University of Portsmouth

Computation of full-field displacements in a scaffold implant using Digital Volume Correlation and Finite Element Analysis

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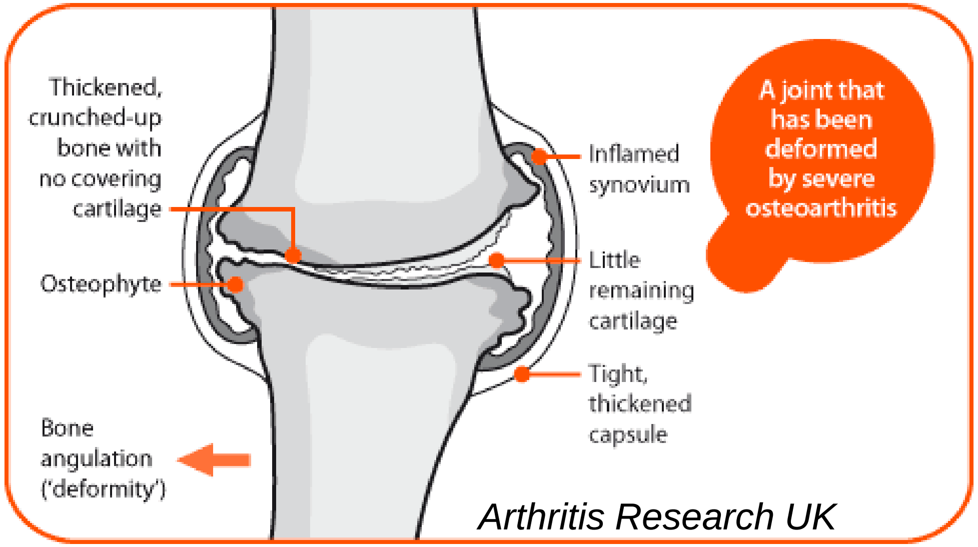
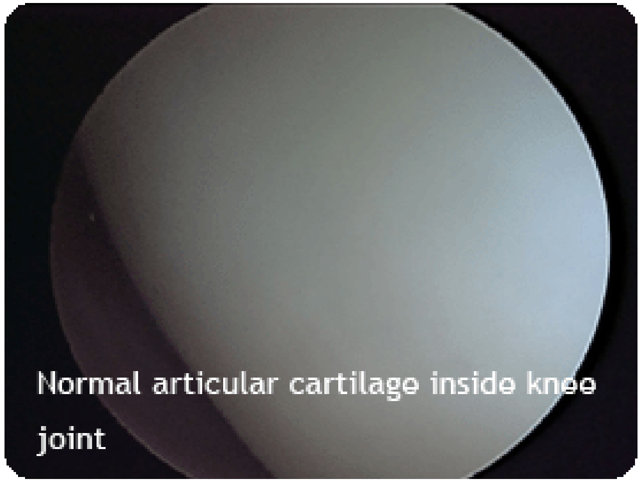
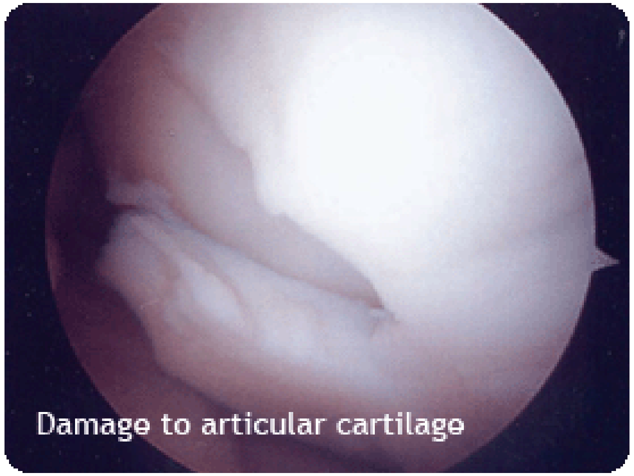
Osteoarthritis





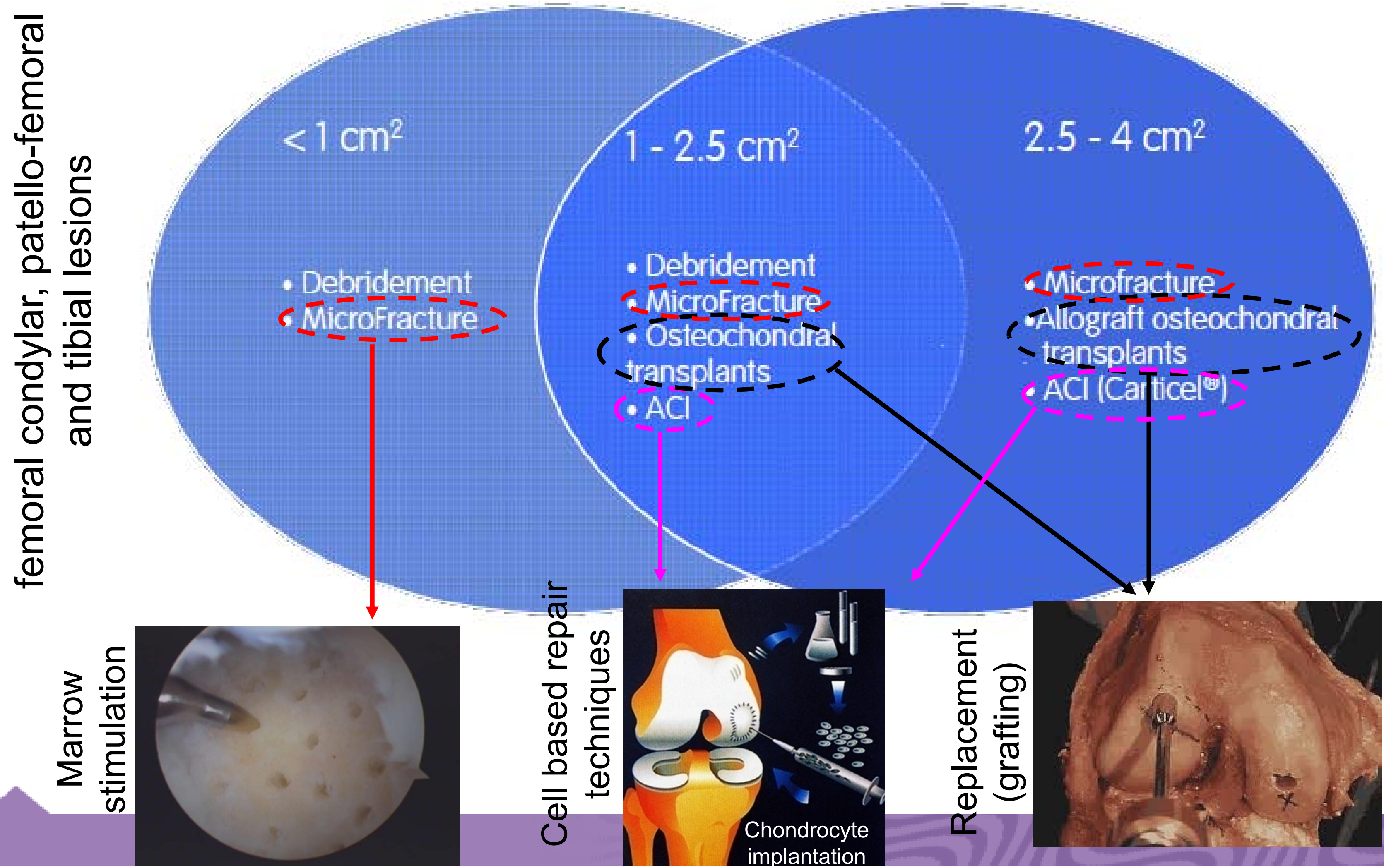
- Issue: cartilage has very limited capacity for self-repair !



Dr. G.Reddaiah Chunduri, Consultant Orthopaedics, Image hospitals, Hyderabad

Cartilage repair techniques

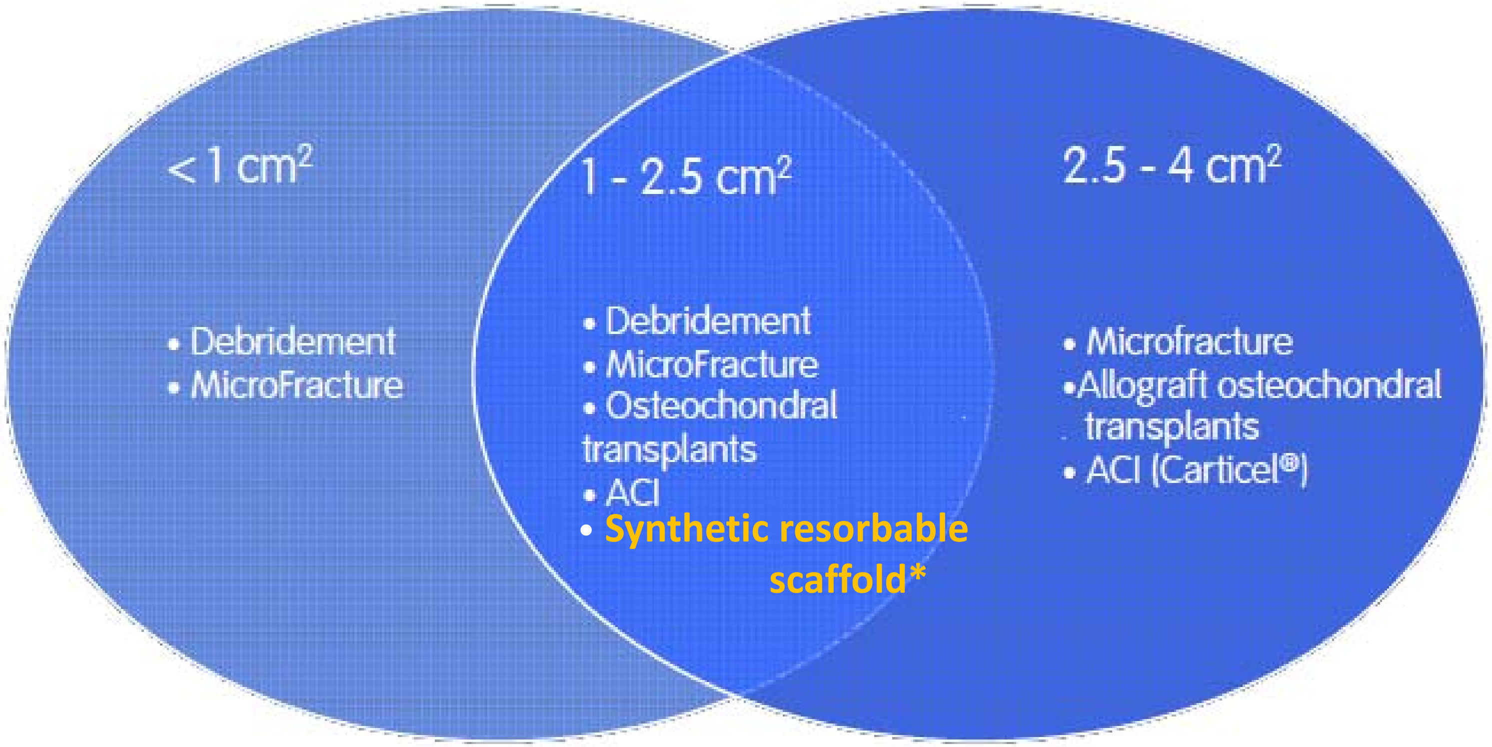
O.S. Schindler, Articular cartilage surgery in the knee, Orthopaedics and Trauma 24:2



