20.GEM GEM4 Summer School: Cell and Molecular Biomechanics in Medicine: Cancer
Summer 2007

Magneto-Mechanical Stimulation of Early Bone Growth into Surface Layers on Implants

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University of Cambridge

Outline

- *Prosthetic Implants*
- *Magneto-Mechanical Actuation of Fibre Network Materials: Deflections and Strains*
- *Elastic Properties of Fibre Network Materials*
- *Design of an Integrated Magneto-Active Prosthesis*
- *Fibre Compatibility and Topography*

Bone-Implant Adhesion in Implants

- Bonding via:

a) bone cement (durability often poor)
b) rough/porous surface, into which bone tissue grows (post-operative period critical)

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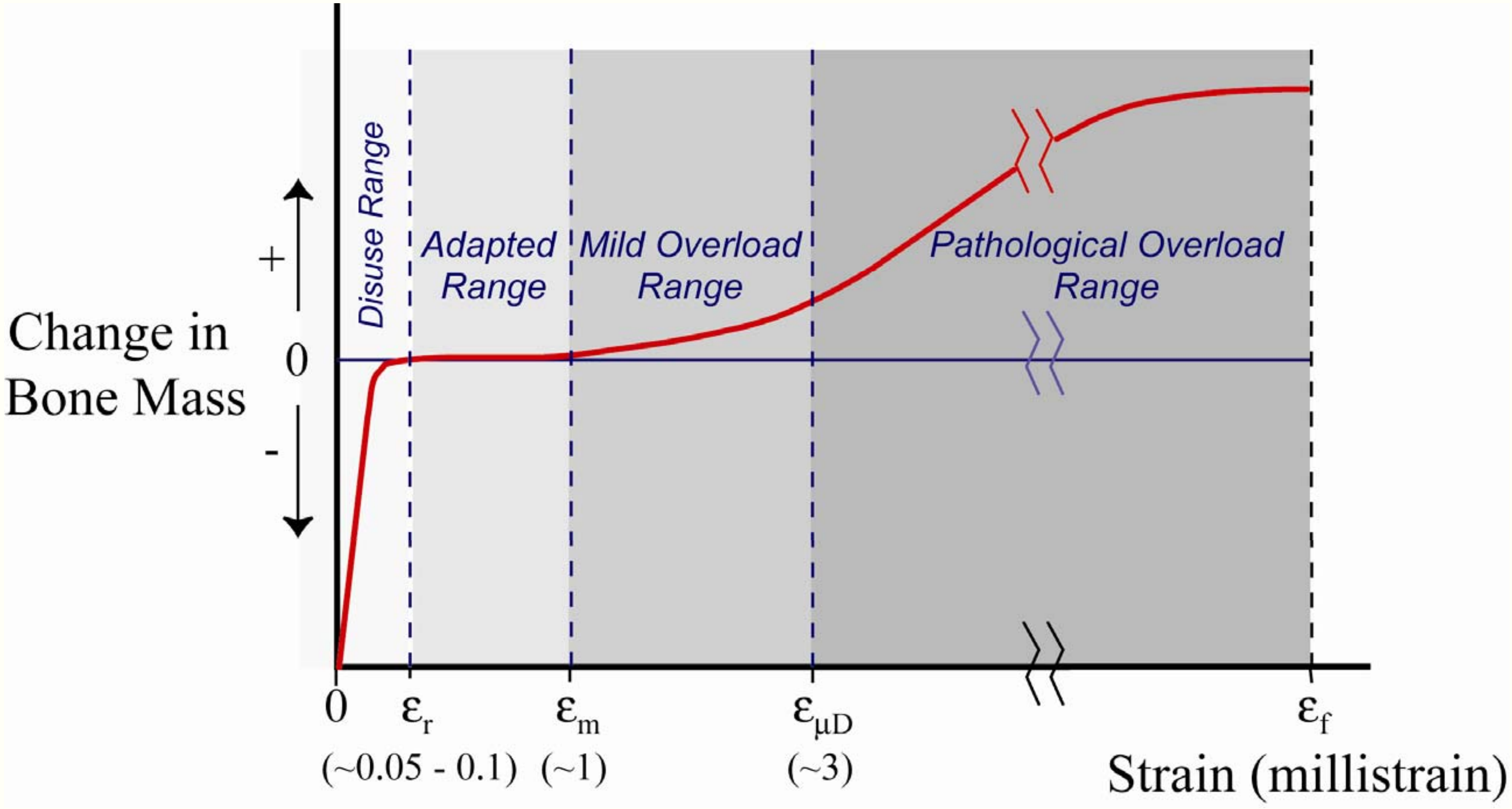
Loosening at bone-implant interface

Caused by:

- poor interfacial adhesion
- stress shielding
  (inhibits straining of the bone)

Cementless & Cemented
Stems (Smith & Nephew)

Strain Regulated Bone Modelling (Formation) and Remodelling (Resorption) (H.M. Frost 1987)



Healthy bone growth is stimulated by mechanical strain. Physiologically benefits start at ~ 1 millistrain.

Use of Porous Metals for Prosthesis

- Porous metals have often been proposed for prostheses
- Pores ~ 100-300 µm & biocompatible surface - bone tissue in-growth does occur
- Fibre Network Materials

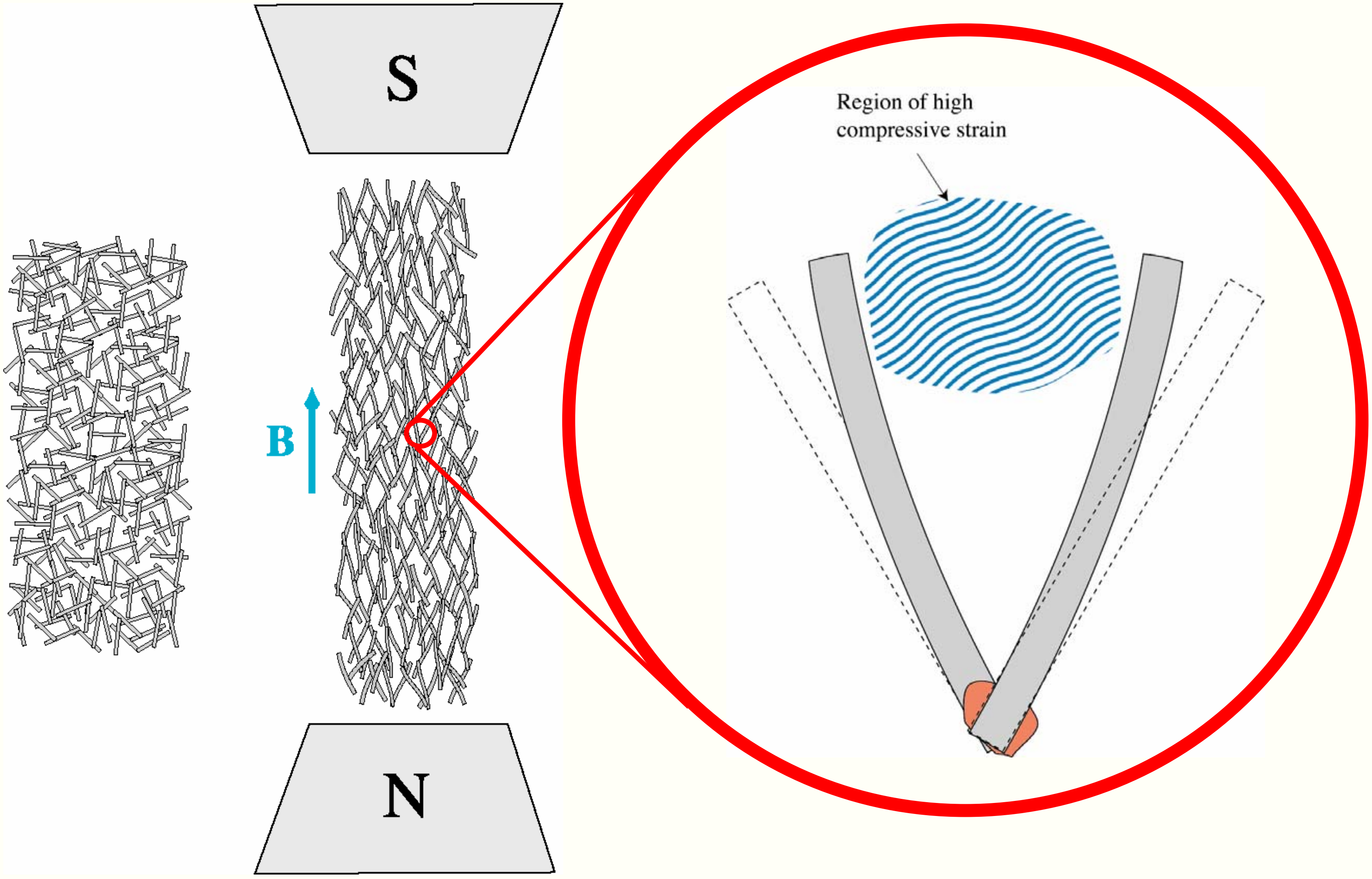
Good Potential for Control over:

