Imperial College London

An Inverse Method for Determining the Stiffness of Impact Damage in Laminated Composites

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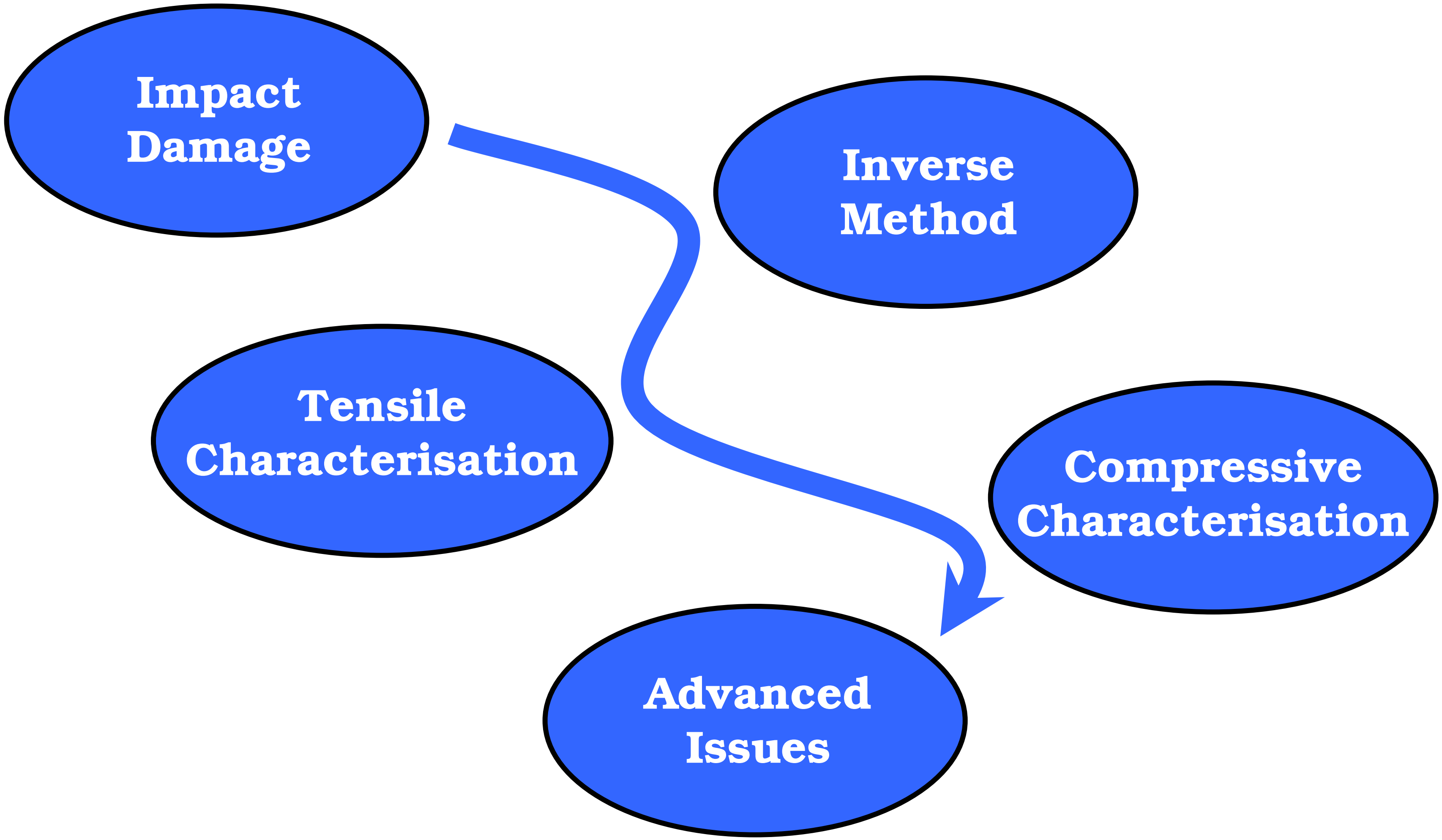
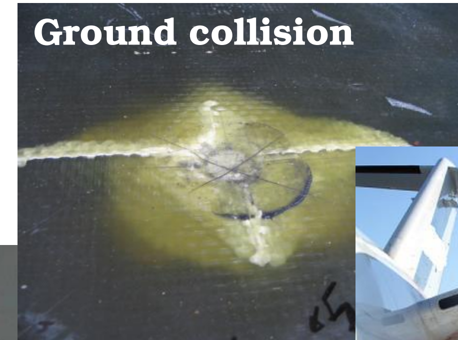
EPSRC Engineering and Physical Sciences Research Council

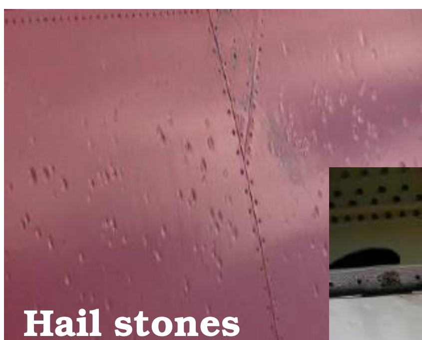
Presentation Layout

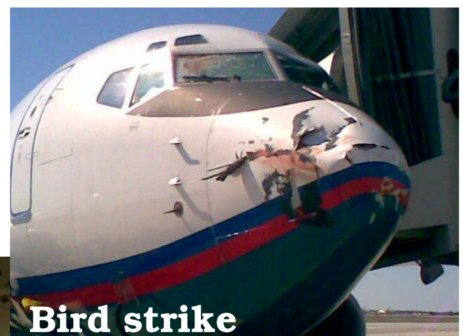


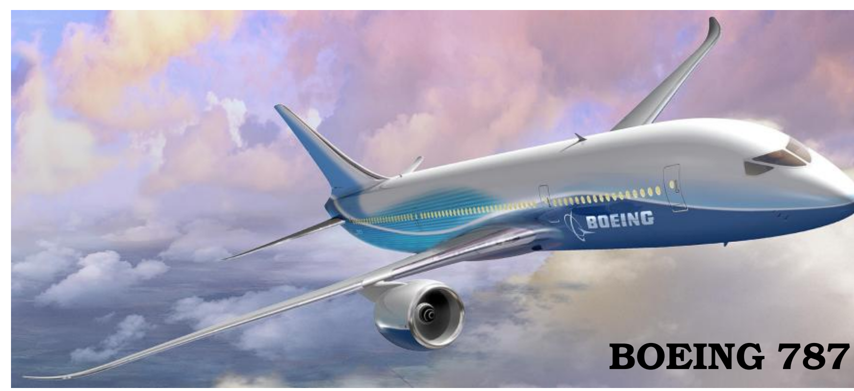
Impact Damage

Composites and Impact

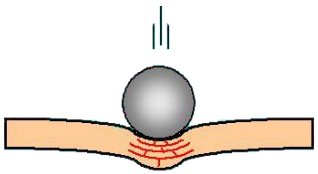




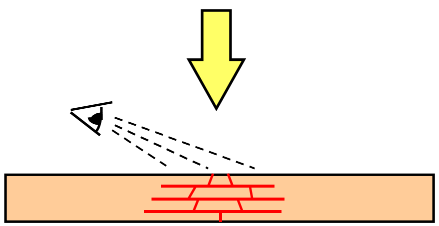




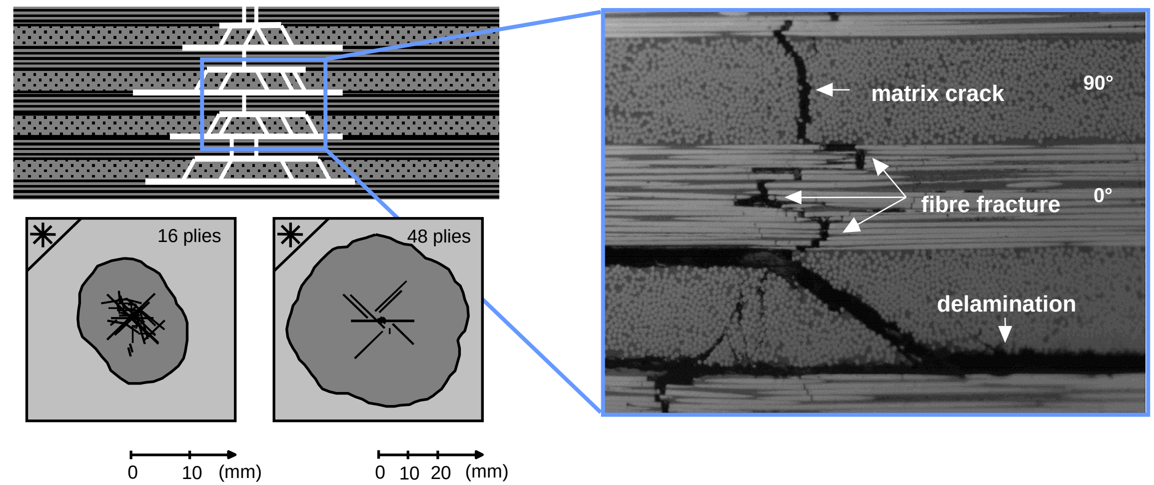
Problem of Impact Damage



Impact damage

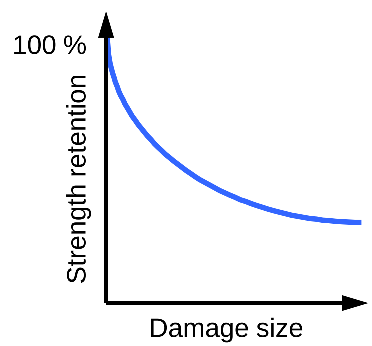


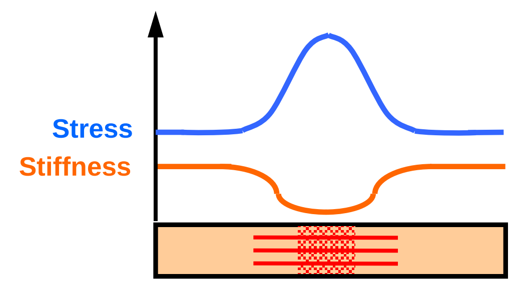
Often invisible by naked eye inspection



Nature and severity of damage

- Impact happens accidentally
- Impact often causes damage
- Damage reduces strength
- Damage affects buckling
- *How much???*
- **STIFFNESS DISTRIBUTION IS KEY!!!**