Engineering new cartilage using a biodegradable scaffold

O.S. Schindler, Articular cartilage surgery in the knee, Orthopaedics and Trauma 24:2

femoral condylar, patello-femoral and tibial lesions

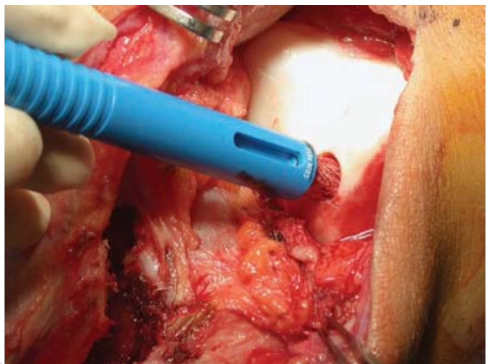


Trufit plug: biphasic scaffold

- Promising implant: Trufit plug scaffold (Smith & Nephew)
  - Designed to capture and retain bone marrow elements and encourage differentiation into articular cartilage and bone

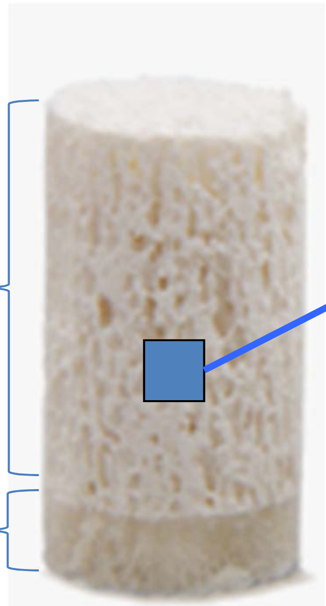
Creating a surgical defect over the lesion

Implanting the plug



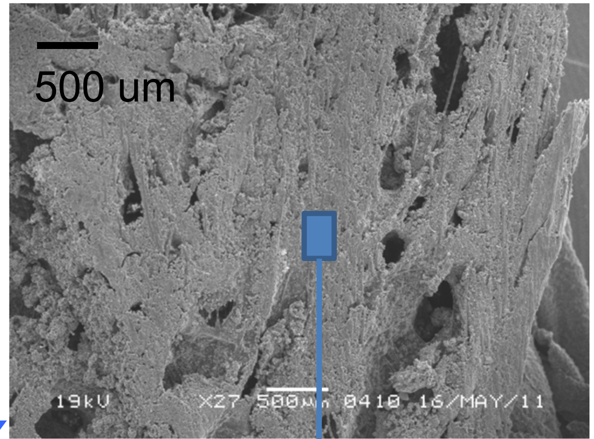
Bone layer

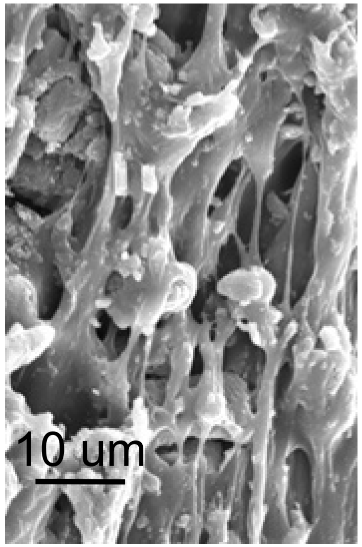
Cartilage layer



5 -11 mm diameter

polylactide-co-glycolide (PLGA) matrix reinforced with polyglycolide (PGA) fibres, surfactant, and with calcium sulphate in the bone phase





Motivation

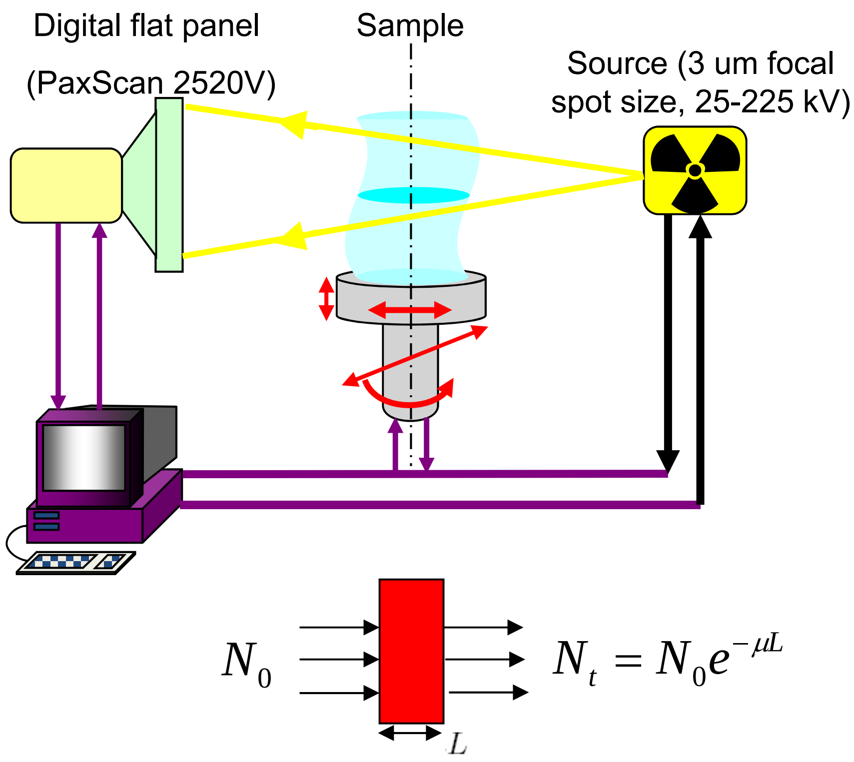
Although used in clinical procedures, little has been done to investigate the biomechanical behaviour of the implant under physiological conditions

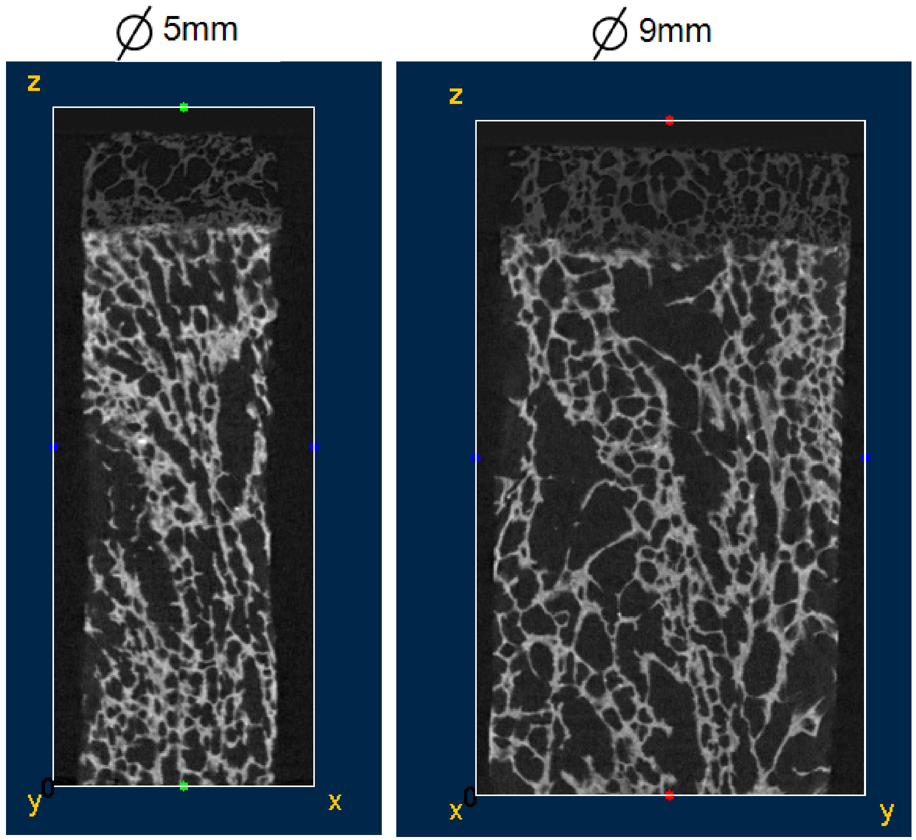
In situ mechanical testing coupled with DVC is a valuable tool for characterizing the mechanical behaviour and for investigating the failure mechanisms

- Demonstrate the feasibility of the technique on the implant
- Assessment of the reliability of the DVC displacements and strain fields
- How DVC measurements compare with finite element predictions ?