(a) Material (fibre diameter, section shape)

(b) Architecture (porosity, fibre orientation distribution, inter-joint spacing)

Canine femur after incorporation
of a Ti mesh (Oka *et al*, J. Bone
& Joint Surgery, 1997;79:1003-1007)

Magneto-Mechanical Actuation of Bonded Fibre Networks: A New Approach to Bone Growth Stimulation



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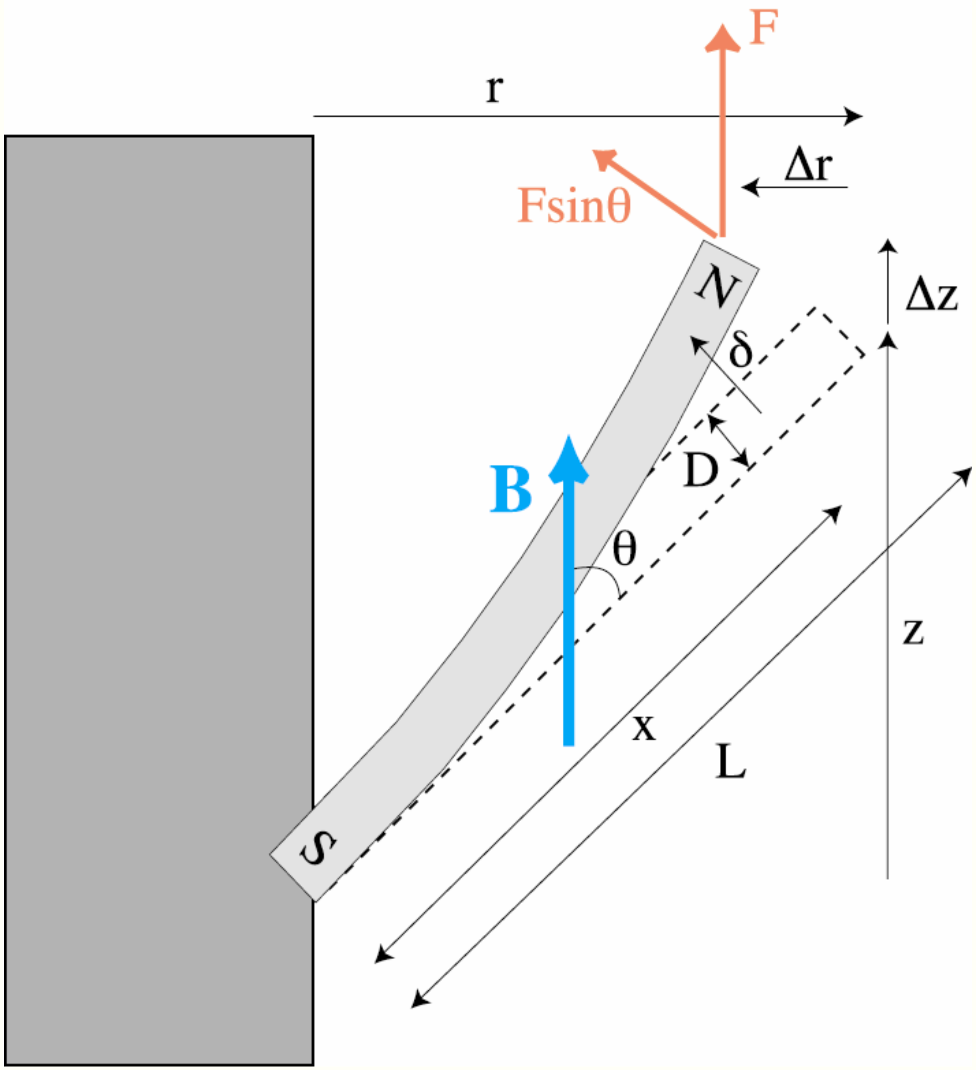
Moment acting on a Single Ferromagnetic Fibre in an Applied Magnetic Field



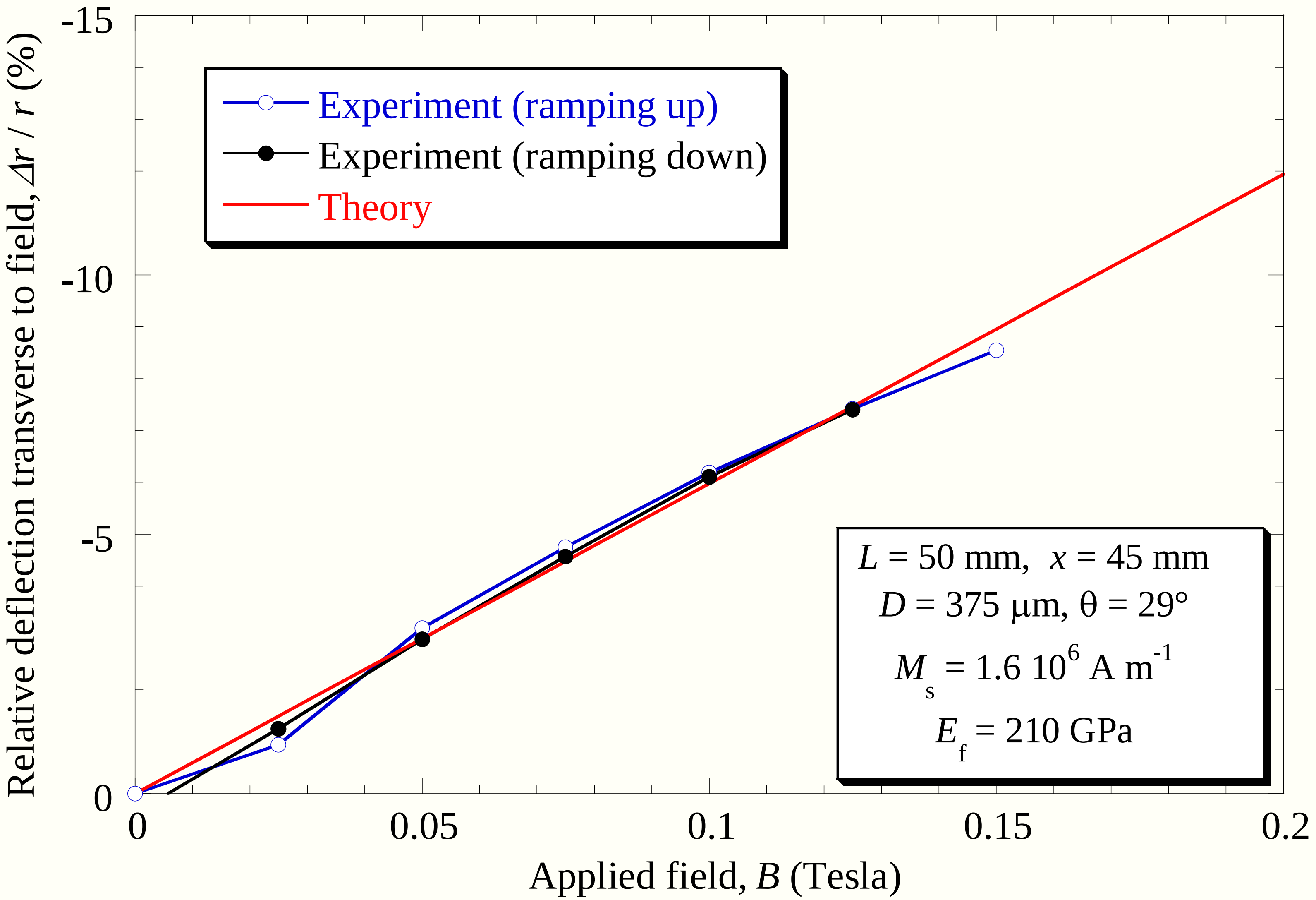
$$\frac{\Delta r}{r} = \frac{-\delta\cos\theta}{x\sin\theta}$$