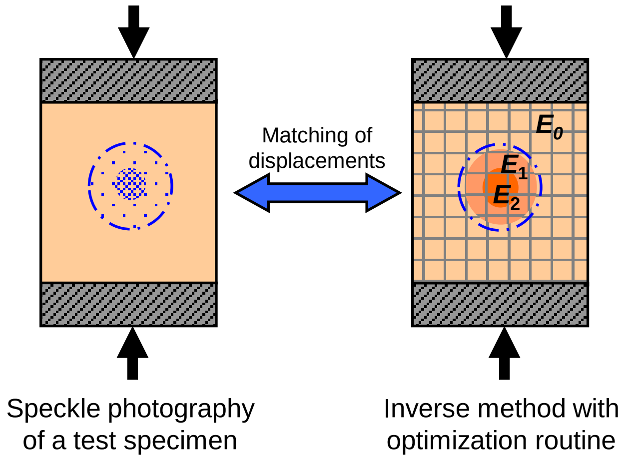


Stress and stiffness distribution

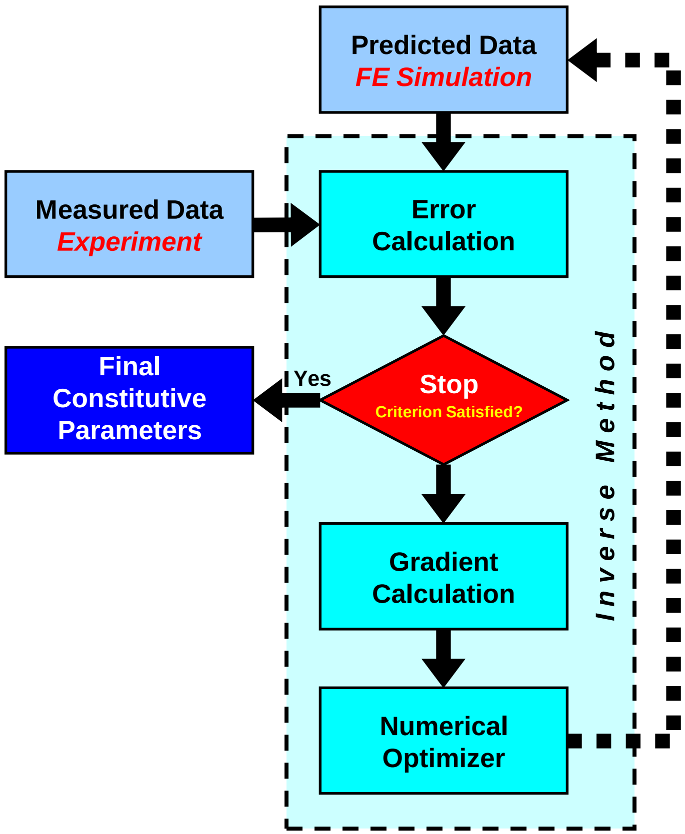
Inverse Method

Inverse Method

Iterative updating of constitutive material parameters in Finite Element model - ABAQUS



Fundamentals of the approach



Flowchart of the approach

Displacement fields measured by Digital Image Correlation - ARAMIS

Sztefek & Olsson (2008), *Composites Part A*.

Optimization Approach

Aim

Seeking minimum of displacement error function by updating material parameters

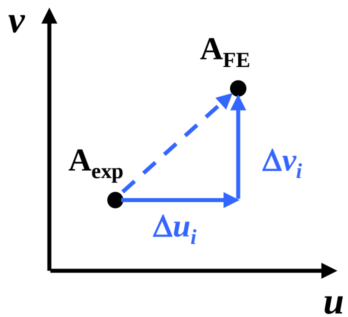
Approach

Gradient method *Steepest Descent* combined with *Davies, Swann, and Campey's algorithm*

Description

Mean squared error function:

$$f(x)=\frac{1}{N}\sum_{i=1}^{N}\left[\left(\frac{\Delta u_i}{u_{\max}}\right)^2+\left(\frac{\Delta v_i}{v_{\max}}\right)^2\right]$$

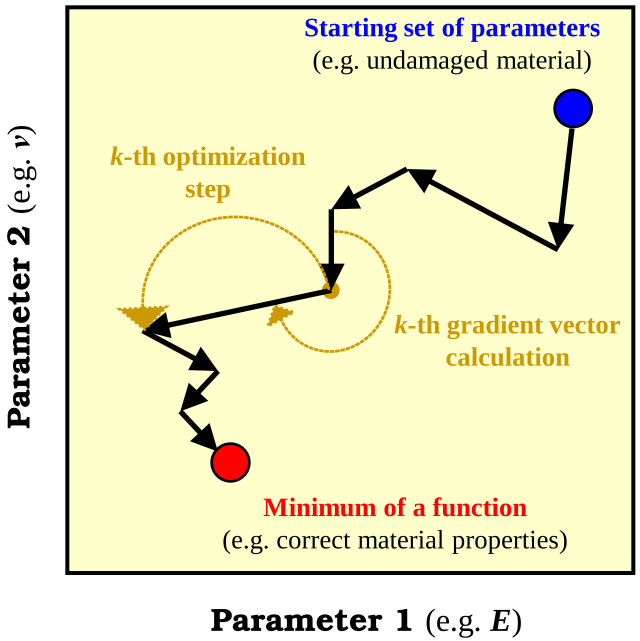


Gradient and Search direction:

$$g_k=\Delta f/\Delta P_k \qquad u_k=g_k/\left|g_k\right|$$

Parameter vector:

$$\mathbf{x}_{k+1}=\mathbf{x}_k+\lambda_k\mathbf{u}_k$$



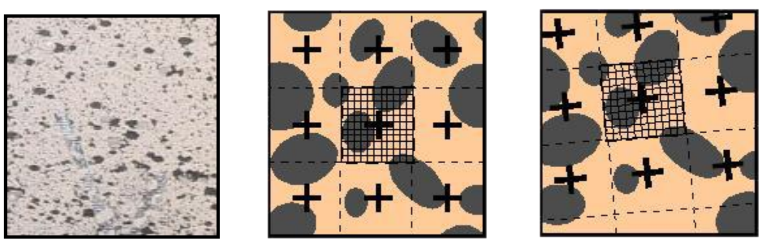
Optimization search procedure

Experiments

Digital Image Correlation System

Non-contact optical 3D deformation measuring system ARAMIS from GOM

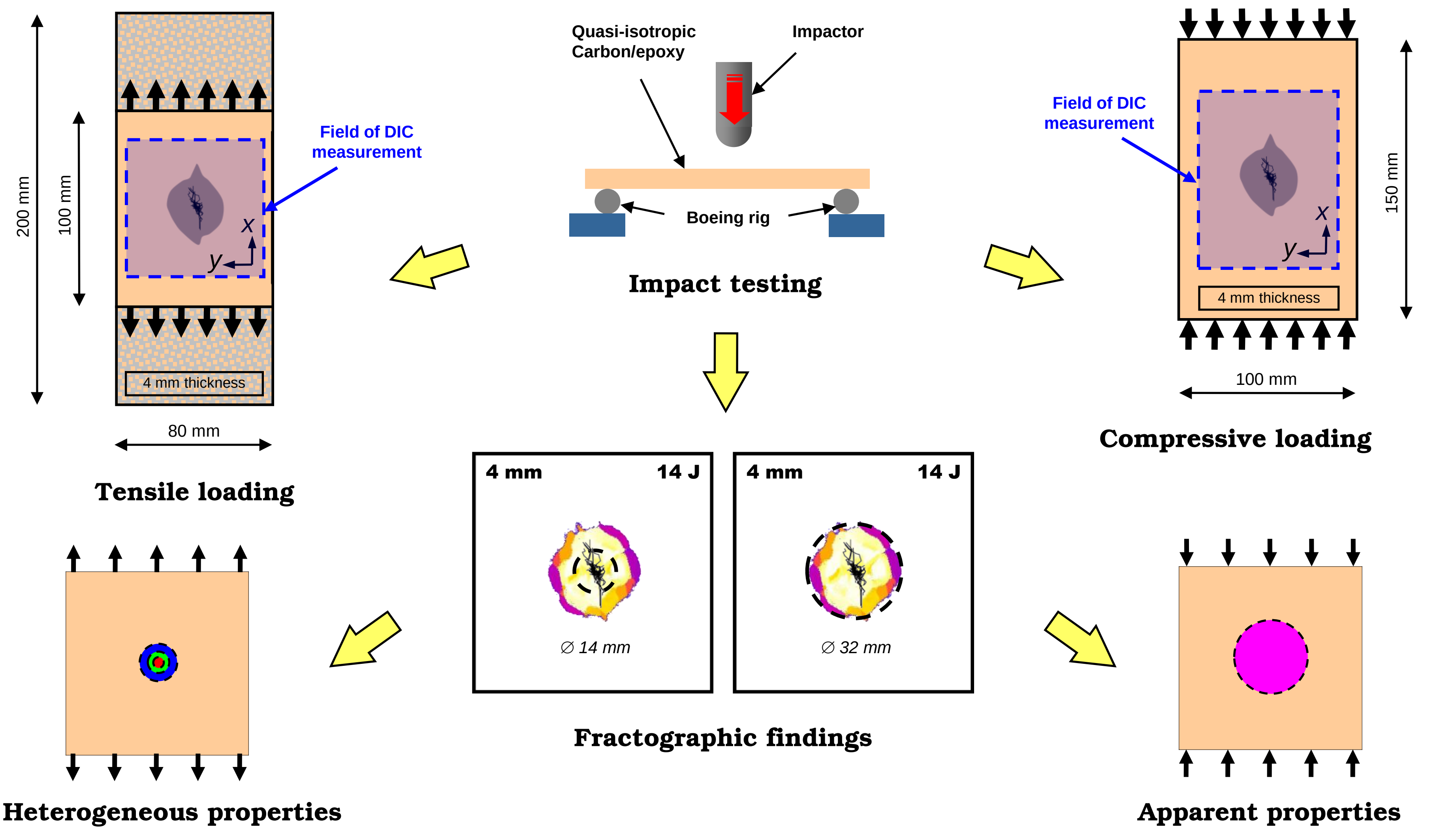
System type	GOM ARAMIS 1.3 M
4 cameras in master and slave mode	
Camera resolution	1280 × 1024 pixels
Measuring volume	10 × 8 × 8 mm^3 to 1.7 × 1.4 × 1.4 m^3
Max. frame rate	12 Hz
Strain range	0.05% up to <100%
Strain accuracy	up to 0.02%



