New Approaches for Performance Definition of Composite Materials and Structures

Thursday 11th March 2010, National Physical Laboratory (NPL)

Application of Digital Image Correlation for Monitoring Damage Progression in Composite Test Specimens

Michael R L Gower

Bio, Polymeric and Composite Materials Group

National Physical Laboratory

United Kingdom

National Physical Laboratory

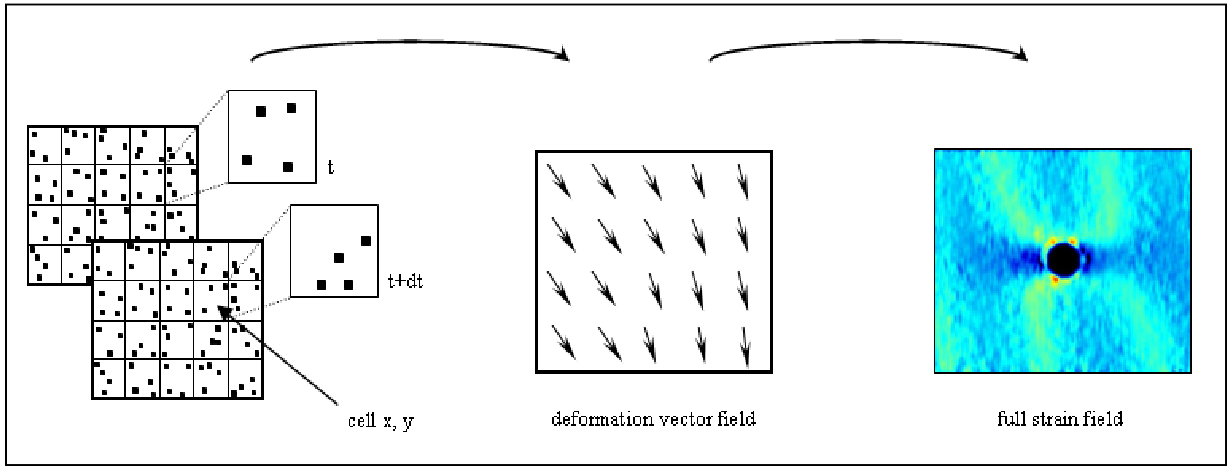
Content of presentation

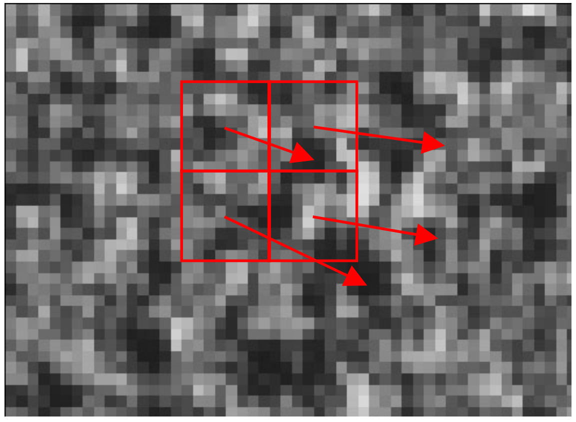
- Overview of Digital Image Correlation technique
- Examples of application
  - De-bond growth detection under CFRP repair laminates
  - Thick section laminates
- Conclusions
- Acknowledgements

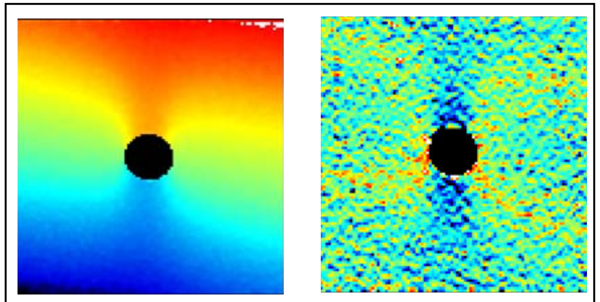
National Physical Laboratory

Digital Image Correlation (DIC)

- technique used to map full-field 2D strain distributions and 3D deformations
- displacements and strains determined by correlating position of blocks of pixels
- requires a speckle pattern (grey intensity) providing sufficient surface detail
- NPL DIC kit: LAVision®