3D representation of the morphology

CT scanner: Nikon Metris XT H 225



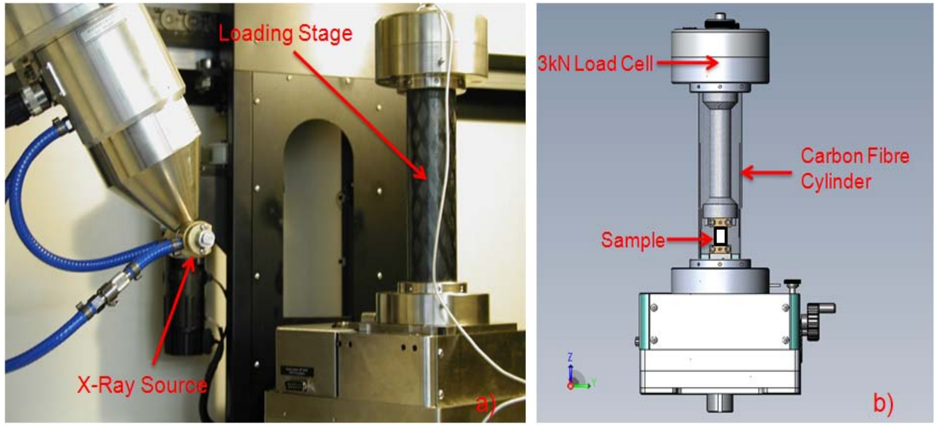


Voxel size: 20 microns
Energy= 51 kV / 160 μA

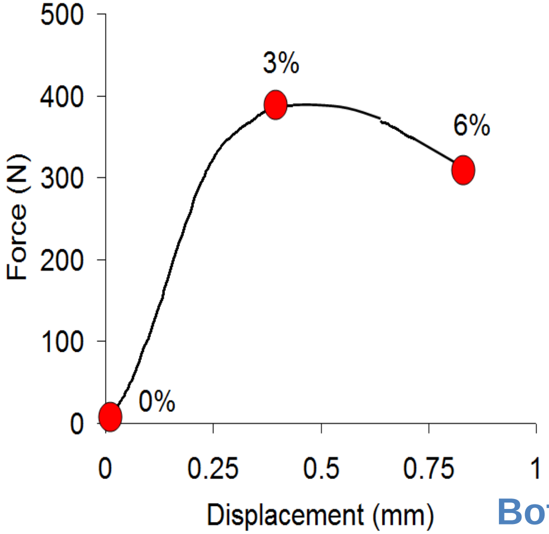
1500 angular projections, ~1 hour scanning time, 10 min reconstruction

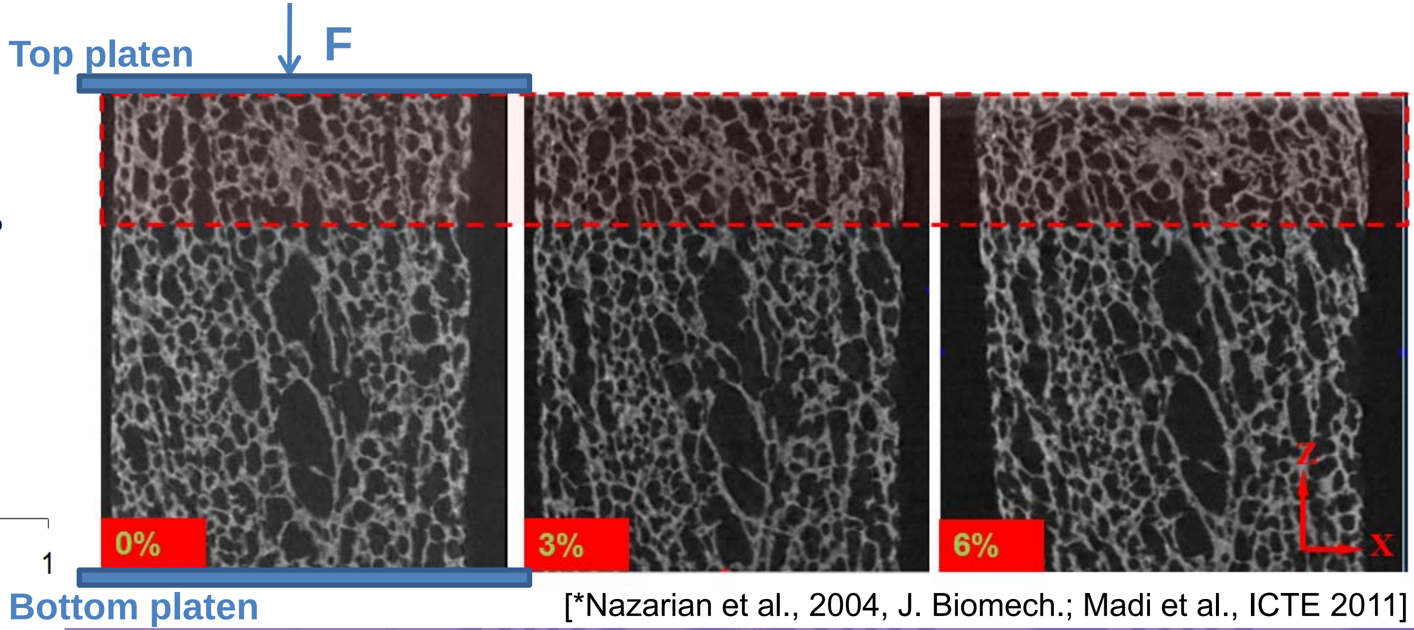
In situ mechanical testing

Deben MICROTEST



- Sample 14.7 mm length, 8.57 mm diameter, fixed on the lower compressive platen
- 15 min-window before CT acquisition (relaxation*)





[*Nazarian et al., 2004, J. Biomech.; Madi et al., ICTE 2011]

Digital Volume Correlation - Micro-FE modelling

- Two approaches of DVC have been mainly used: local approach and global approach.

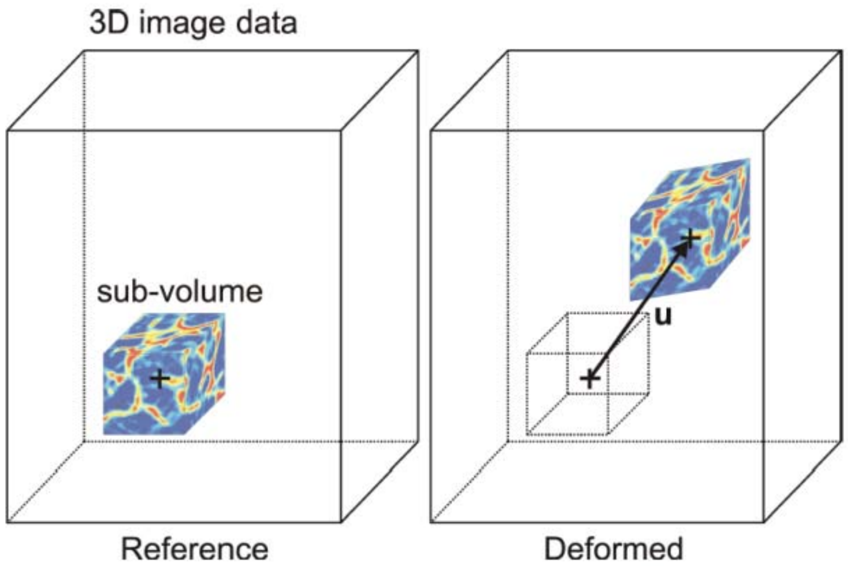
- Systematic comparison of their performances and strain distributions is rarely reported, especially for biological tissues with foam-like morphologies [Liu et al., 2007, J. Biomech.]

- Micro-FE models have proven to be very powerful to understand and predict the mechanical behaviour of cellular materials [Muller et al., 1995, Med. Eng. Phys.; Youssef et al., 2005, Acta Mat.]

- First attempt to compare DVC measurements of cellular materials with FE predictions: [Zauel et al., 2006, J. Biomech. Eng]. Good agreement along the loading direction but less accuracy along the lateral directions.