Speckle pattern | Before deformation | During deformation

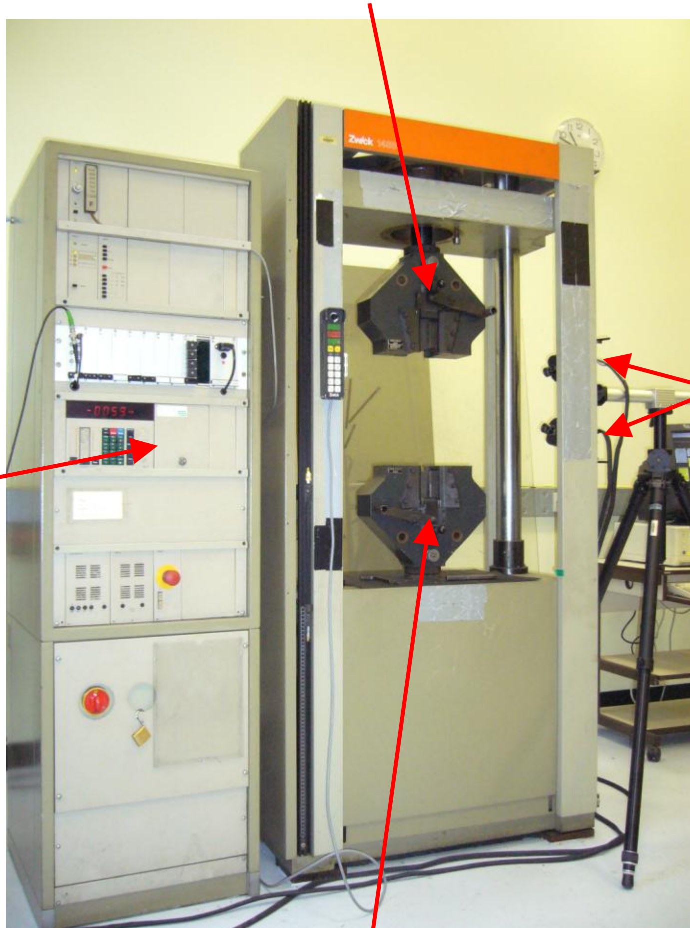
DIC Principle

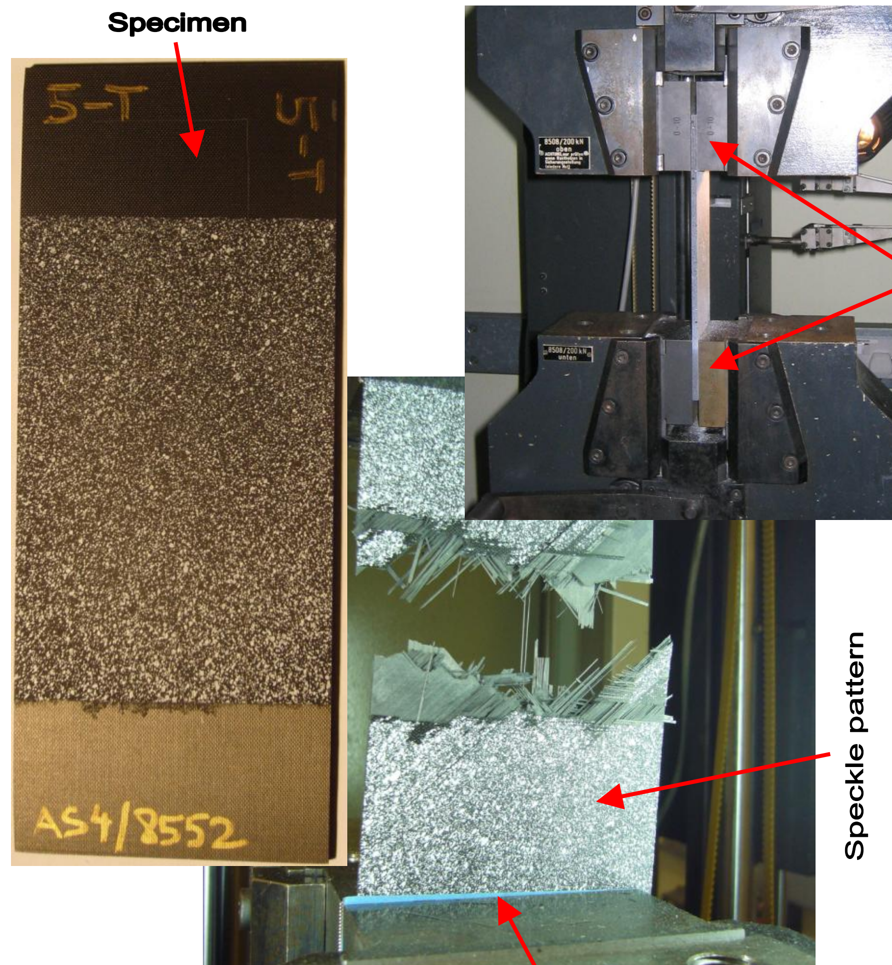
Overview of Experiments



Tensile Characterisation

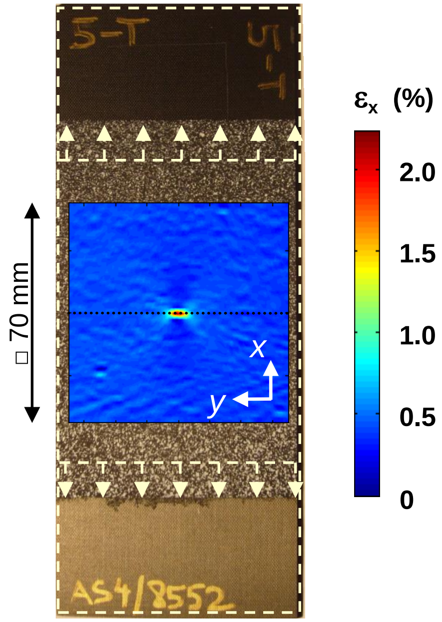
Experimental Setup

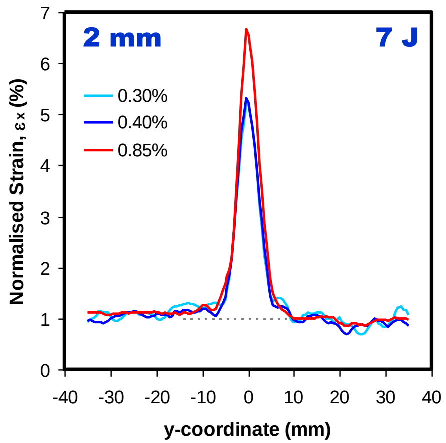


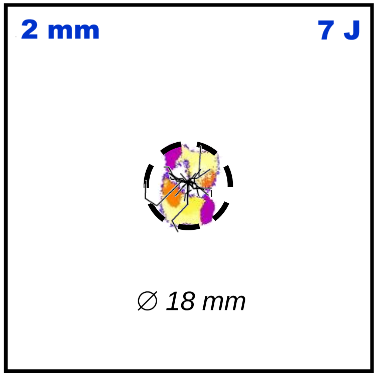


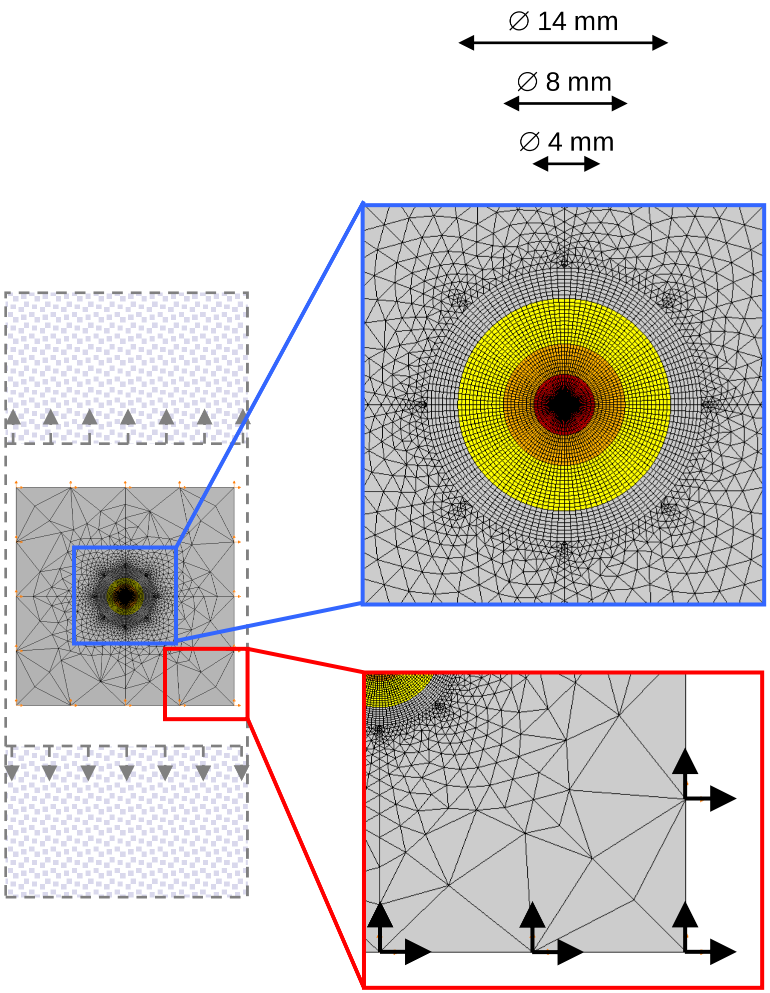
ABAQUS analysis

- **Homogeneous isotropic thin shell**
- **Full-field boundary conditions**

