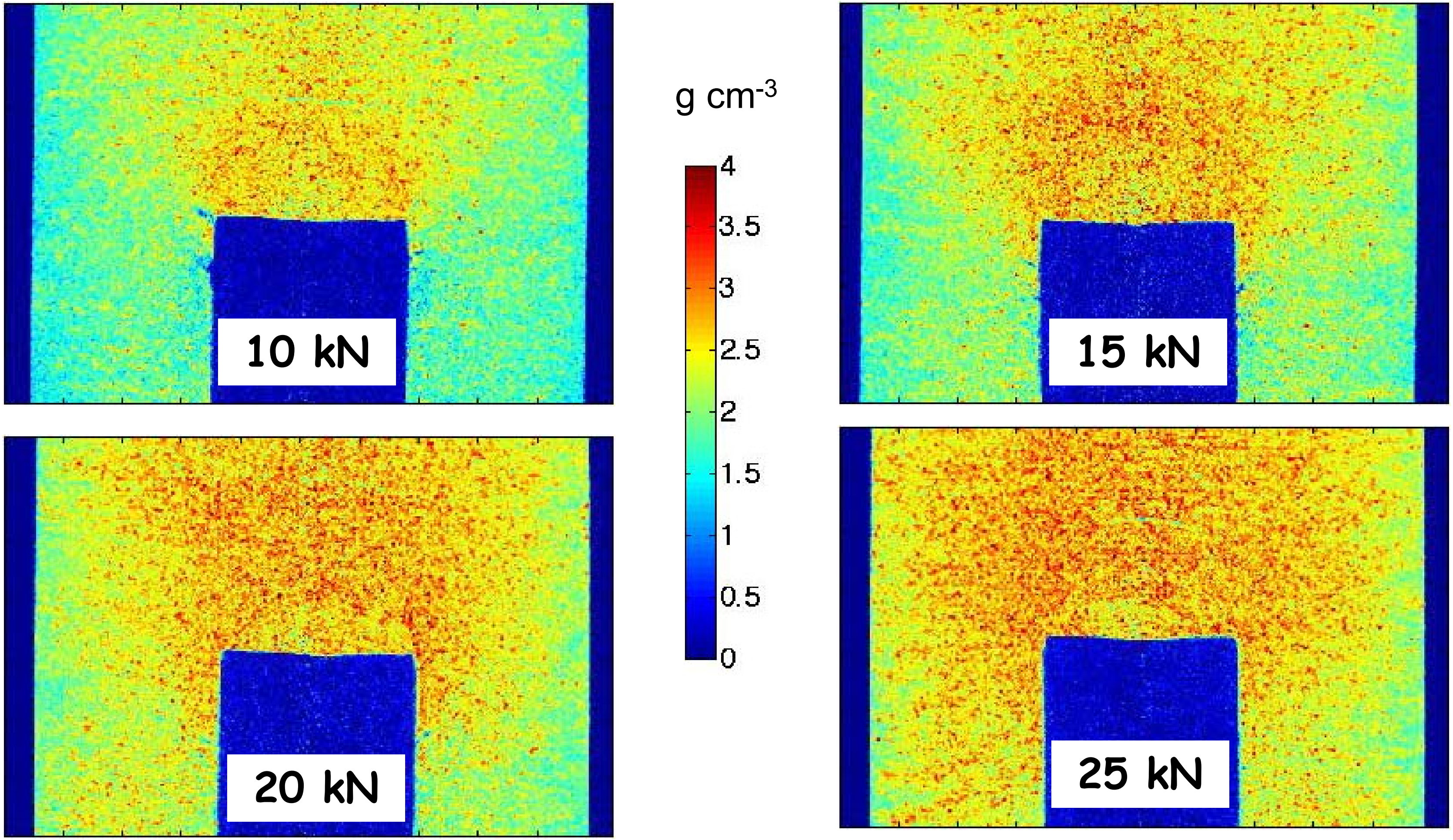


Vertical displacement map

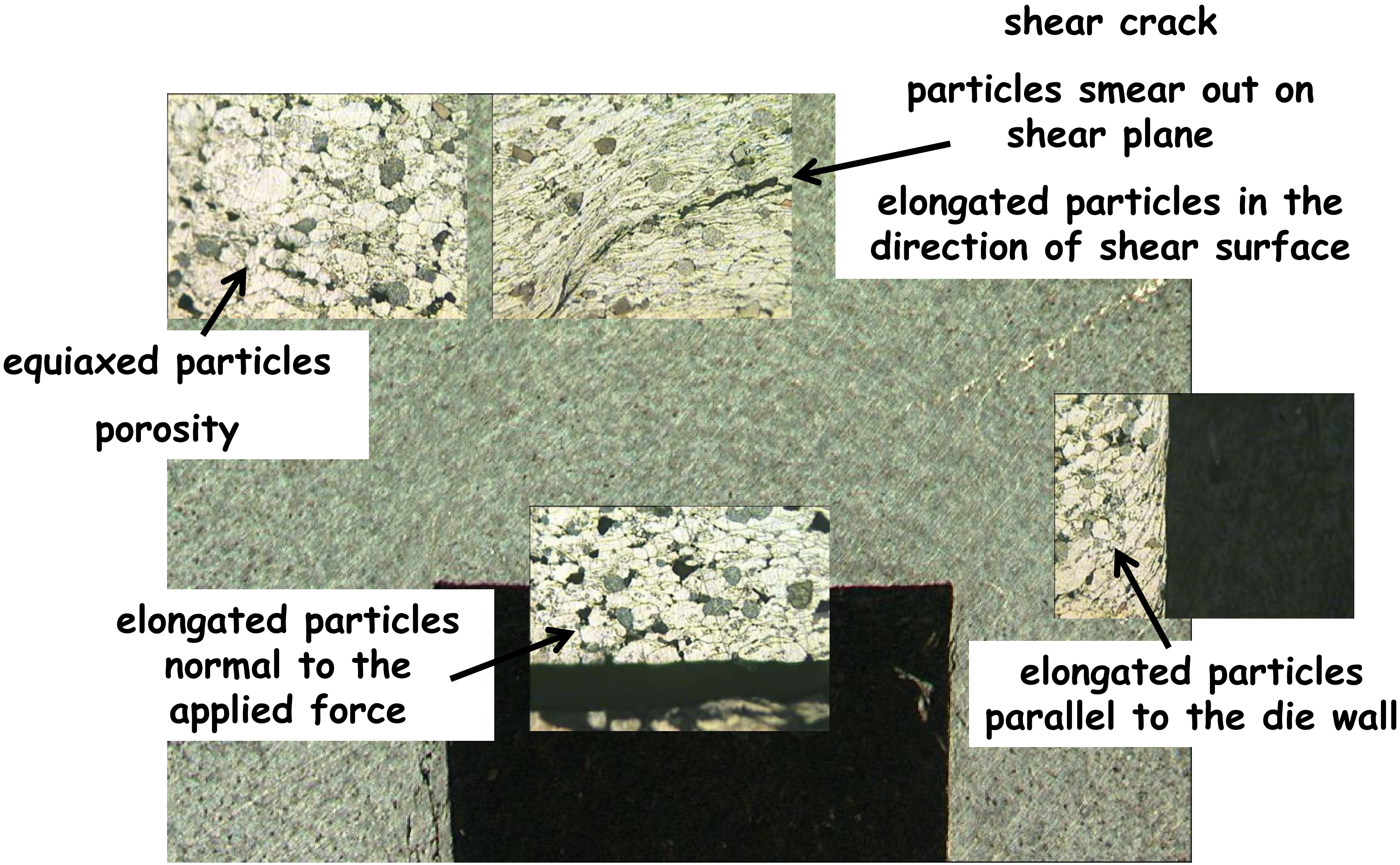
- Powder compacted above pin more than elsewhere; material becomes harder than surroundings
- Eventually material approaches full density; more difficult to deform and becomes extension of pin
- Material forced to shear around rigid domed region

Density Evolution during Compaction

Compact densifies initially above the pin and then expands around the die into the gaps with the die wall



Metallographic Investigation



Summary

- Laboratory X-ray microtomography has been used to study the structural evolution of open-cell foams
- Helped to understand the mechanisms of auxetic behaviour

  Straightening of bent ribs

  Rotation of junctions connecting ribs
- The movement of a granular material within a die and around punches/inserts during compaction has been studied
- Use of analysis tools, such as digital image and volume correlation and microstructurally faithful modelling
- Use of *in situ* rigs has enabled the mechanical loading of the foams to be studied and the compaction of a granular material to be followed

Acknowledgements

- **Work on auxetic foam in collaboration with:**

  Andy Alderson, University of Bolton

  Fabrice Pierron, Arts et Métiers Paris Tech

- **Work on powder compaction in collaboration with:**

  Alan Cocks, University of Oxford