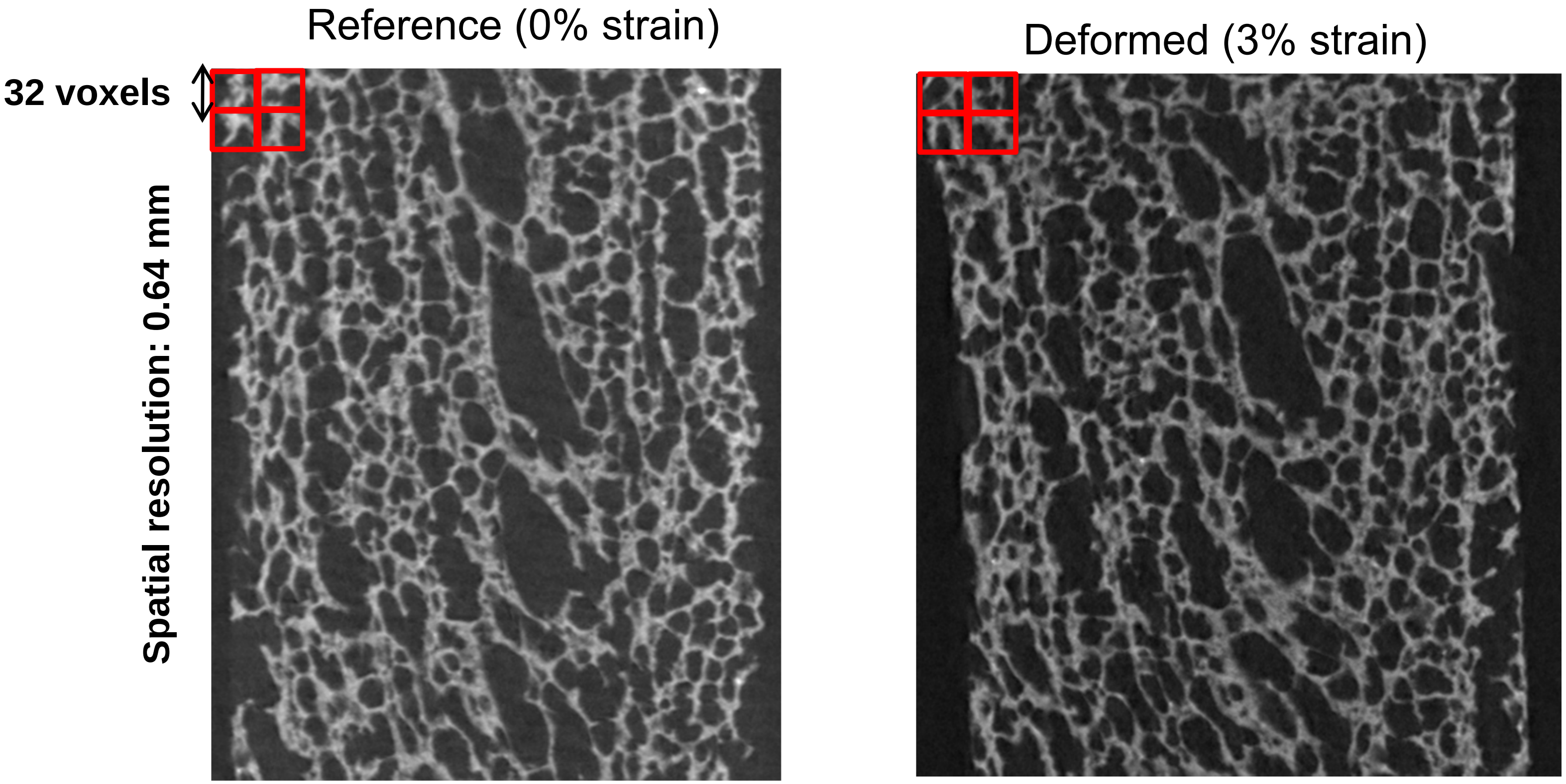
Local approach to DVC

- Gray level (2D or) 3D images $f(\underline{x}),\ g(\underline{x})$
- Principle of optical flow conservation: $f(\underline{x}) \cong g(\underline{x}+\underline{u}(\underline{x}))$
- Find the best match between grey level intensity of the reference and deformed image, in small zones of interest (cross-correlation, sum of squared differences)



*[Peters et al., 1982, Opts Eng.; Bay et al., 1999, Exp Mechanics; Bornert et al., Inst. Mes. Métrol, 2004; Verlhup et al., 2004, J. Biomech.; Quinta Da Fonseca, 2005, J. Microscopy.; Benoit et al., J. Biomech., 2009]

Local approach to DVC (LA-DVC)



- FFT algorithm (cross-correlation) implemented in DaVis* (LaVision, StrainMaster)
- Multi-pass approach
- Final sub-volumes: 32 x 32 x 32 voxels^3 overlapped by 75%

*[Quinta Da Fonseca, 2005, J. Microscopy; McDonald et al., 2011, Phys. Status Solidi B]

Global approach to DVC

- Principle of optical flow conservation: $f(\underline{x}) \cong g(\underline{x}+\underline{u}(\underline{x}))$

- Select a specific displacement basis $\underline{\varphi}_i(\underline{x})$

  such that $\underline{u}(\underline{x}) = \sum_i a_i \underline{\varphi}_i(\underline{x})$

- Minimize correlation residuals*

$$\Phi^2\{a_i\} = \iiint \left[f(\underline{x}) - g(\underline{x} + a_i \underline{\varphi}_i(\underline{x})) \right]^2 d\underline{x}$$

Linearization

*[Roux *et al.*, 2008, *Comp. Part A*]

Finite element DVC (GA-DVC)

$$\Phi^2_{\text{lin}}(\delta \underline{u}) = \int_{\Omega} \left[f(\underline{x}) - \hat{g}(\underline{x}) - (\delta \underline{u} \cdot \underline{\nabla} f)(\underline{x}) \right]^2 d\underline{x}$$

$$= \sum_e \int_{\Omega_e} \left[f(\underline{x}) - \hat{g}(\underline{x}) - \delta a_i^e \left(\underline{\varphi}_i \cdot \underline{\nabla} f \right)(\underline{x}) \right]^2 d\underline{x}$$

Elementary matrix and vector (e.g., C8P1*), Correli

$$M_{ij} \delta a_j = b_i$$

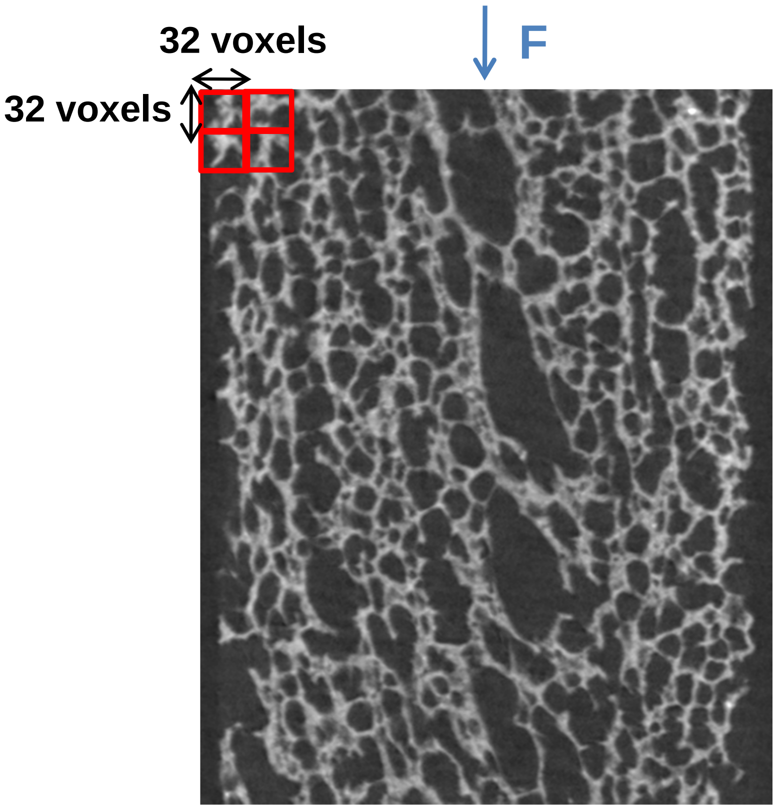
$$M_{ij}^e = \int_{\Omega_e} \left(\underline{\nabla} f \cdot \underline{\varphi}_i \right)(\underline{x}) \left(\underline{\nabla} f \cdot \underline{\varphi}_j \right)(\underline{x}) d\underline{x}$$

$$b_i^e = \int_{\Omega_e} \left[f(\underline{x}) - g(\underline{x}) \right] \left(\underline{\nabla} f \cdot \underline{\varphi}_i \right)(\underline{x}) d\underline{x}$$

- Multi-scale approach to deal with secondary minima and to be consistent with Taylor approximation*

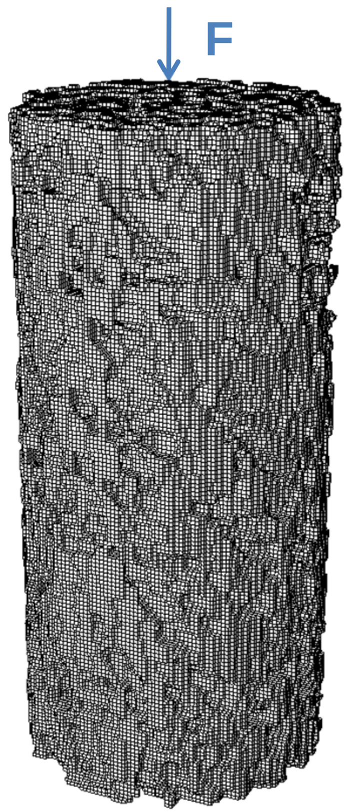
*[Roux *et al.*, 2008, *Comp. Part A*]

DVC vs FE comparison



DVC method: continuum level

?