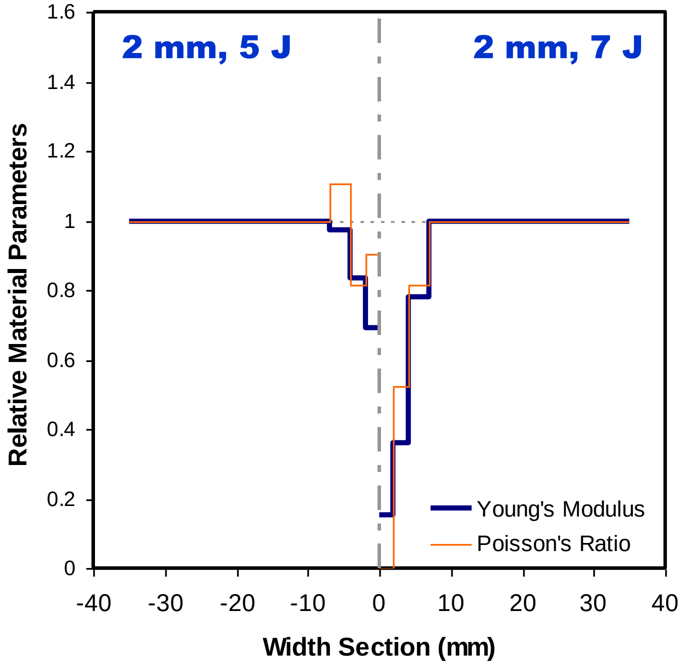


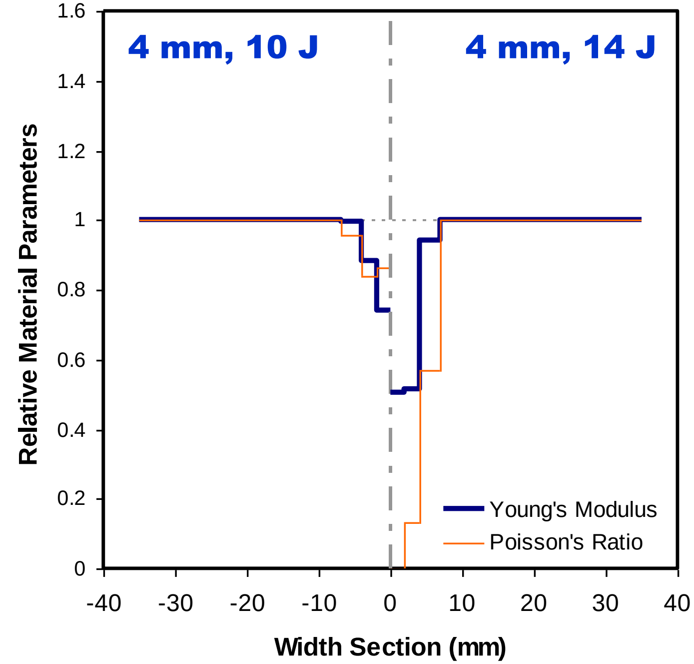


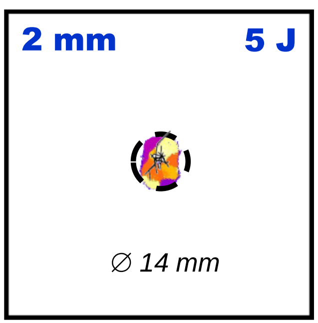


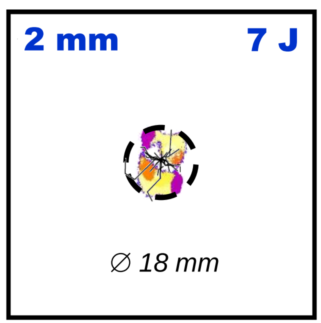


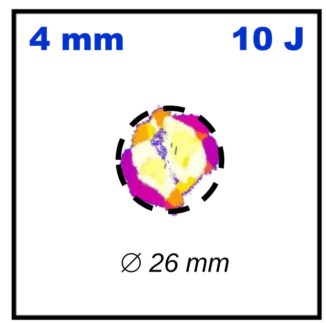
Heterogeneous Material Parameters

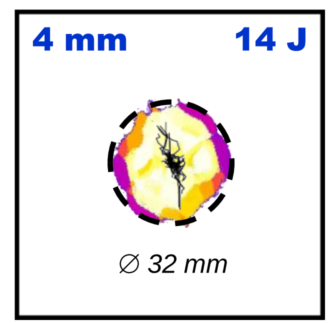




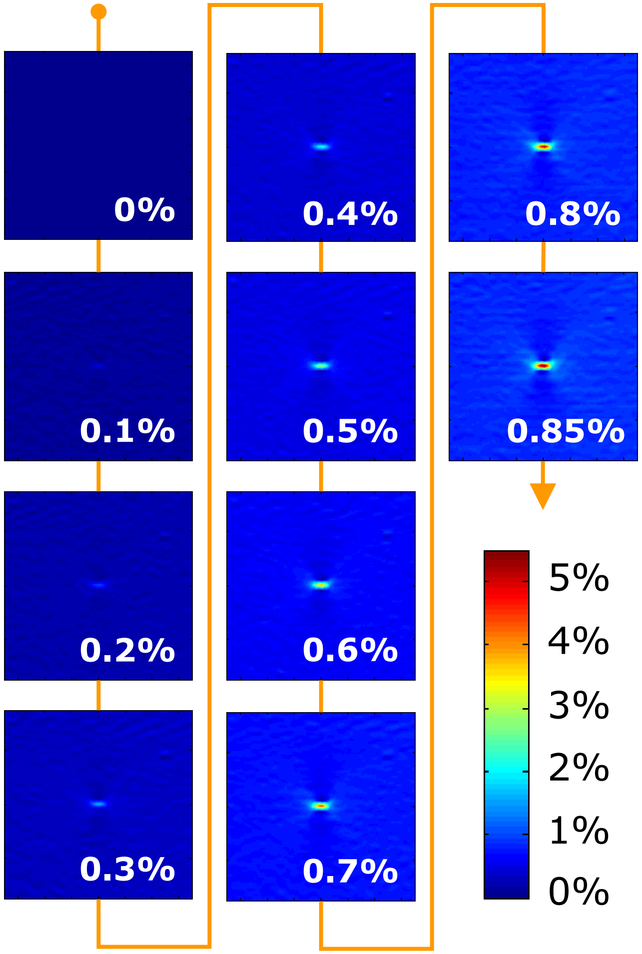




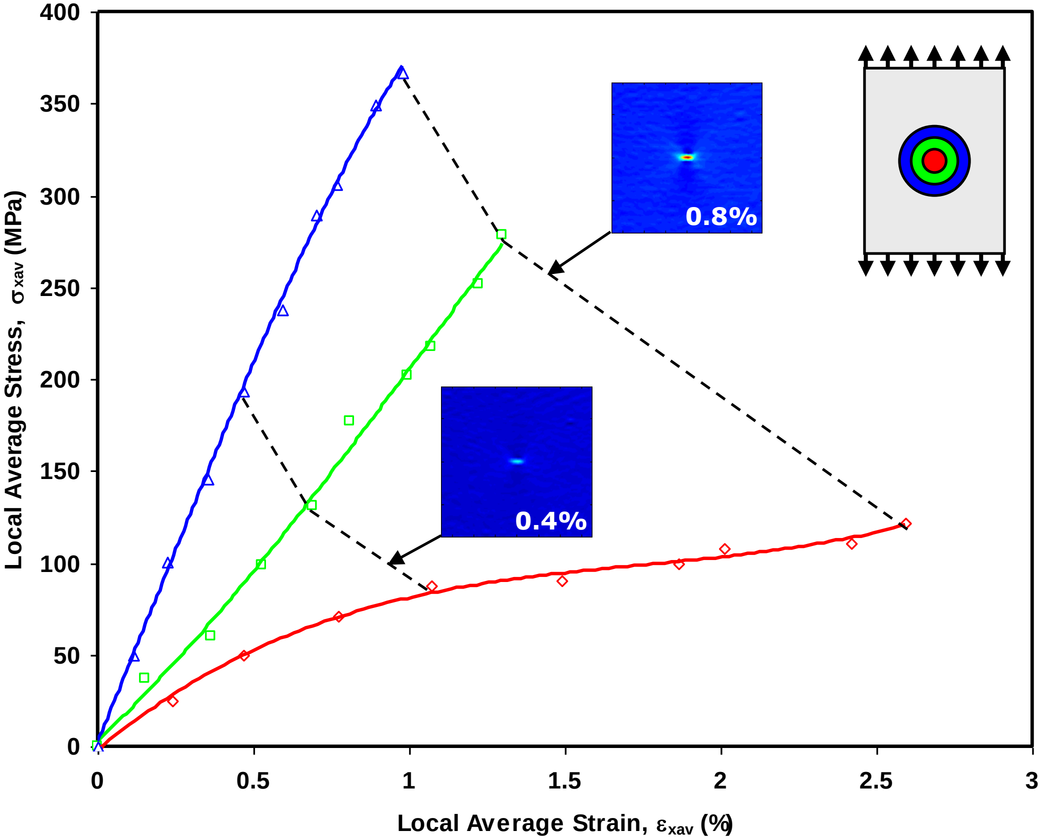




Nonlinear Material Behaviour



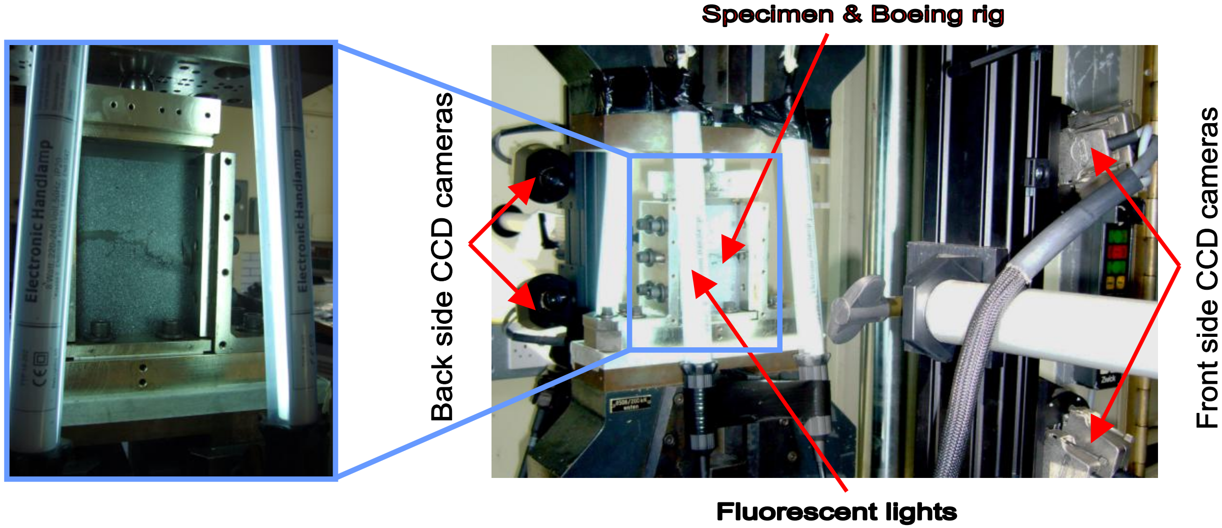
Strain concentrations at different applied (far-field) strains