$$= \frac{-8 M_s B\cos\theta}{3\ E_f}\left[3\left(\frac{x}{L}\right)-\left(\frac{x}{L}\right)^2\right]\left(\frac{L}{D}\right)^2$$

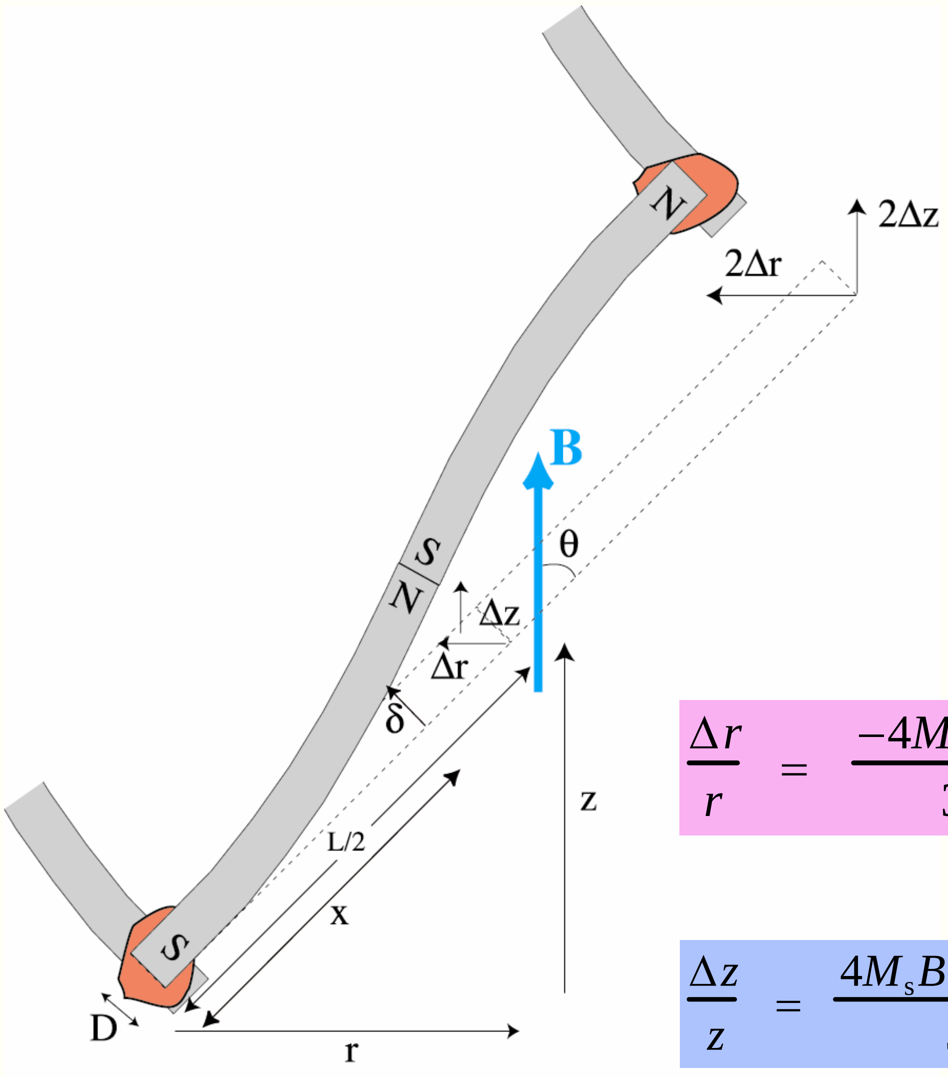
$$\frac{\Delta z}{z} = \frac{\delta\sin\theta}{x\cos\theta}$$

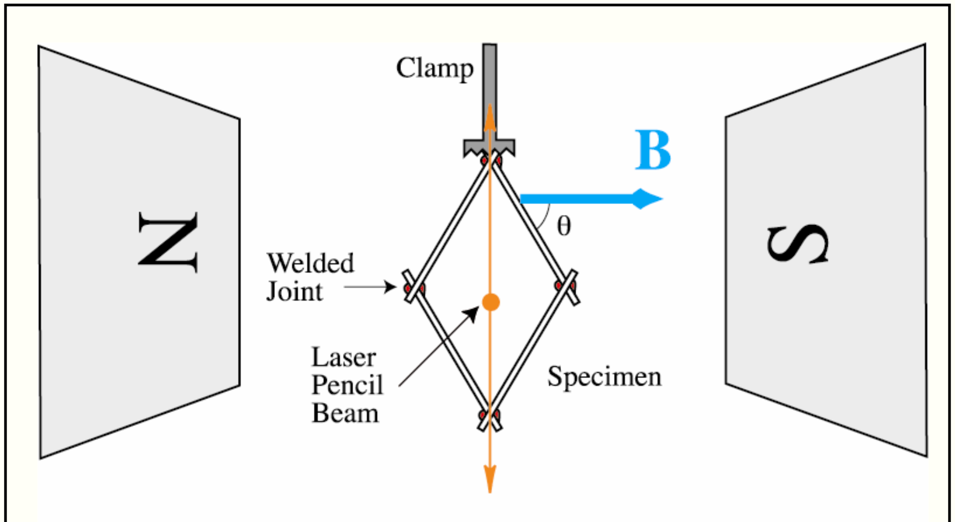
$$= \frac{8 M_s B\sin\theta\tan\theta}{3\ E_f}\left[3\left(\frac{x}{L}\right)-\left(\frac{x}{L}\right)^2\right]\left(\frac{L}{D}\right)^2$$