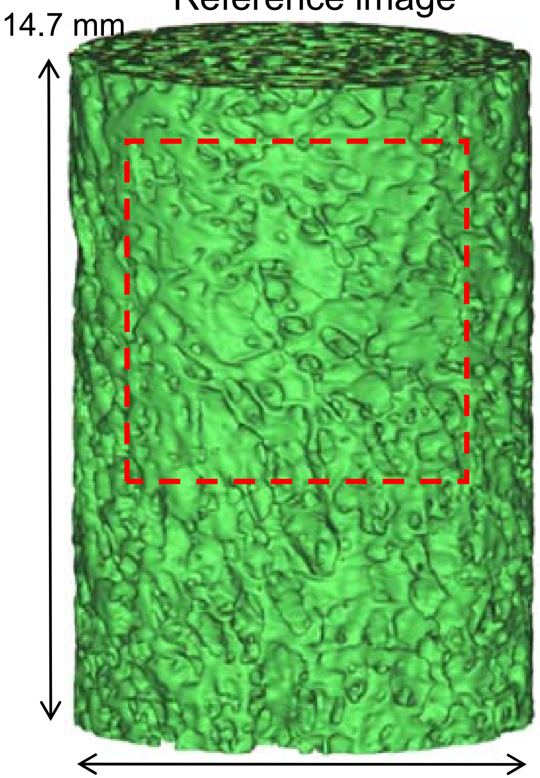


FE method: strut level

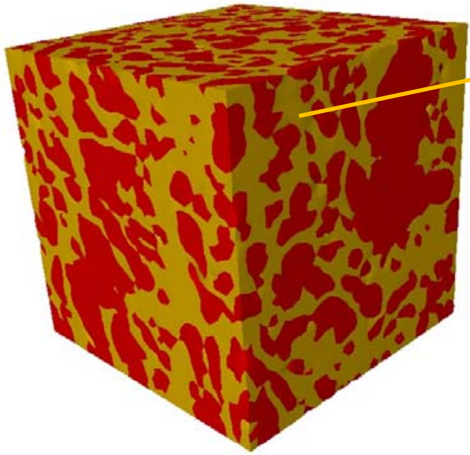
- Size of the sub-volumes: 0.64 mm > size of the pore walls (struts~0.1mm)

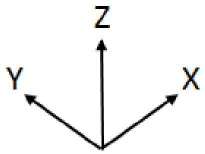
Micro-FE model

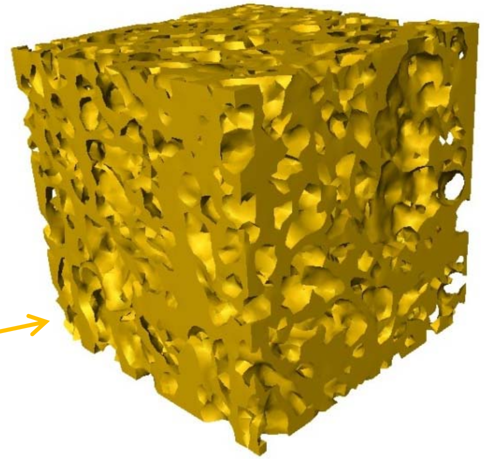
Reference image



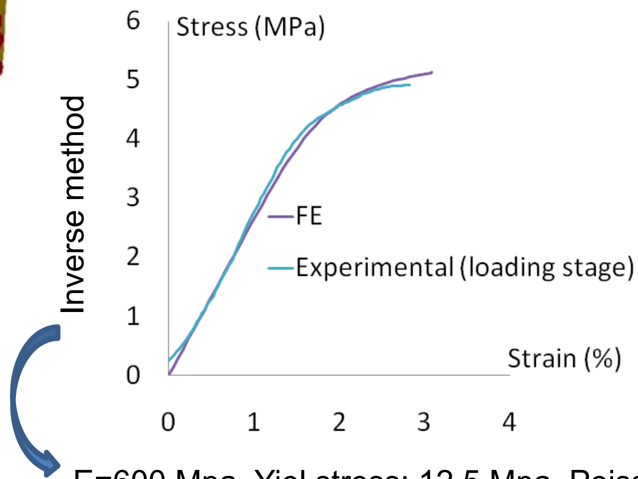
Cube of size 5.12 mm
(256 x 256 x 256 voxels^3)

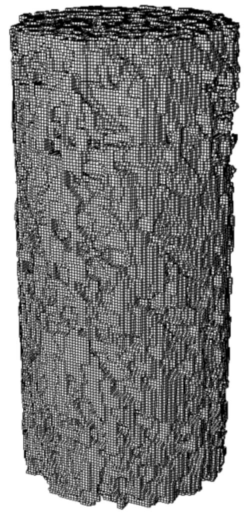






Solid phase

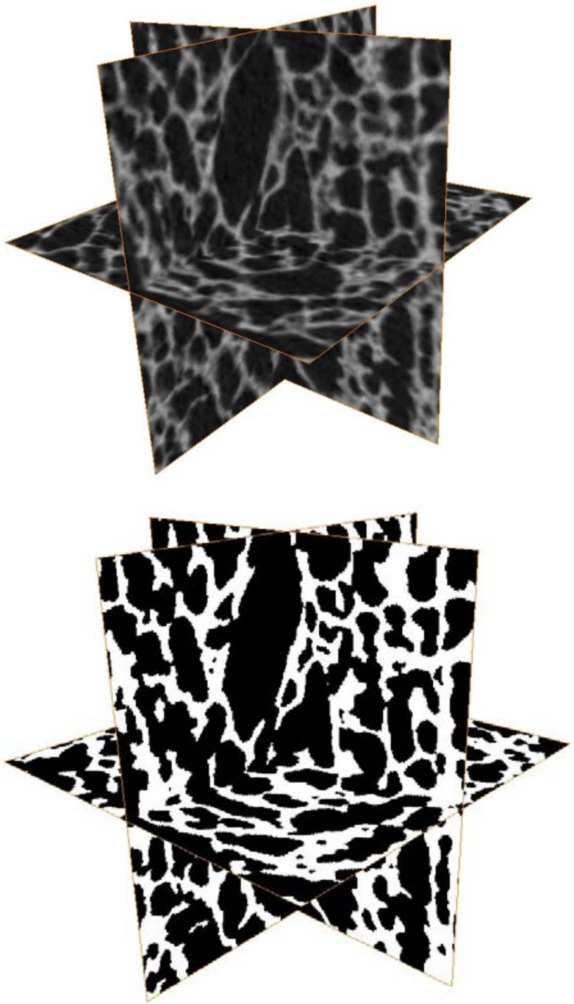




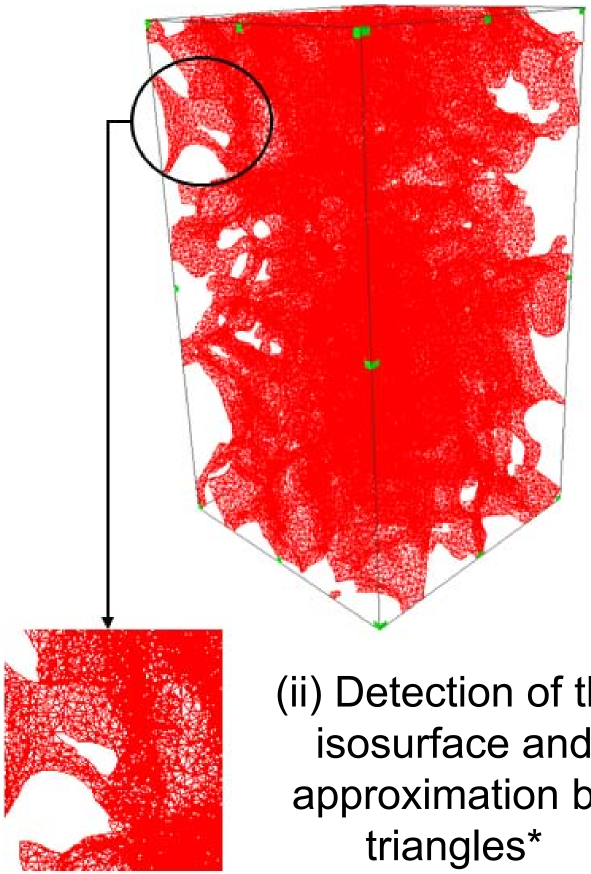
E=600 Mpa, Yiel stress: 12.5 Mpa, Poisson coefficient: 0.3

- Solid phase: elastic perfectly plastic
- Porous phase: linear elastic (contrast: 10000)

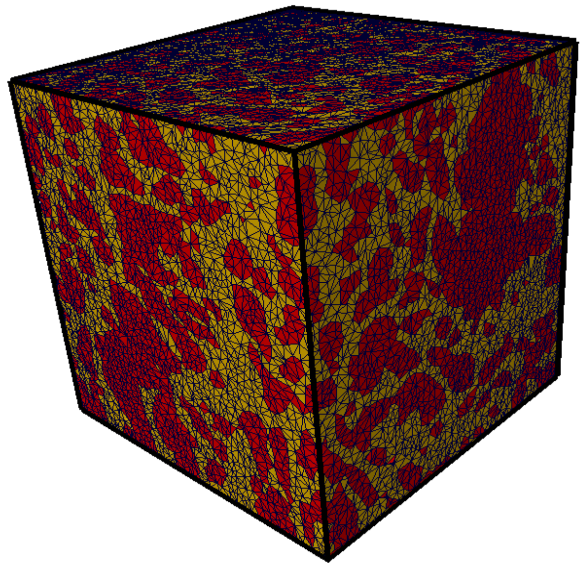
3D meshing



(i) Binarisation



(ii) Detection of the isosurface and approximation by triangles*

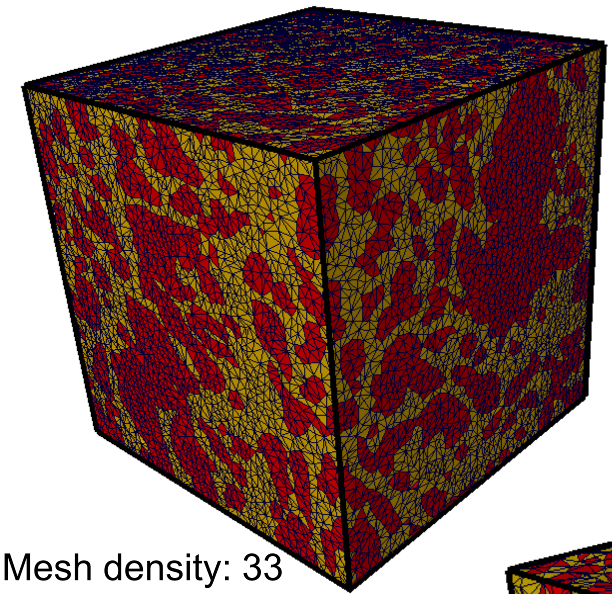


(iii) Volumetric grid* (tetrahedra)