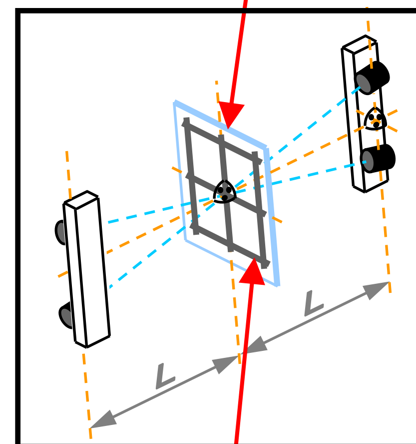


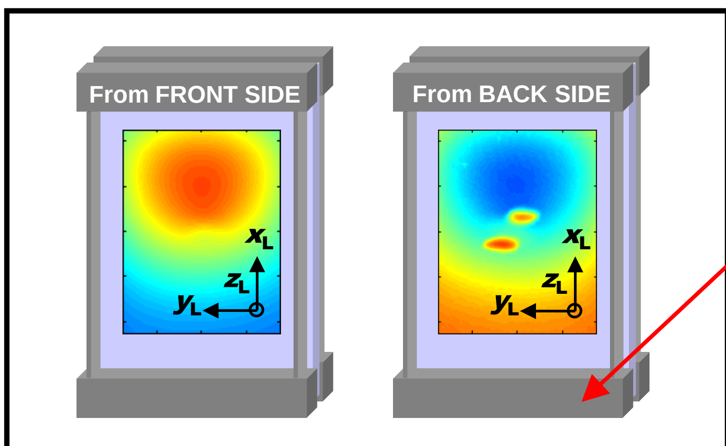
Heterogeneous nonlinearity

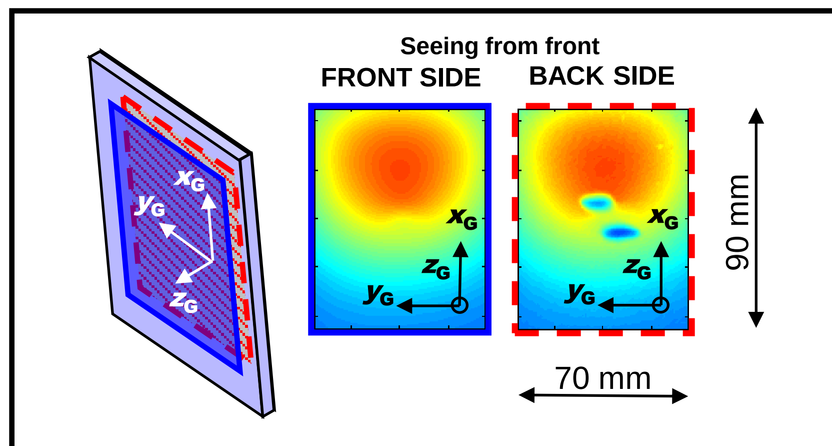
Compressive Characterisation

Experimental and Optical Setup

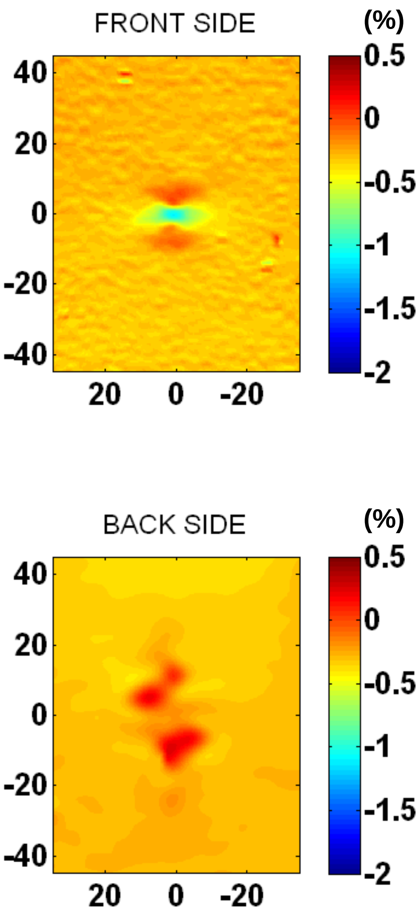




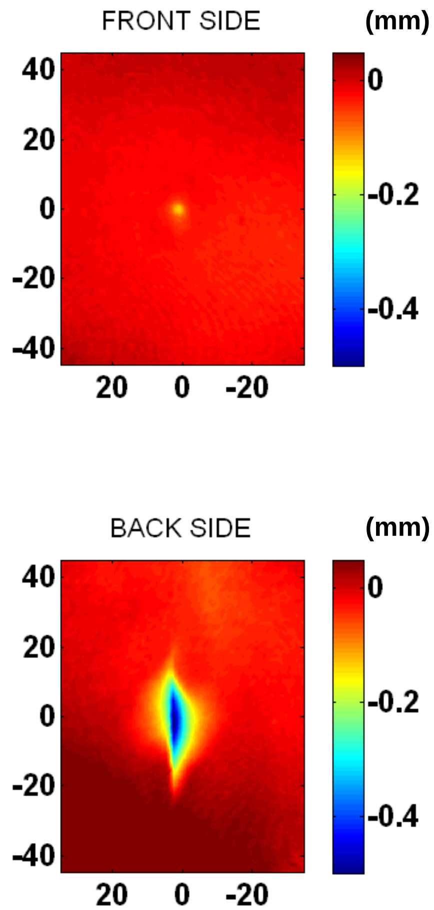




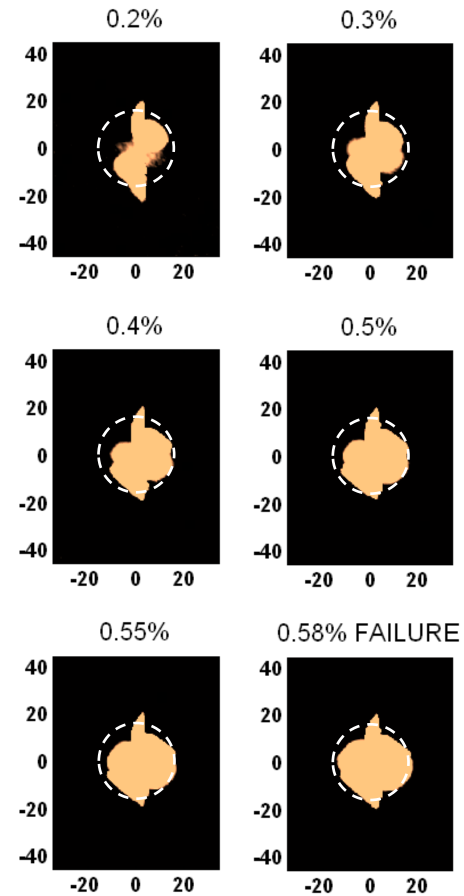
Full-field Benefits



Strain concentration

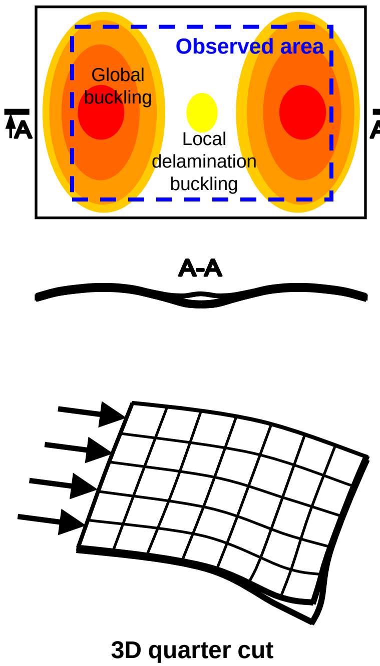


Post-impact deflections