Measured and Predicted Deflections of a Single Ferromagnetic Fibre



Magnetically-induced Deflection of a Welded Parallelogram



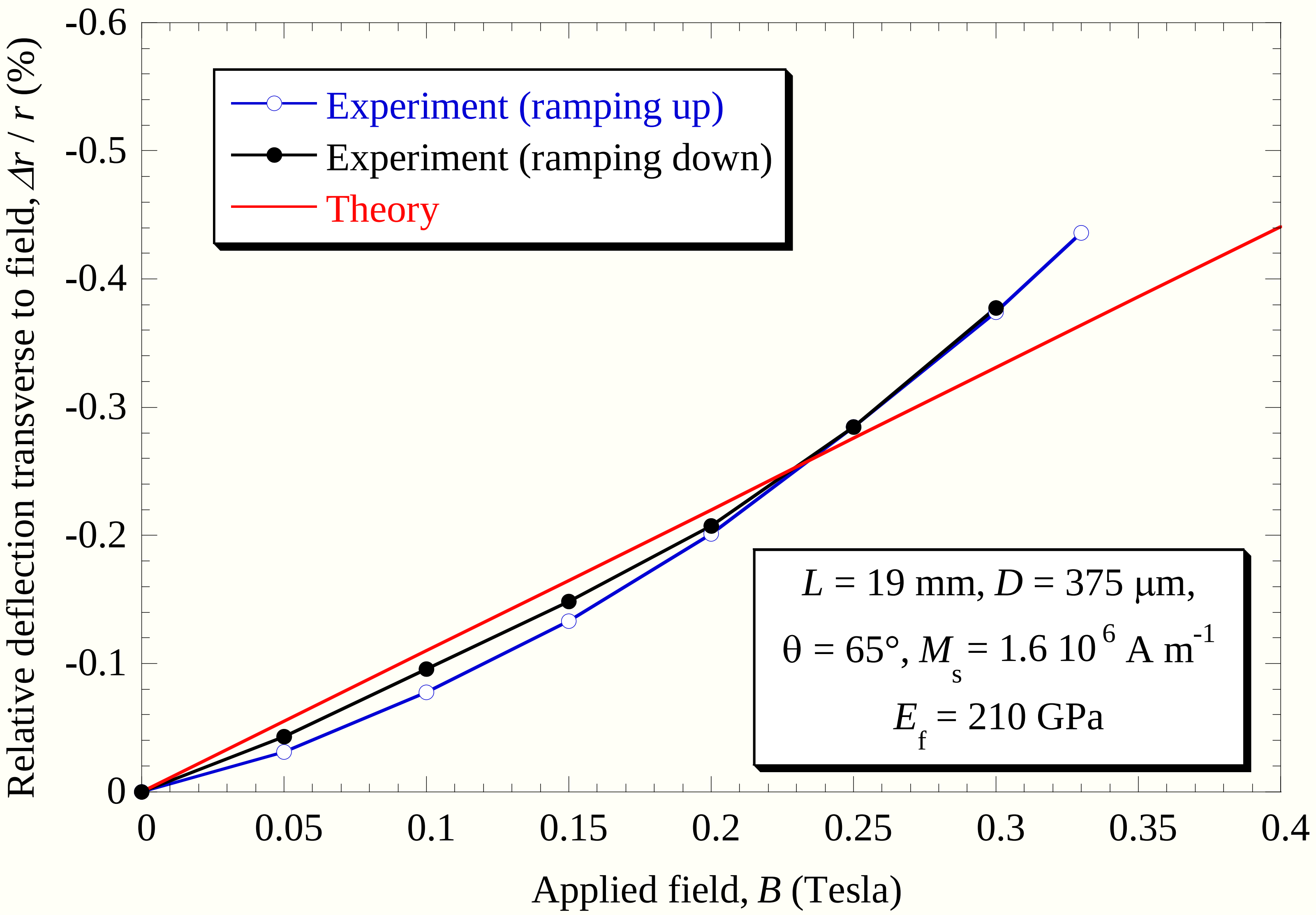


Experimental Set-Up

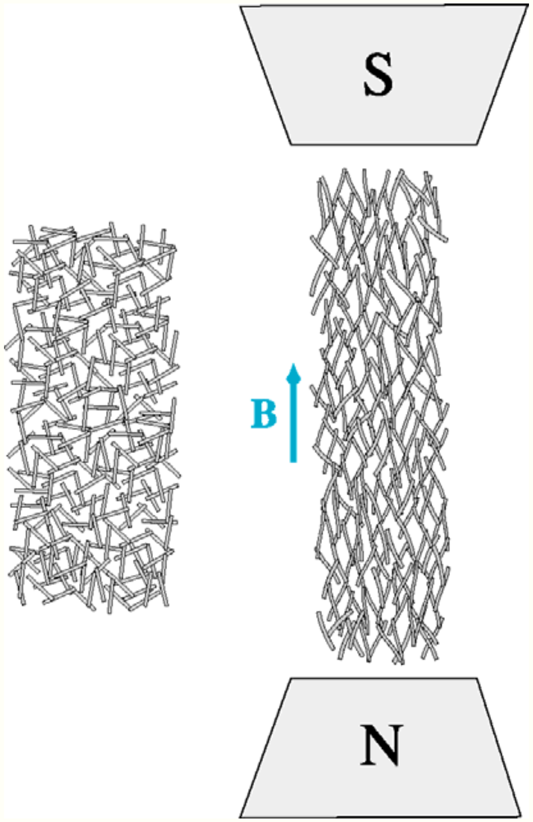
$$\frac{\Delta r}{r} = \frac{-4M_s B\cos\theta}{3\ E_f}\left(\frac{L}{D}\right)^2$$

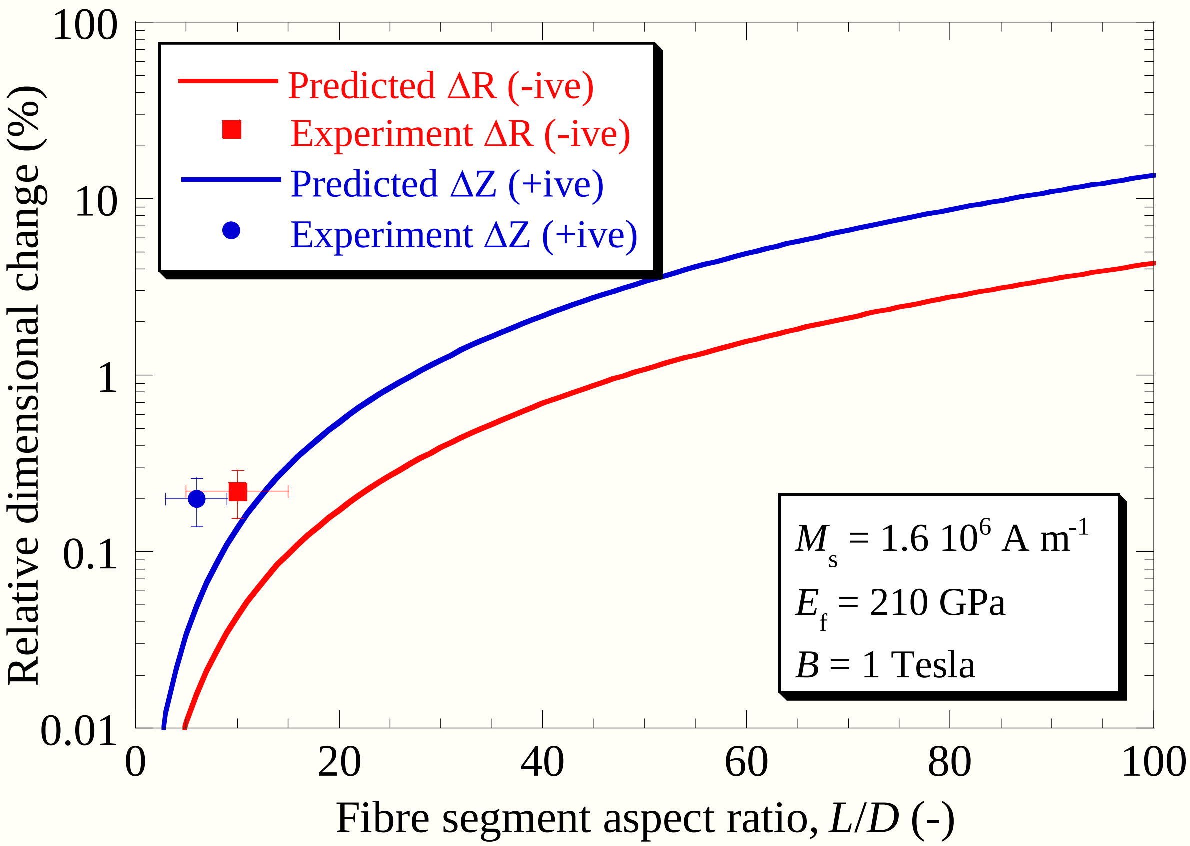
$$\frac{\Delta z}{z} = \frac{4M_s B\sin\theta\tan\theta}{3\ E_f}\left(\frac{L}{D}\right)^2$$