Mesh density: 33 voxels/element

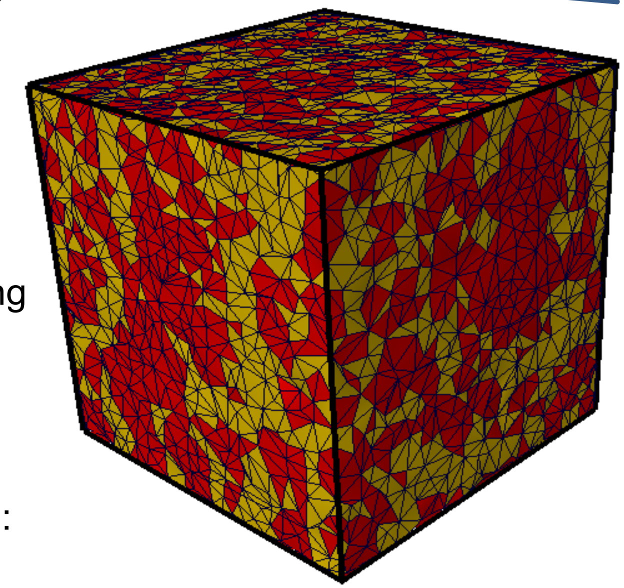
*[Avizo, http://www.vsg3d.com/avizo/standard]

Boundary conditions

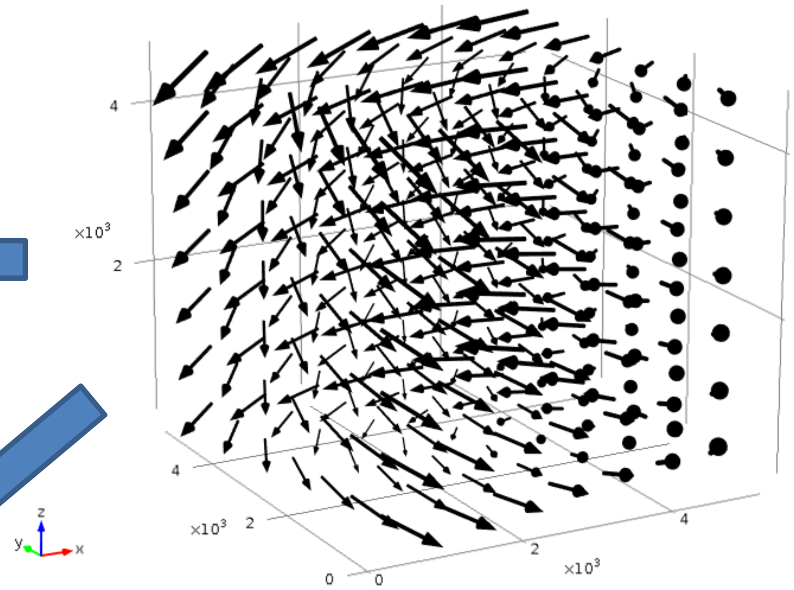


Mesh density: 33 voxels/element

Edge collapsing algorithm*



Mesh density: 795 voxels/element (LA-DVC: 512 voxels/sub-volume)

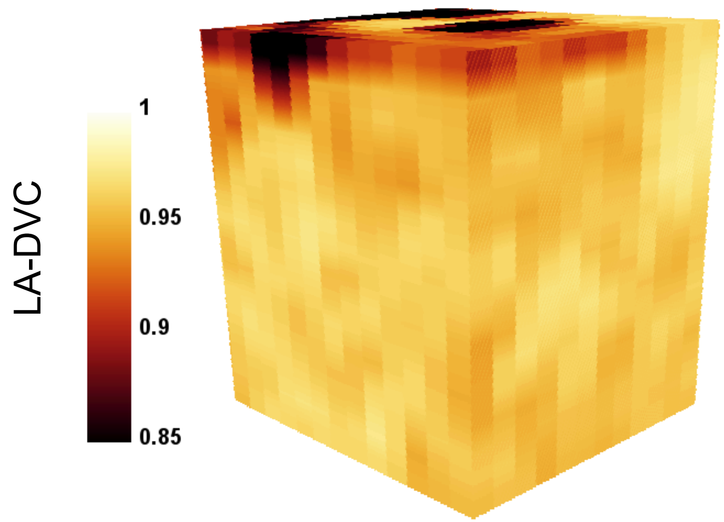


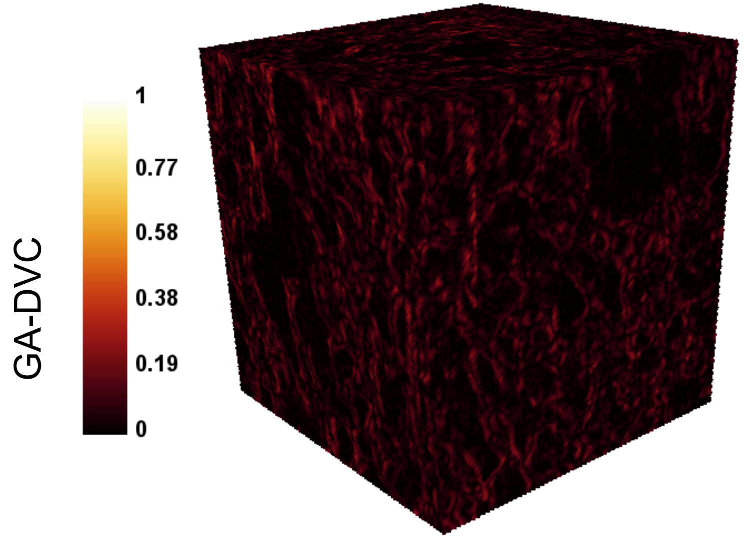
Displacement vectors obtained by DVC applied as boundary conditions at the mesh faces

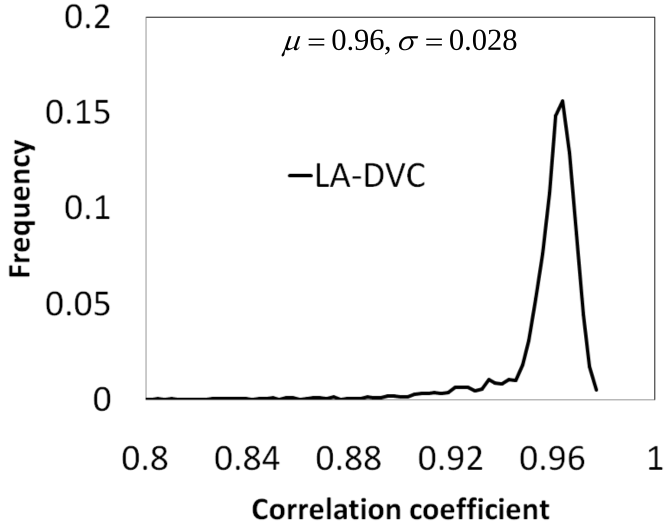
*[Avizo, http://www.vsg3d.com/avizo/standard]

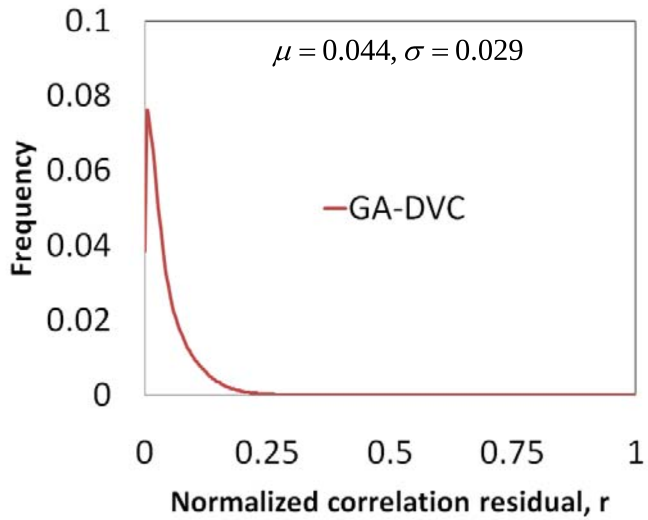
Correlation quality

$$r = \frac{<|\, g(x) - f(x + u(x)) \,|>}{\max(f) - \min(f)}$$

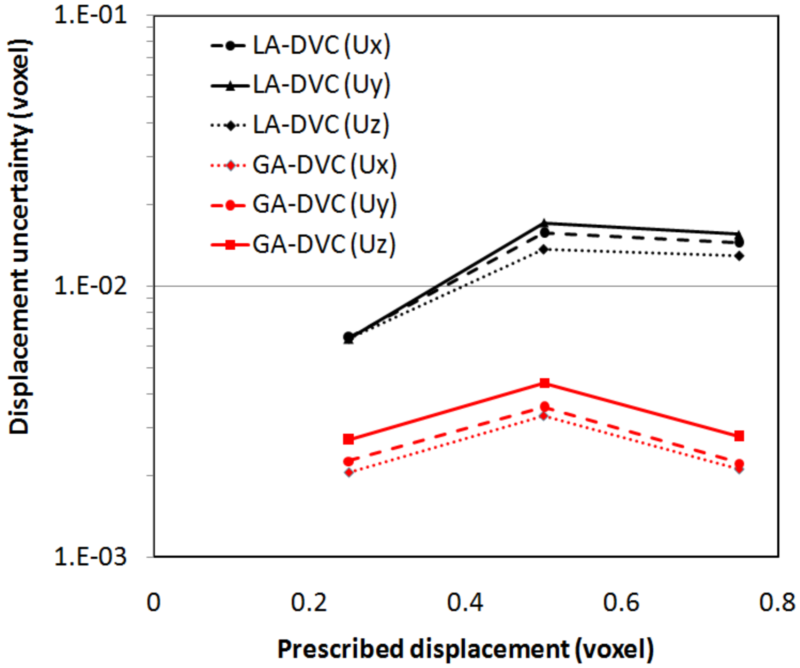








DVC Accuracy (subset size: 32 voxels)