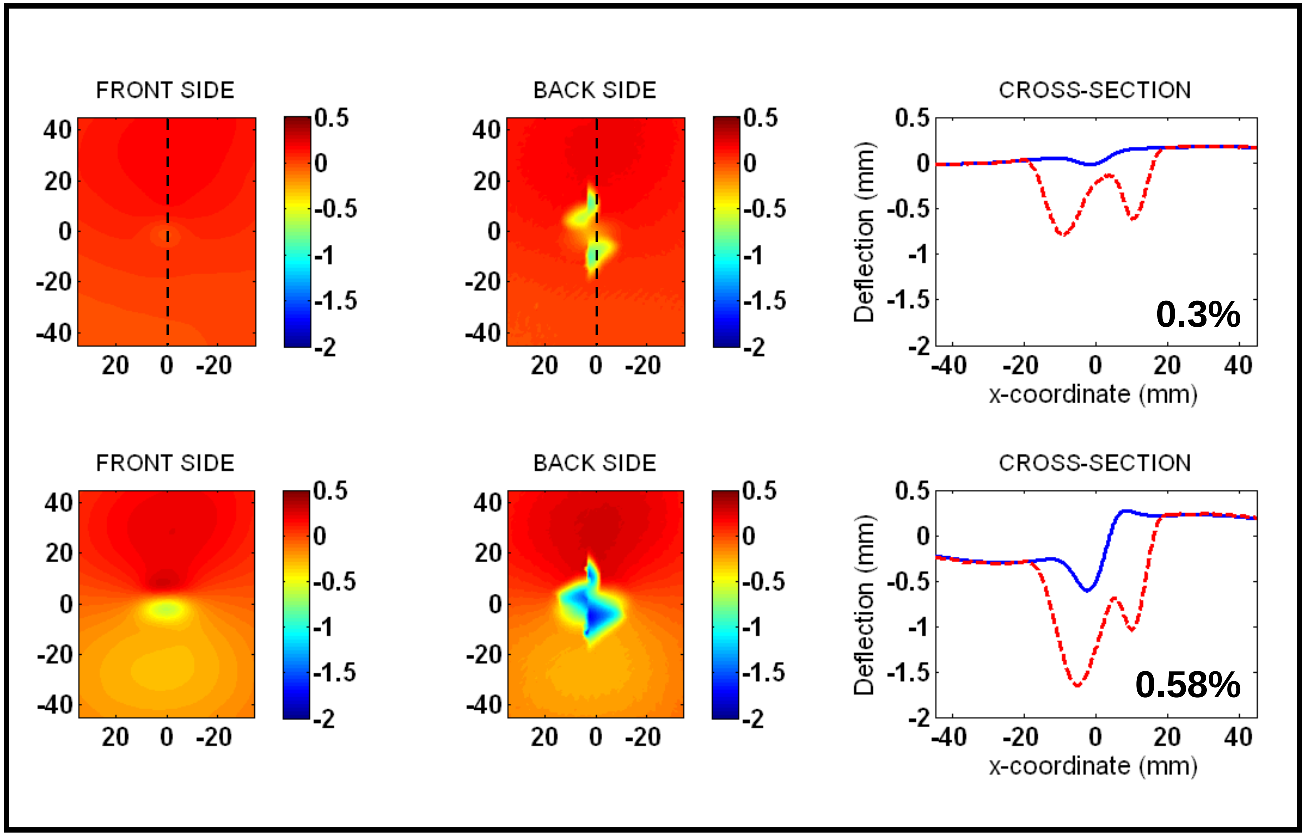


Delamination opening

Full-field Buckling Patterns



Schematic buckling

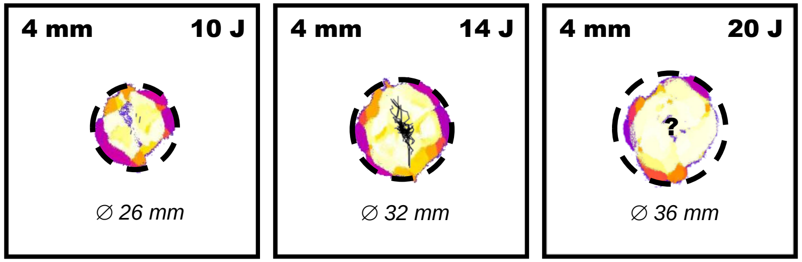


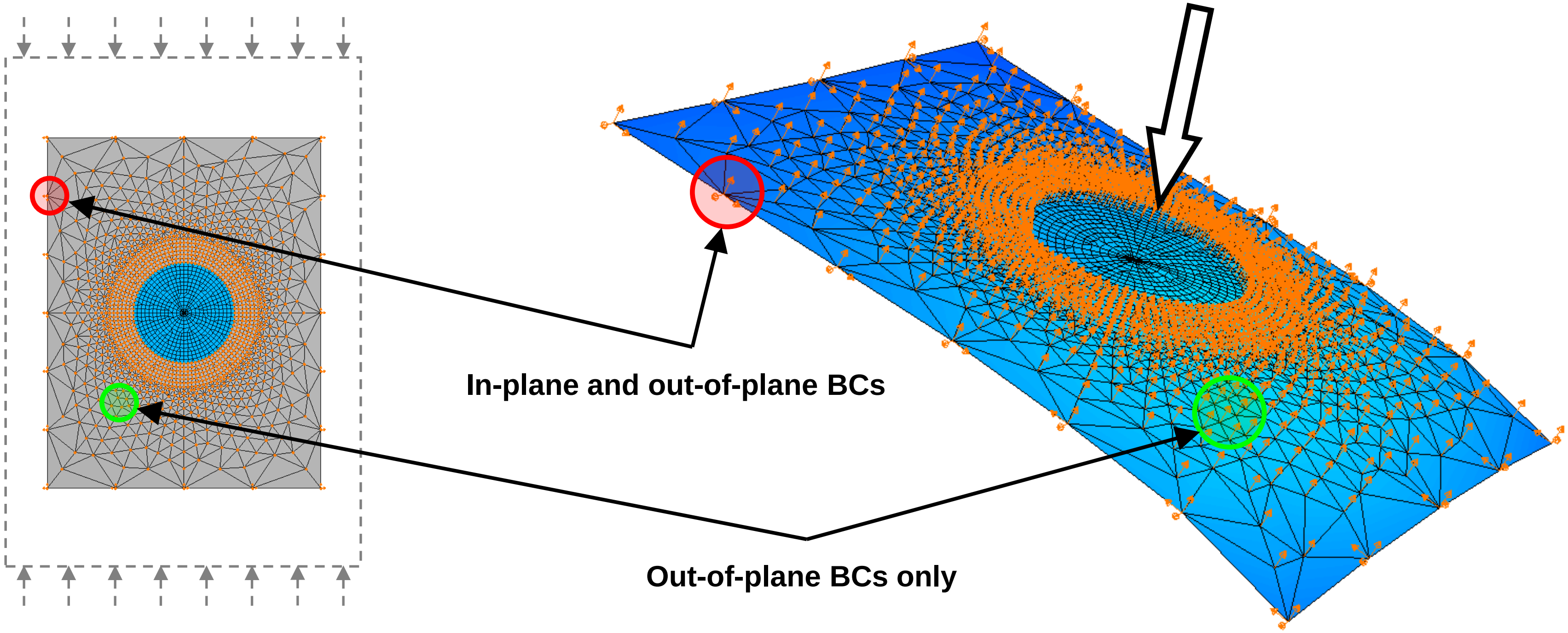
Local and global buckling development

Finite Element Model

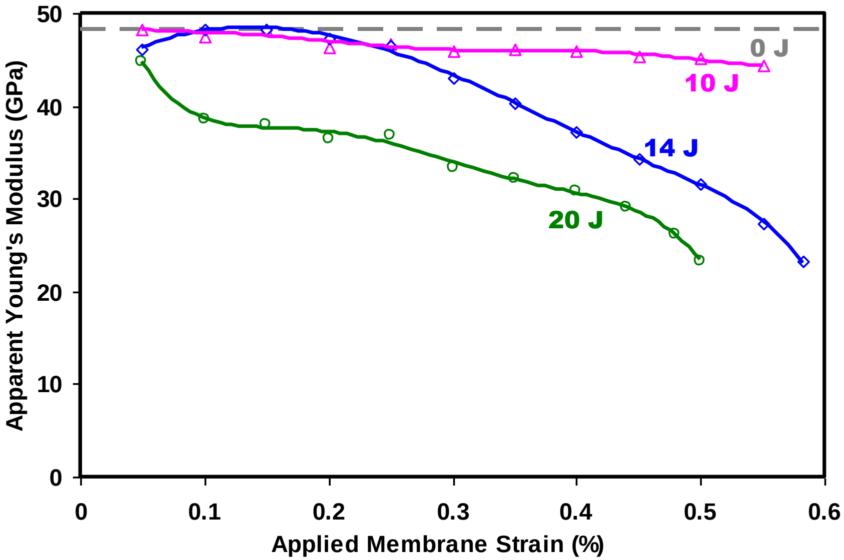
ABAQUS analysis

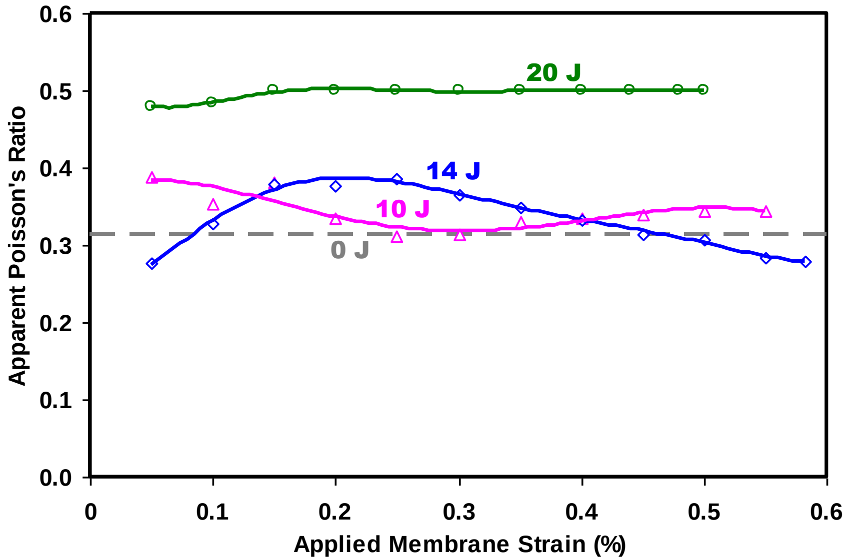
- **Homogeneous isotropic thin shell**
- **Geometrically nonlinear analysis**
- **Full-field boundary conditions**