Measured and Predicted Deflections of a Welded Parallelogram



Magneto-Mechanical Induction of an Isotropic Fibre Network Material





Axial:

$$\frac{\Delta Z}{Z} = \frac{\int_0^{\pi/2} \Delta z \sin\theta \, d\theta}{\int_0^{\pi/2} z \sin\theta \, d\theta} = \left(\frac{16 M_s B}{9 E_f}\right)\left(\frac{L}{D}\right)^2$$

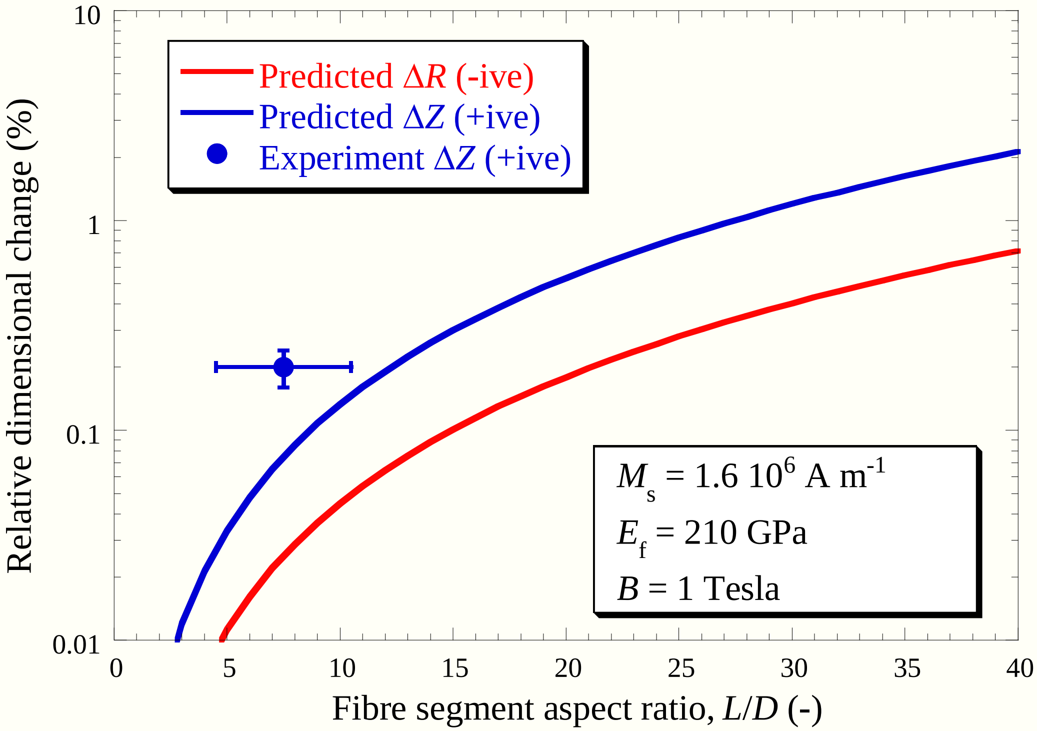
Transverse:

$$\frac{\Delta R}{R} = \frac{\int_0^{\pi/2} \Delta r \sin\theta \, d\theta}{\int_0^{\pi/2} r \sin\theta \, d\theta} = \left(\frac{-16 M_s B}{9\pi E_f}\right)\left(\frac{L}{D}\right)^2$$

Magneto-Mechanical Induction of a Transversely Isotropic Fibre Network Material using X-ray Tomography