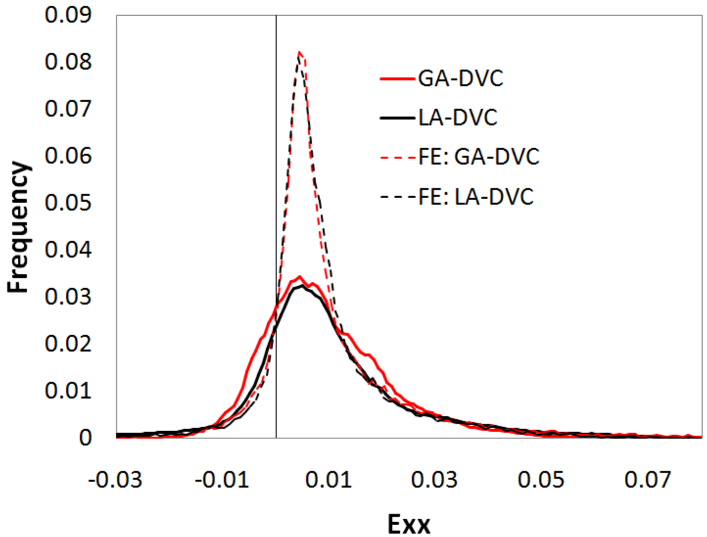


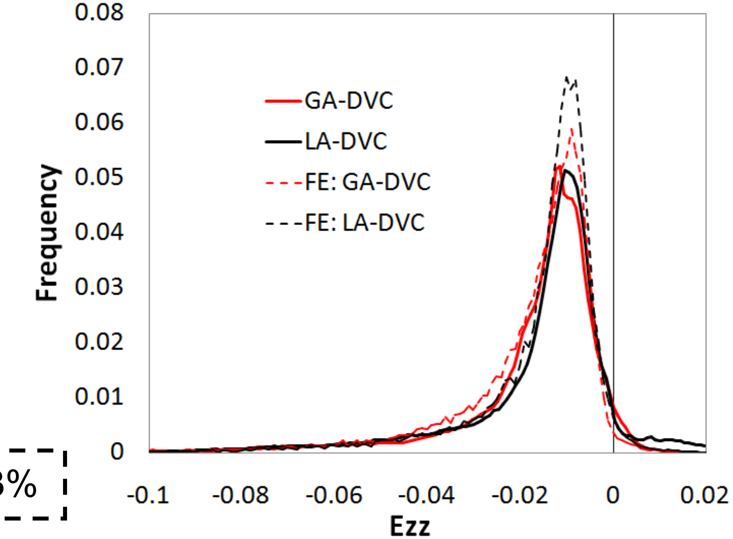
Prescribed displacement (voxel)	DVC method	Spatial average displacement (voxel)		
		$<u_x>$	$<u_y>$	$<u_z>$
0.25	GA-DVC	0.249955	0.249997	0.249941
	LA-DVC	0.244904	0.245639	0.244712
0.5	GA-DVC	0.500000	0.500094	0.500024
	LA-DVC	0.490688	0.494992	0.490341
0.75	GA-DVC	0.750023	0.750081	0.750073
	LA-DVC	0.741899	0.738276	0.737006

GA-DVC: Global approach to DVC; LA-DVC: Local approach to DVC

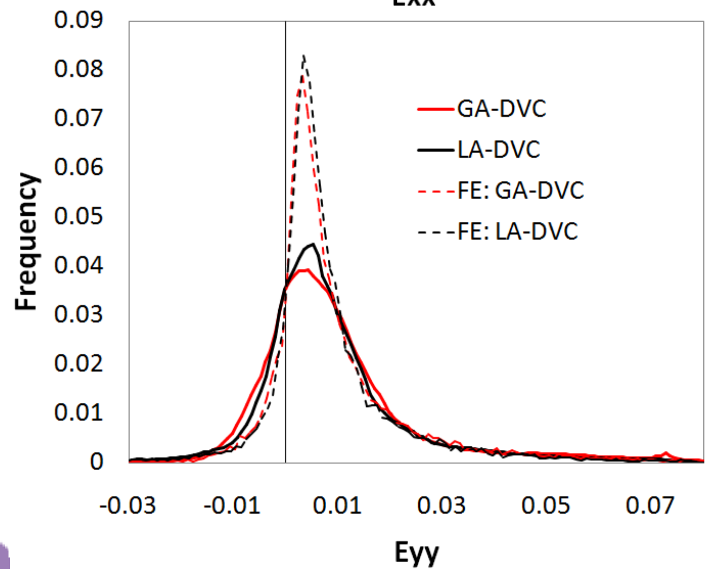
- Displacement uncertainty:
  - Local approach: 0.006-0.02 voxel
  - Global approach: 0.002-0.004 voxel

Strain distributions (subset size: 32 voxels)