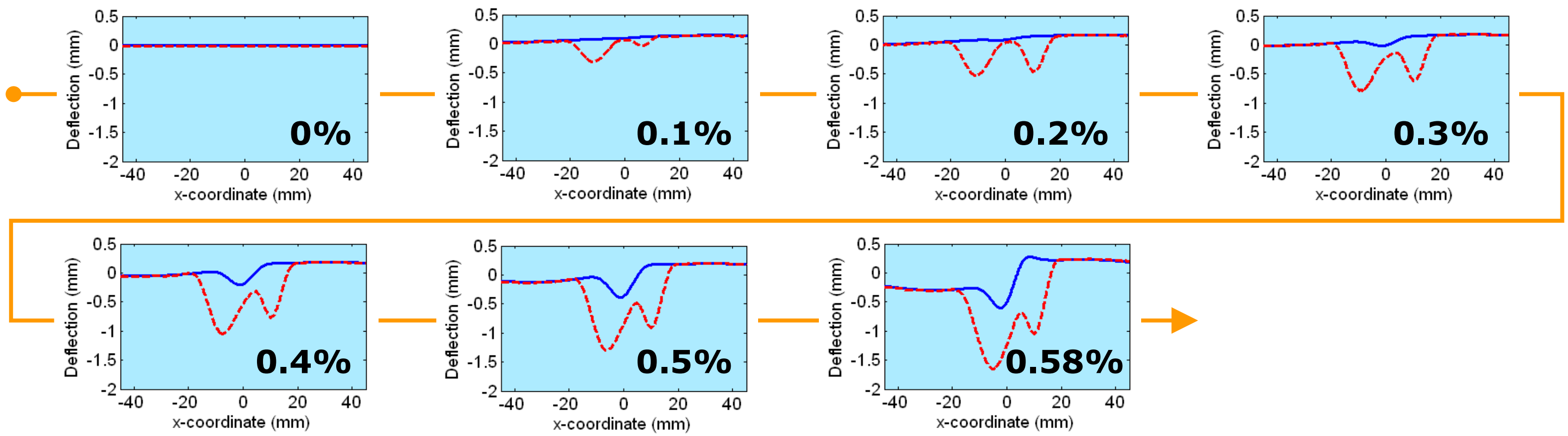




Apparent Material Parameters

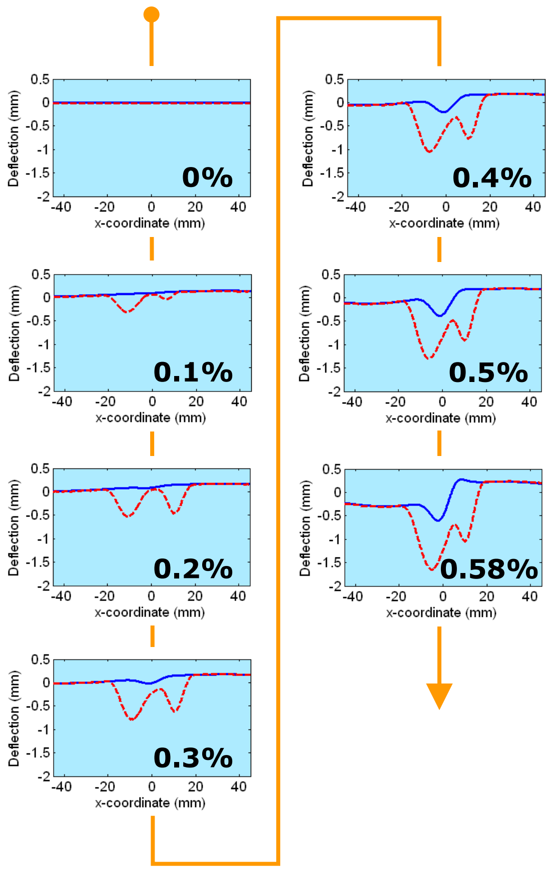




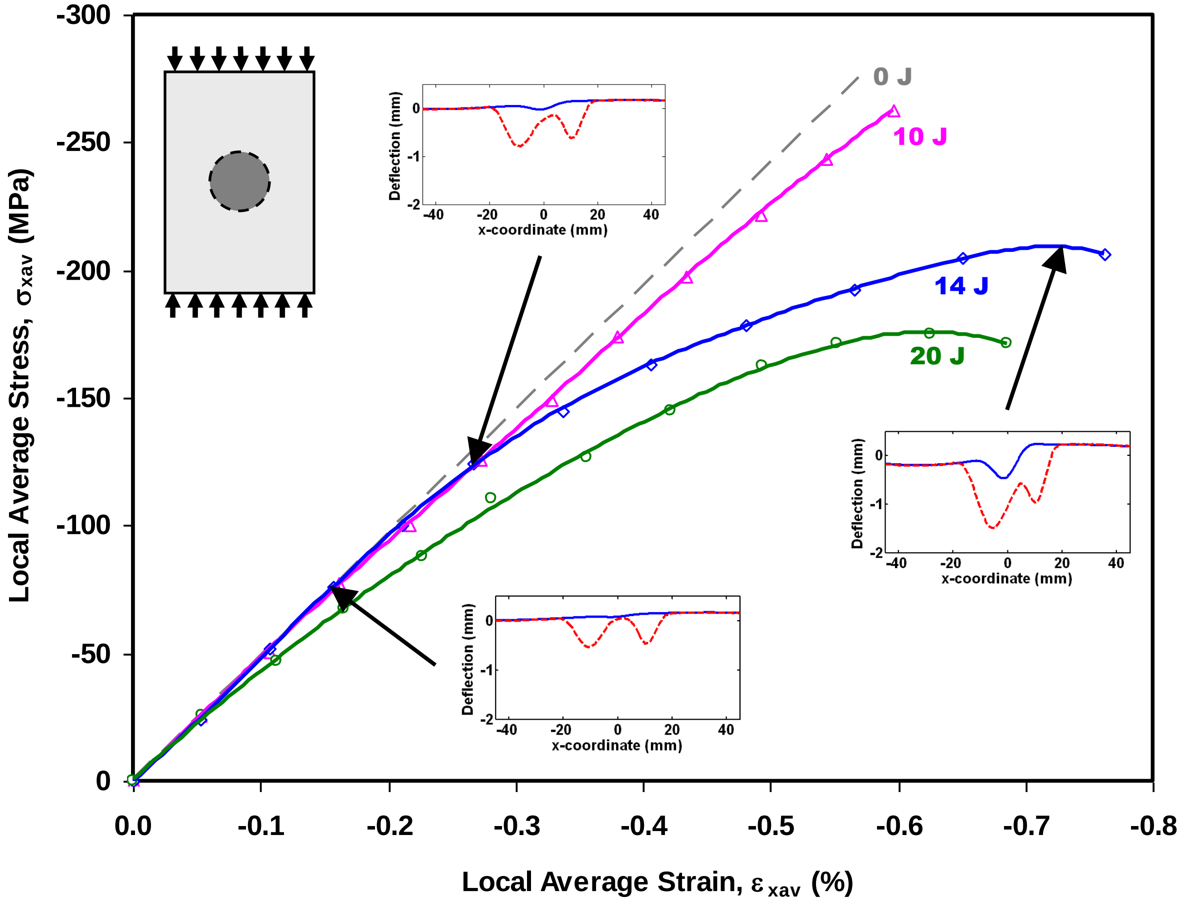


Buckling patterns at different applied strains

Apparent Material Nonlinearity



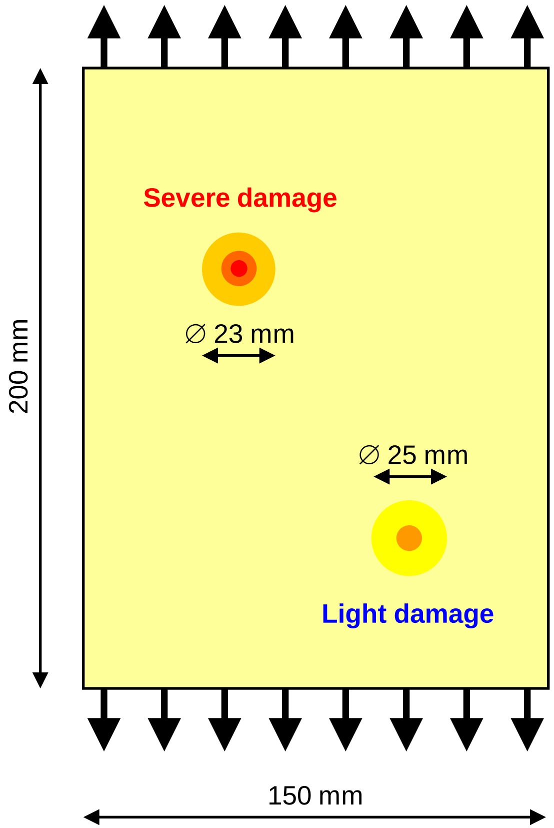
Buckling patterns at different applied strains