3-D tomographic reconstruction

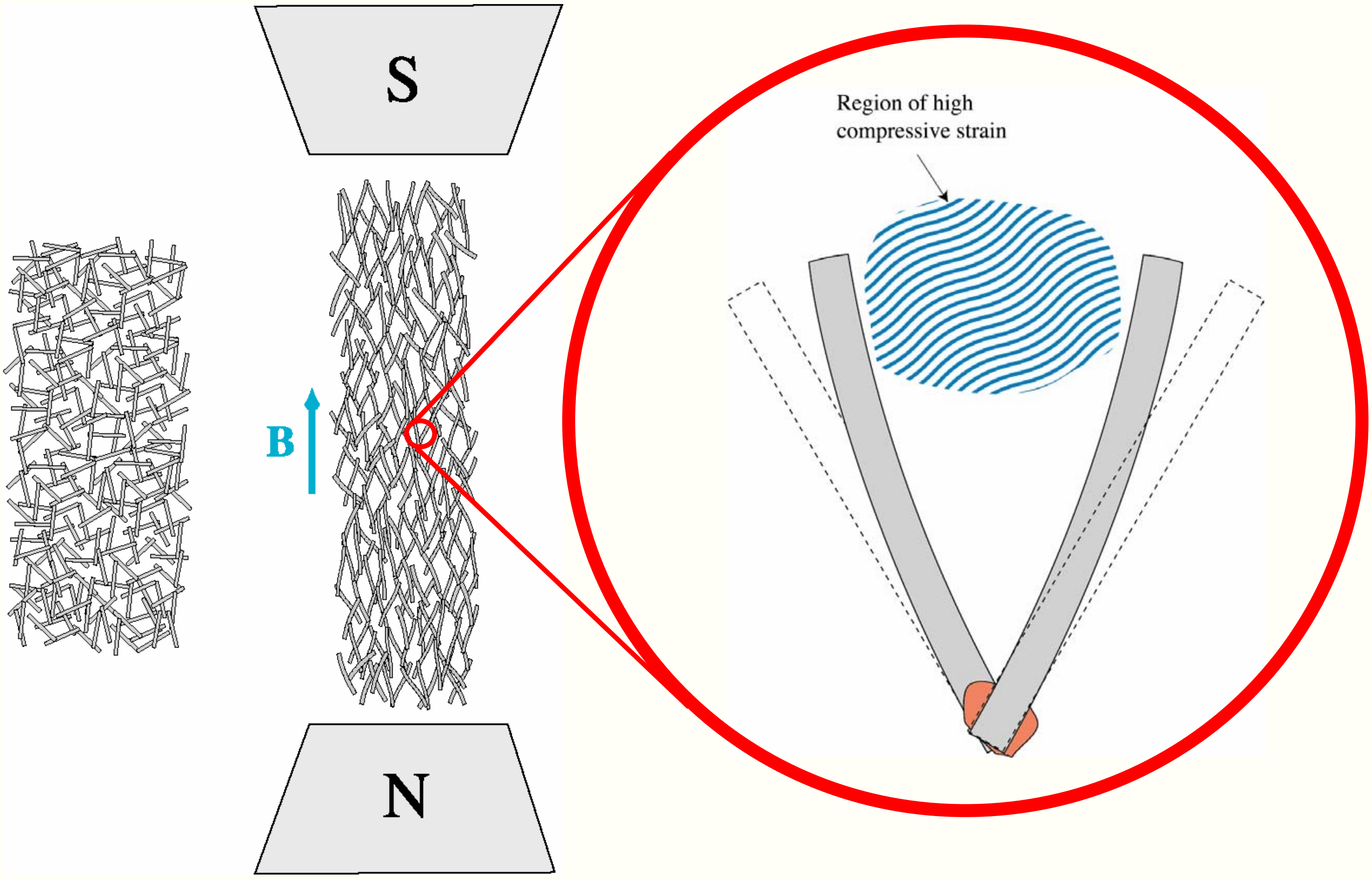
500 µm



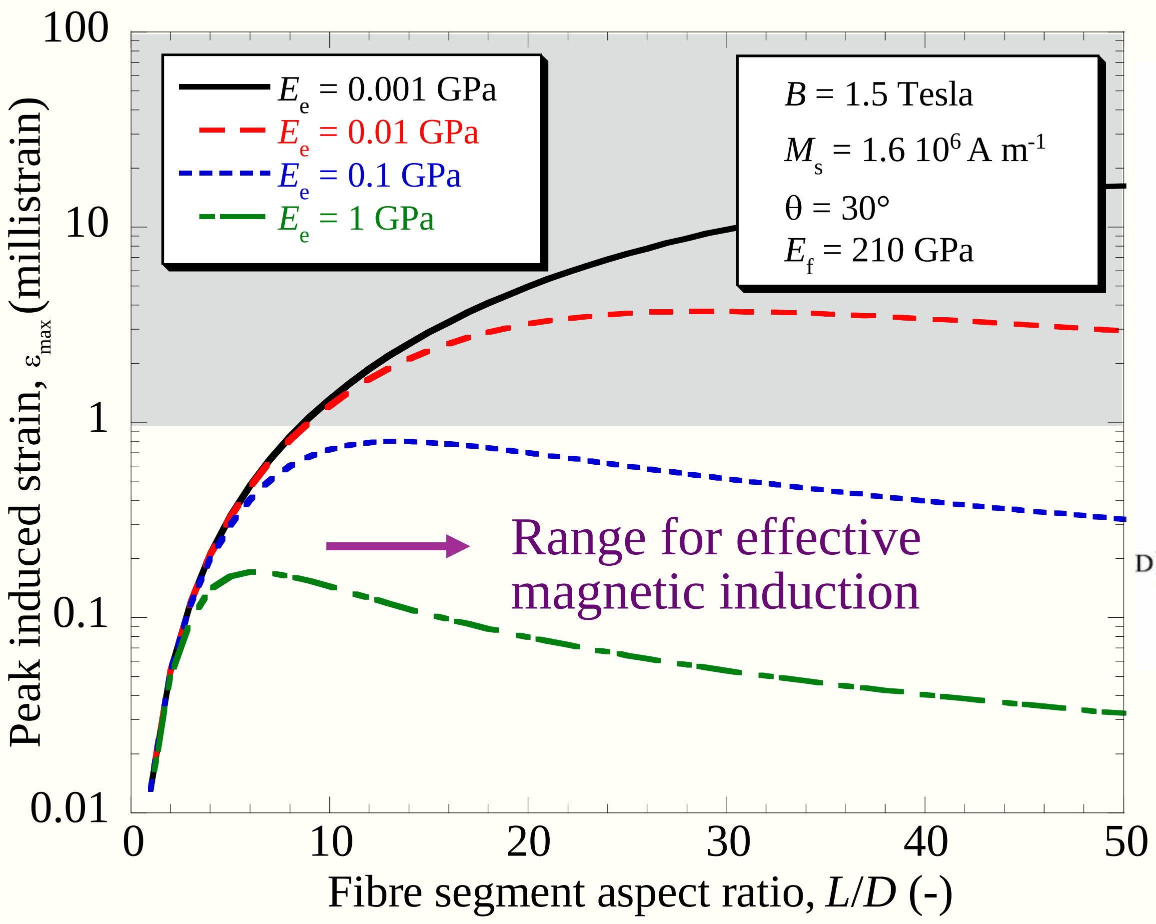
$$\frac{\Delta Z}{Z} = \left(\frac{4M_s B}{3E_f}\right)\left(\frac{L}{D}\right)^2 \frac{\sum_i^n N_{\theta_i}\sin^2\theta_i}{\sum_i^n N_{\theta_i}\cos\theta_i}$$

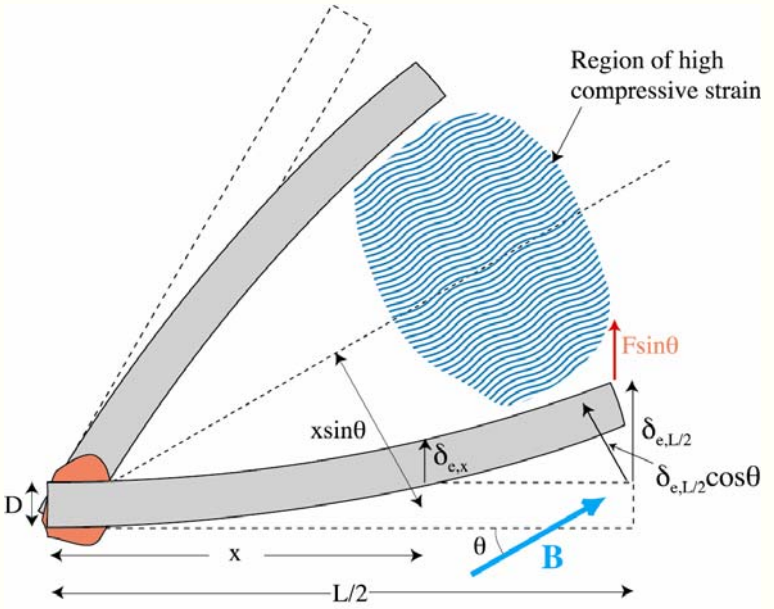
$$\frac{\Delta R}{R} = \left(-\frac{4M_s B}{3E_f}\right)\left(\frac{L}{D}\right)^2 \frac{\sum_i^n N_{\theta_i}\sin\theta_i\cos\theta_i}{\sum_i^n N_{\theta_i}\sin\theta_i}$$

Effect of the presence of an Environment (Compliant Matrix) on Network Straining



Predicted Peak Strains in a Surrounding Environment, as a function of its Stiffness