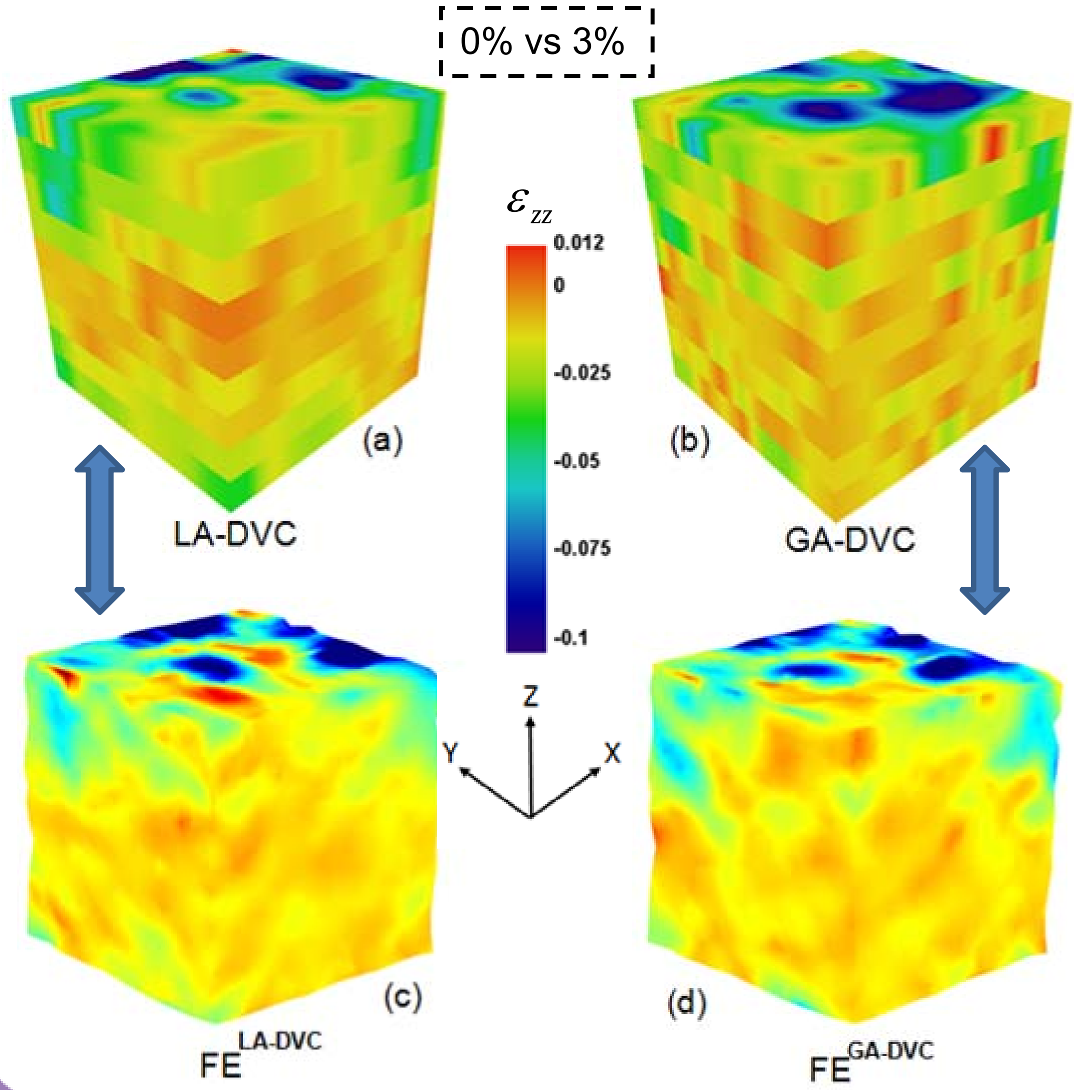


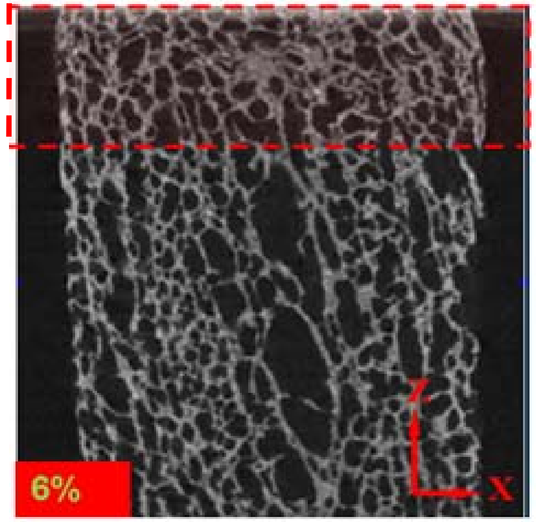
0% vs 3%



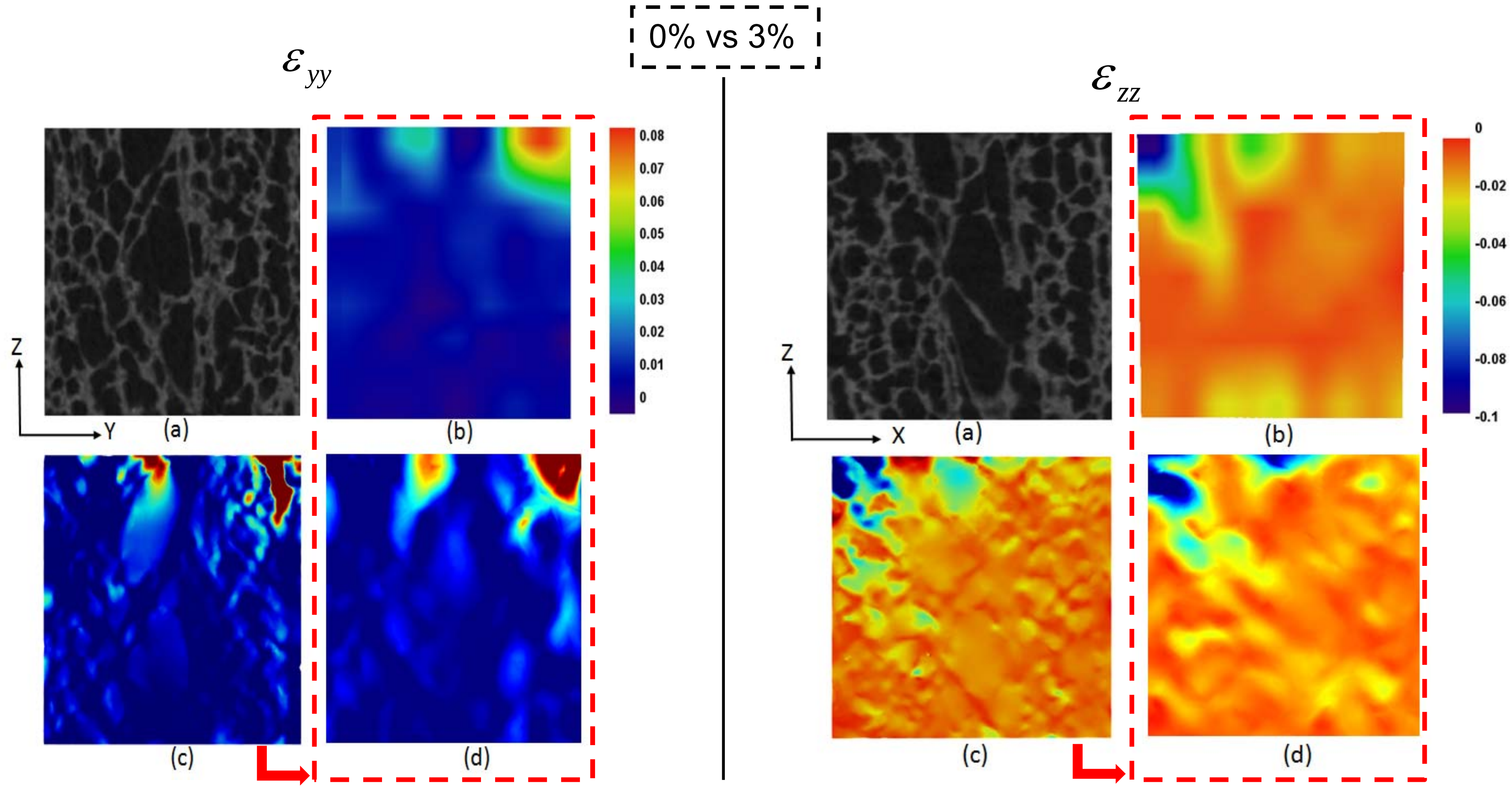
Method	<Exx> Std(Exx)	<Eyy> Std(Eyy)	<Ezz> Std(Ezz)
LA-DVC	**0.0094** **0.0130**	**0.0097** **0.0168**	**-0.0176** **0.0282**
GA-DVC	**0.0095** **0.0124**	**0.0105** **0.0171**	**-0.0172** **0.0165**
FE_{LA-DVC} model	**0.0092** **0.0144**	**0.0097** **0.0170**	**-0.0172** **0.0184**
FE_{GA-DVC} model	**0.0094** **0.0177**	**0.0105** **0.0176**	**-0.0173** **0.0192**

Vertical strain map





Lateral and vertical strain maps



(a): 2D section extracted at the core of the VOI
(b) DVC: 512 voxels/subvolume
(c) FE: 33 voxels/element
(d) FE: 795 voxels/element

Discussion (1)

- Strains maps and histograms obtained with the local approach are in good agreement with those obtained with the global approach

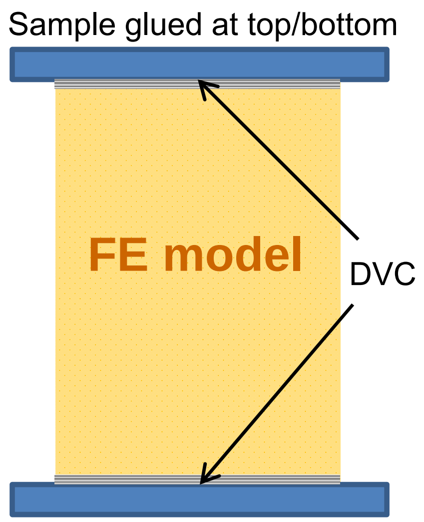
- Local approach:
  - FFT combined with the multi-pass approach allowed fast calculations with displacement uncertainties ranging from 0.006 to 0.02 voxel
  - Literature*: 0.005 – 0.056 voxel

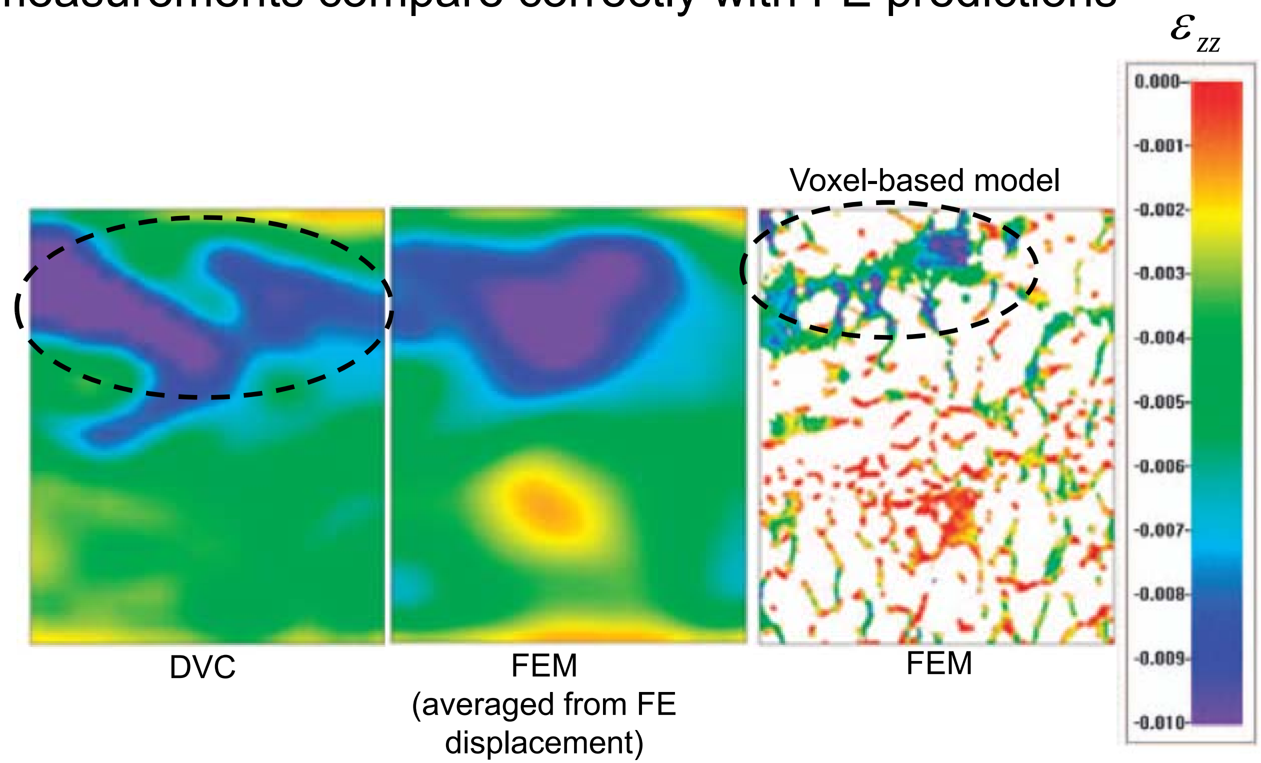
- Global approach:
  - Displacement uncertainty can be reduced by a factor ranging from 3 to 10.
  - Might be suitable for applications where small strain levels are required ?

[* Bay et al., 1999, Exp Mechanics ; Liu et al., 2007, J. Biomech.]

Discussion (2)

- DVC measurements compare correctly with FE predictions





<u>Previous work*:</u>

- vertical strain: good agreement
- lateral strains: smaller predicted strains than measured

*[Zauel et al., 2006, J. Biomech. Eng.]

Conclusions

- In situ uniaxial compression combined with DVC performed on a scaffold implant developed for knee repair purposes
- Displacements and strains assessed using two different approaches to DVC
- Strain measurements compare well with FE predictions
- Feasibility of the DVC technique demonstrated

Perspectives

- Comparison of mechanical behaviour and failure mechanisms of the implant with that of native tissues: trabecular bone, cartilage