Comparison of apparent material behaviours

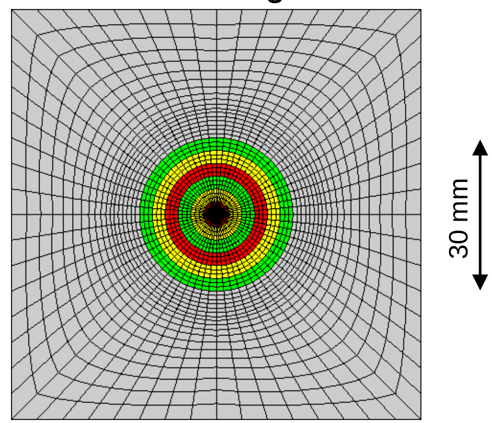
Advanced Issues

Arbitrary and Multiple Damage Location

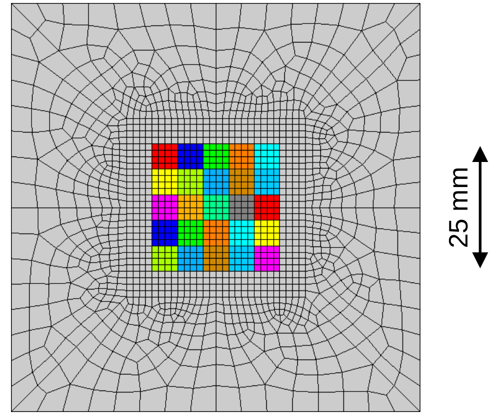


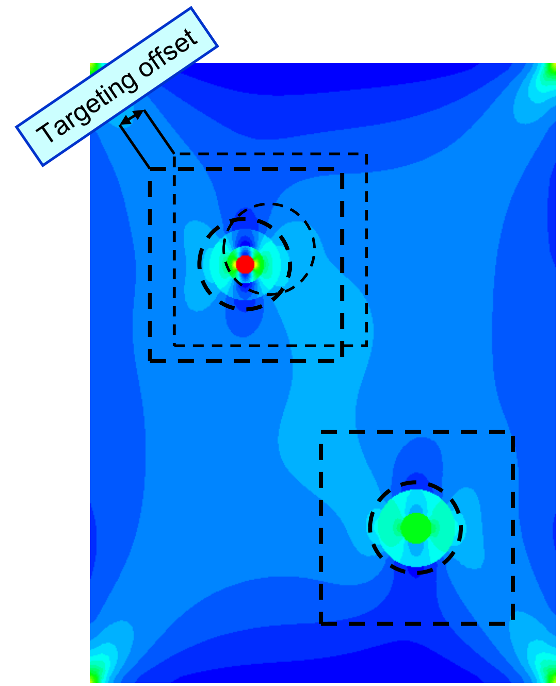
Numerically damaged plate

6 concentric rings model



5 × 5 grid model

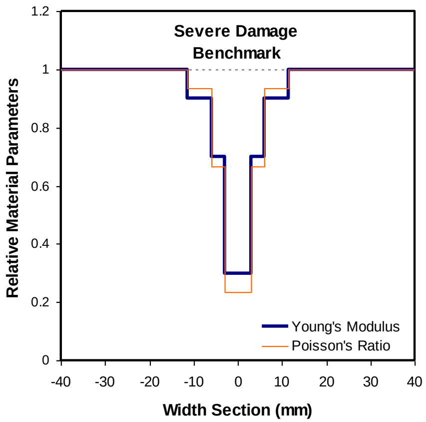


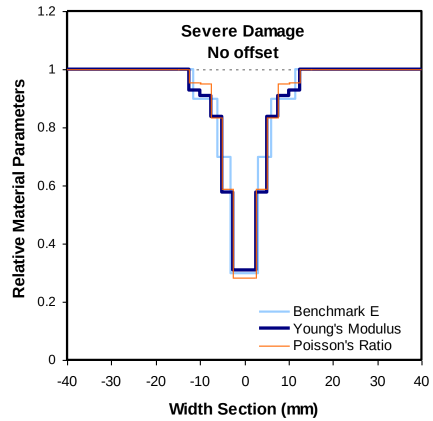


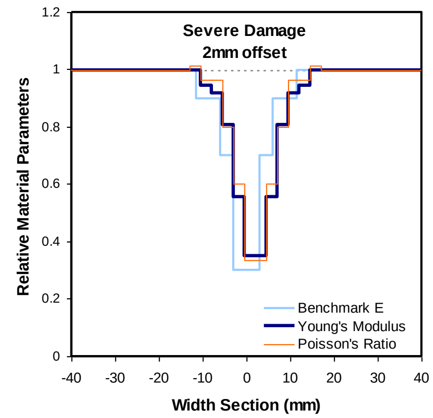
Damage localisation from strain map

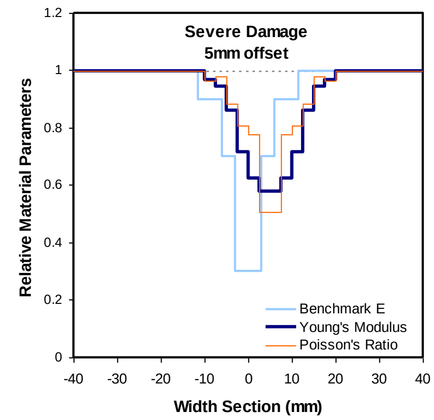
Stiffness Reconstruction

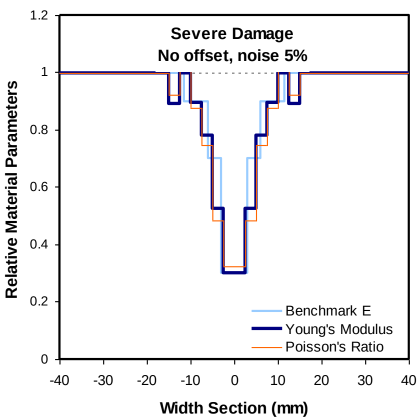
Using 6 concentric rings



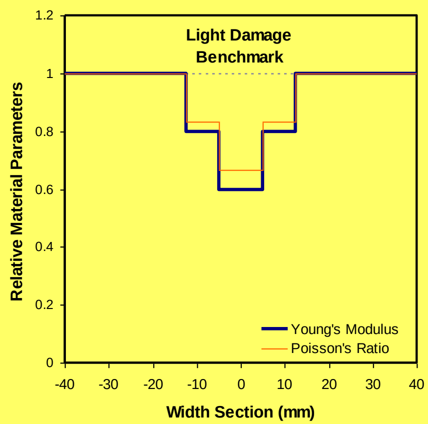


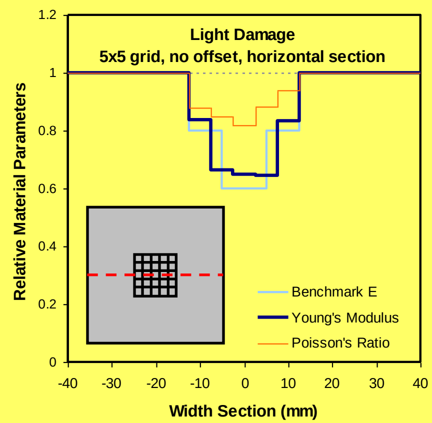


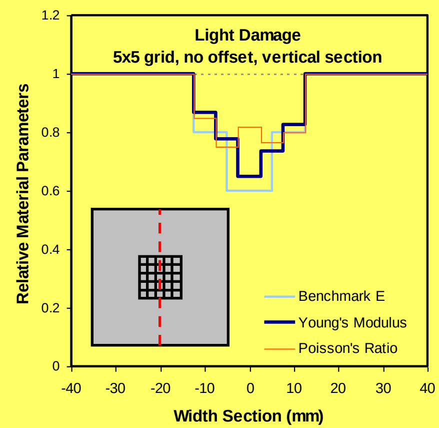




Using 5x5 grid



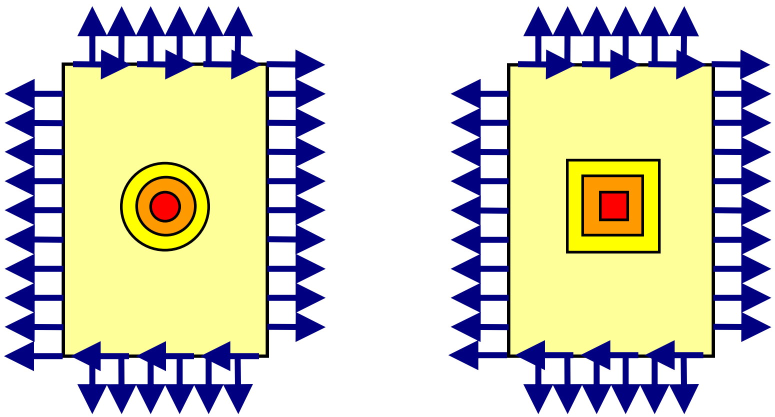




Orthotropic Materials

Findings to date

- **Load dependent material identification**
- **Geometry dependent material identification**



Numerical test

Material set	E_1	E_2	G_{12}	ν_{12}	Error in E_1	Error in E_2	Error in G_{12}	Error in ν_{12}
Inner square	25 GPa	5 GPa	3 GPa	0.35	0.2%	0.1%	2.9%	2.8%
Middle square	35 GPa	10 GPa	4 GPa	0.2	9.4%	12.6%	4.3%	65%
Outer square	50 GPa	20 GPa	5.5 GPa	0.3	8.1%	8.9%	1.5%	40%

Conclusions and Prospects

Conclusions

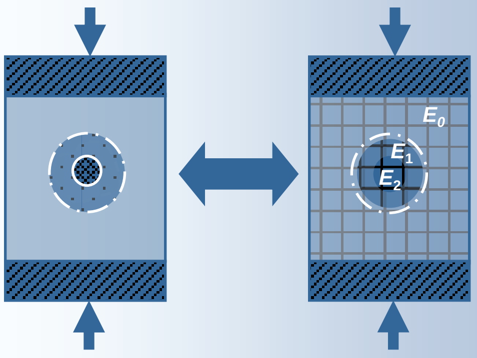
- Inverse method using FEM coupled with DIC
- Applied to impact damage in laminates
- In-plane stiffness reduction in damage zone
- Material nonlinearity described

On-going Work

- Arbitrary and multiple damage location
- Impact damage in orthotropic laminates

Possible Future Applications

- Biomechanics
- Hot objects
- Aircraft inspection



Thank you for your attention

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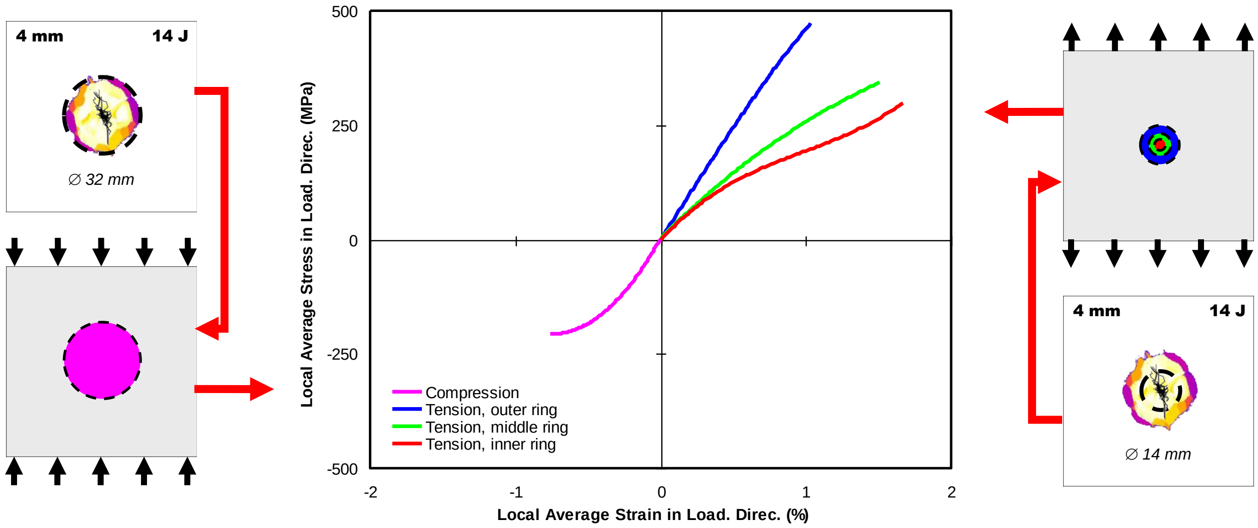

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