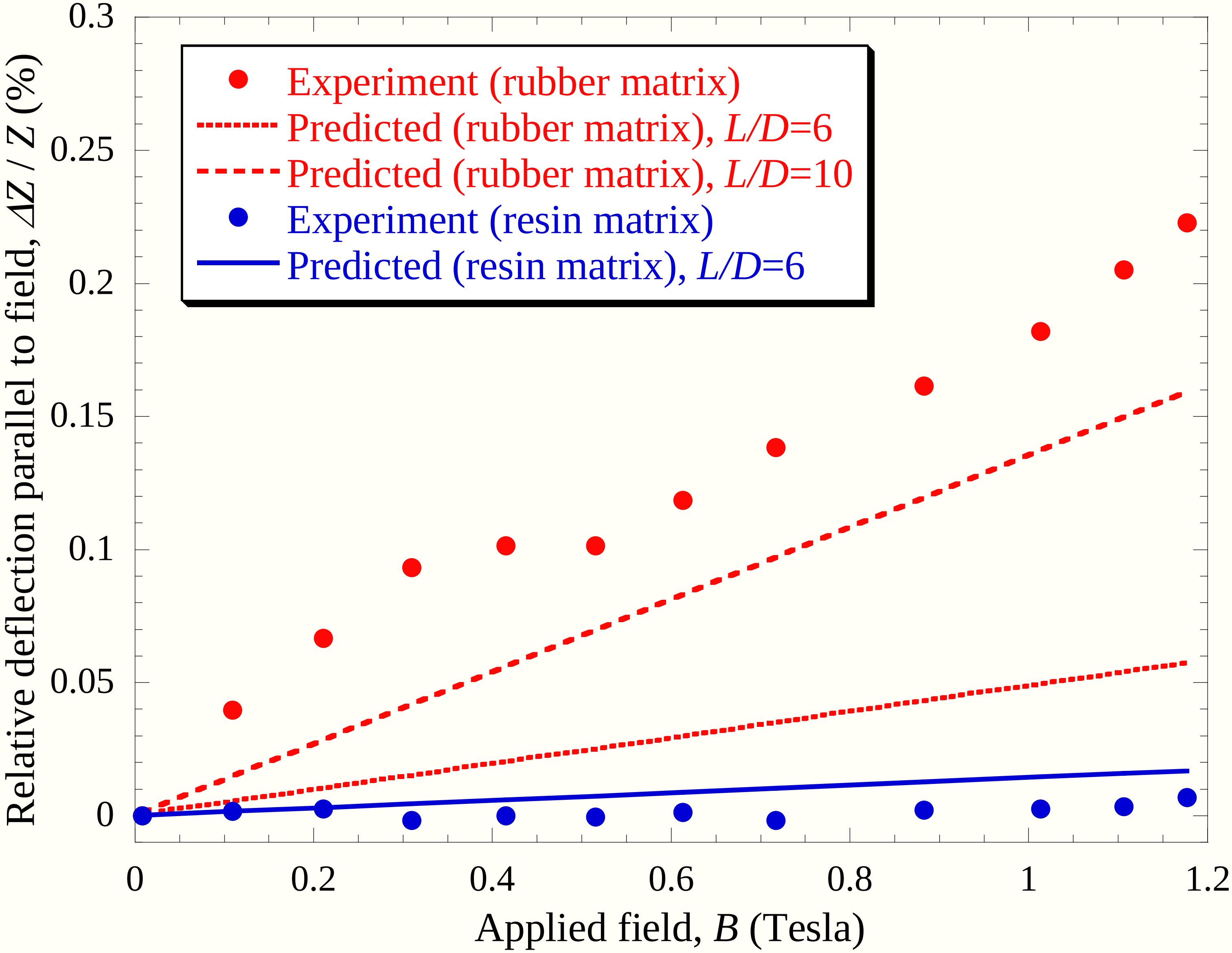




$$\varepsilon_{\max} = \frac{12\pi M_s B \sin\theta \left(\frac{L}{D}\right)^2}{\left(9\pi E_f \tan\theta + 28E_e\left(\frac{L}{D}\right)^3\right)}$$

- ***Beneficial strains (>1 millistrain) at L/D > 10***

Measured and Predicted Magnetic Straining with Surrounding Environments (Matrices)



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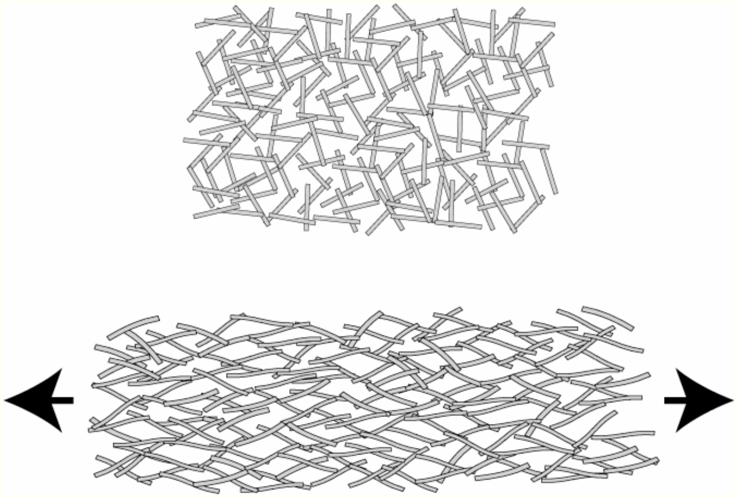
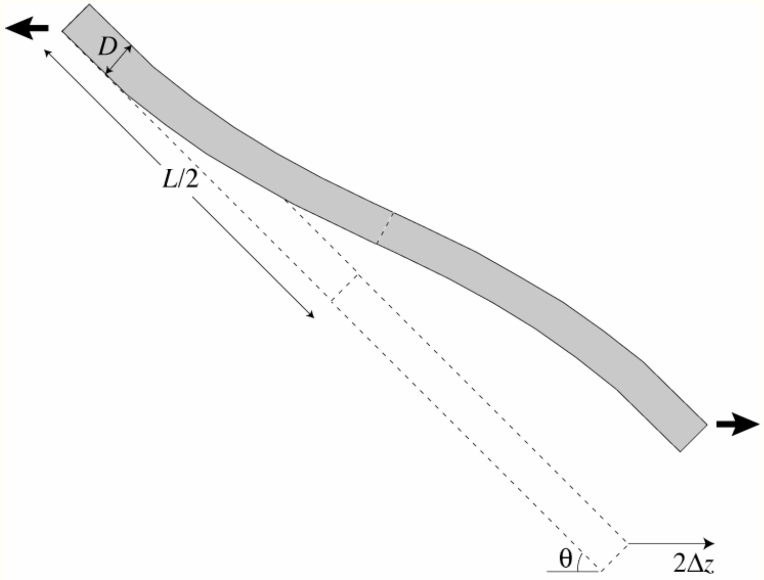
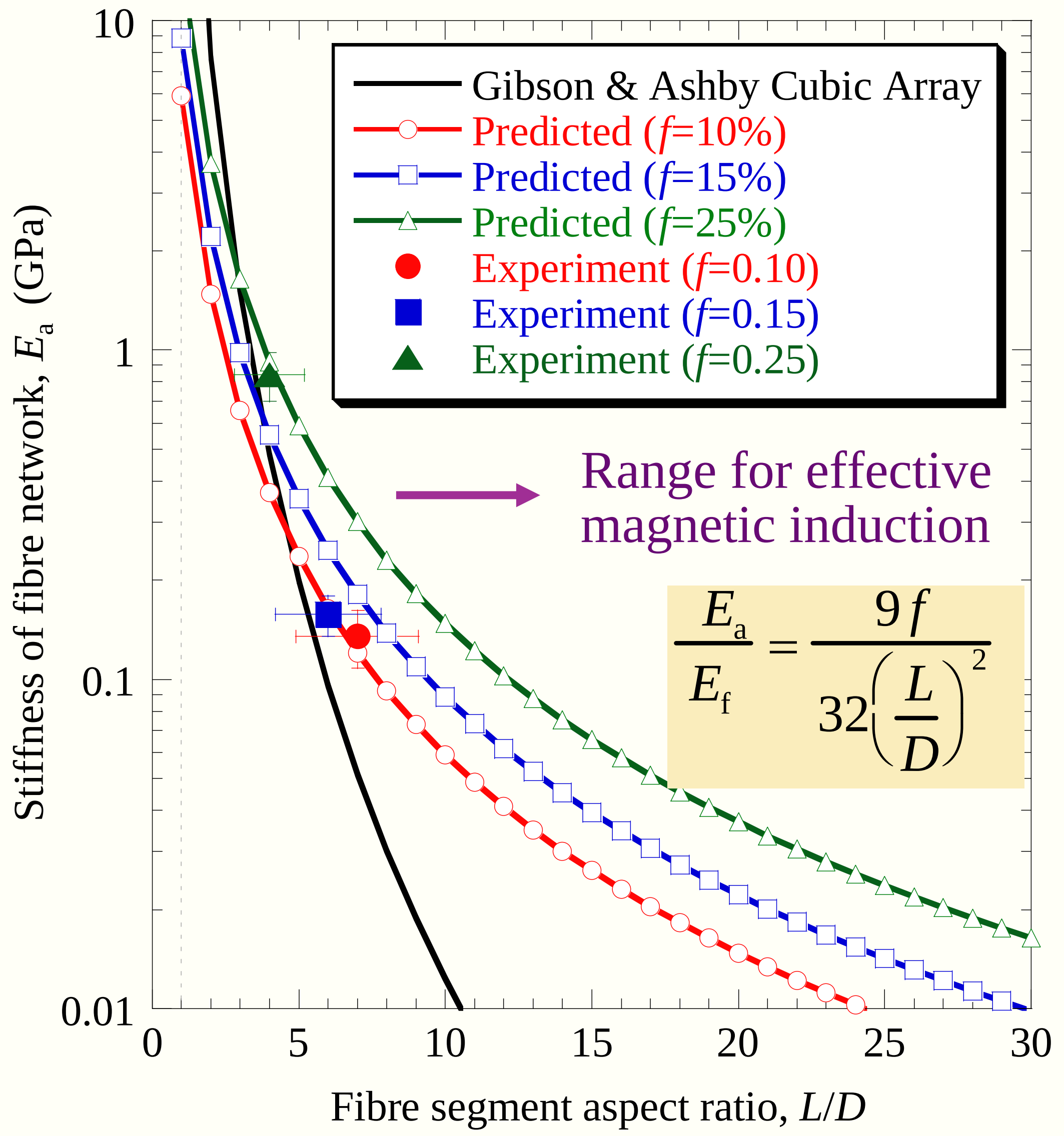
Predicted and Measured Stiffness for an Isotropic Fibre Network







Range for effective magnetic induction

$$\frac{E_a}{E_f} = \frac{9f}{32\left(\frac{L}{D}\right)^2}$$

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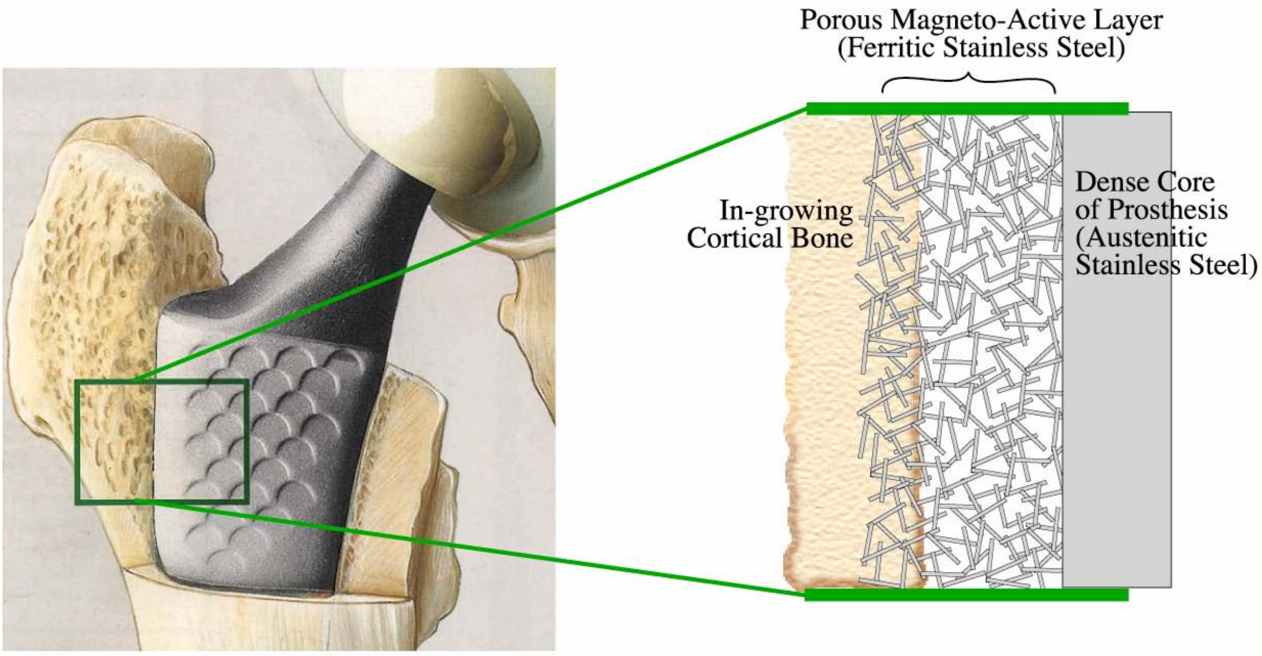
Concept of an Integrated Prosthetic Design



- ***Treatment by Exposure to Applied Field during Post-operative Period***
- ***Only Magneto-Active Layer will respond to Applied Field***
- ***Magneto-Active Layer could be Graded, Anisotropic etc***
- ***All Materials could be Biocompatible***

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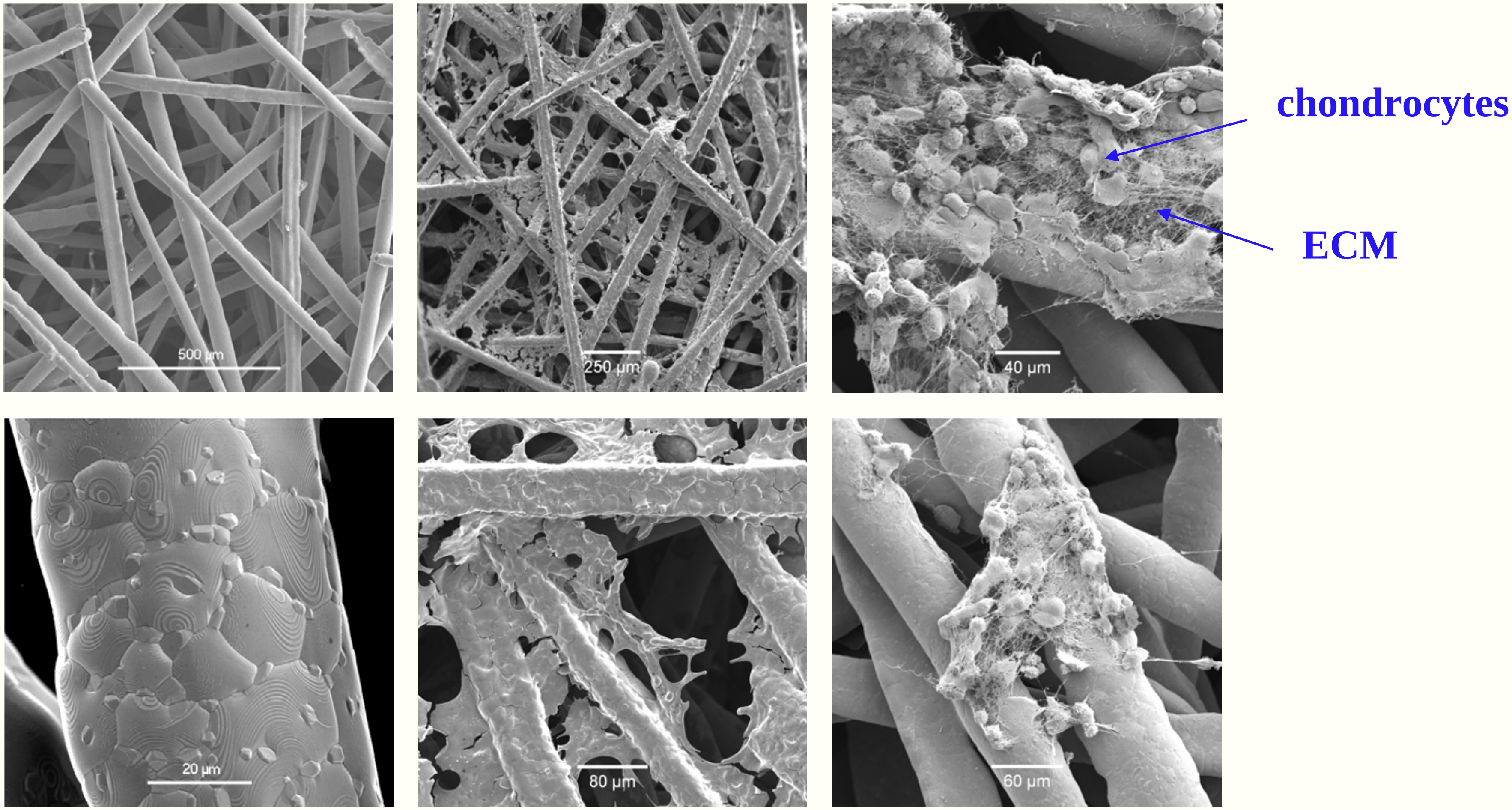
Fibre Biocompatibility and Topography



Freeze dried

Critically point dried

Cartilage Cells (chondrocytes) cultured on a 446 (ferritic) stainless steel fibre network

Summary

- *Network of Ferromagnetic Fibres Deforms Elastically in Magnetic Field, inducing Strain in any Matrix present*

- *An Analytical Model has been Developed describing this Process and has been Experimentally Validated for Simple Fibre Configurations*

- *Model Predictions suggest that Physiologically Beneficial Strains could be induced in In-Growing Bone Tissue using Magnetic Fields already employed for Diagnostic Purposes*

- *In Vitro Experimentation is needed to explore the Viability of the Concept*