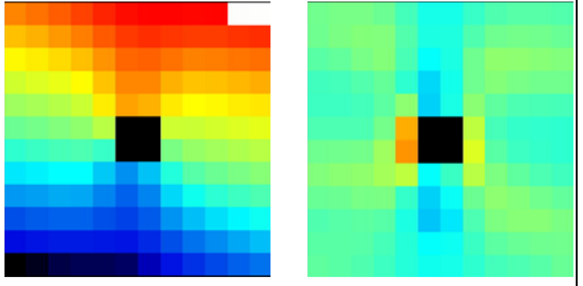




(a) (b)

(a) vector plot and (b) strain map calculated from a 16 x 16 interrogation window

Size of interrogation window	Accuracy of calculated vectors in pixels	Accuracy of calculated strain values
128 x 128	0.01 to 0.03	0.094 %
64 x 64	0.02 to 0.05	0.3 %
32 x 32	0.05 to 0.2	1.25 %
16 x 16	0.1 to 0.3	5 %

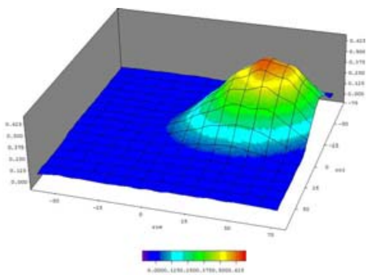


(a) (b)

(a) vector plot and (b) strain map calculated from a 128 x 128 interrogation window

Application 1

De-bond Growth Detection Under CFRP Repairs



Composite over-wrap repairs

• Composite over-wrap repairs used in the oil and gas industry

- repair of corroded pipe-work and pipelines

- applied to pipe systems that are leaking, i.e. a through pipe wall defect, usually caused by excessive internal corrosion.

• Repair materials

- multi-axial fabrics: glass, carbon, aramid fibres

- resins (matrix): epoxy, polyester, vinyl ester, polyurethane (good chemical resistance to hydrocarbons (e.g. alkanes, cyclo-alkanes)),

- adhesives: epoxy, methacrylates, laminate resin systems

• Hand applied either using wet lay-up systems or prefabricated rolls of composite reinforcement bonded together on-site and allowed to cure

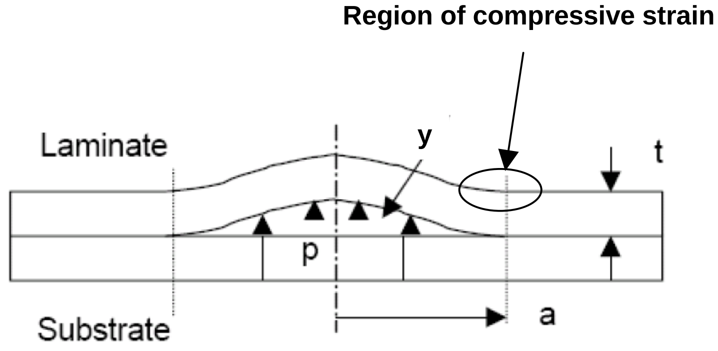
Objectives of application

Work undertaken within TSB Project 'ACLAIM' (2006-2009) (NPL, ESR Technology, Doosan Babcock) – Case Study 5: Over-wrap repairs

- Steel plates with defined circular hole overlaid with carbon fibre composite repair
- Representative of pipe repairs
- Plates were aged in sea water and then pressure tested
- Project investigated the use of DIC to detect de-bond growth, stability of growth and measurement of out-of-plane deformation

Measurements as a function of applied pressure:

- 2D strain field on the surface of the repair laminate
  - track position of region of compressive strain in the vicinity of de-bond front
- derivation of 3D displacement vectors to yield Vz
  - comparison to analytical solution



$$y(r) = P\left[\frac{3(1-\nu^2)}{16\,Et^3}(a^2-r^2)^2 + \frac{3}{8Gt}(a^2-r^2)\right]$$

Where:
y*= *vertical displacement
***r* = radial distance**
***a* = radius of de-bond area**
υ = Poisson's ratio
***E* = Young's modulus of the composite**
***G* = Shear modulus of the composite**

National Physical Laboratory

Test specimens

- Test specimen details:

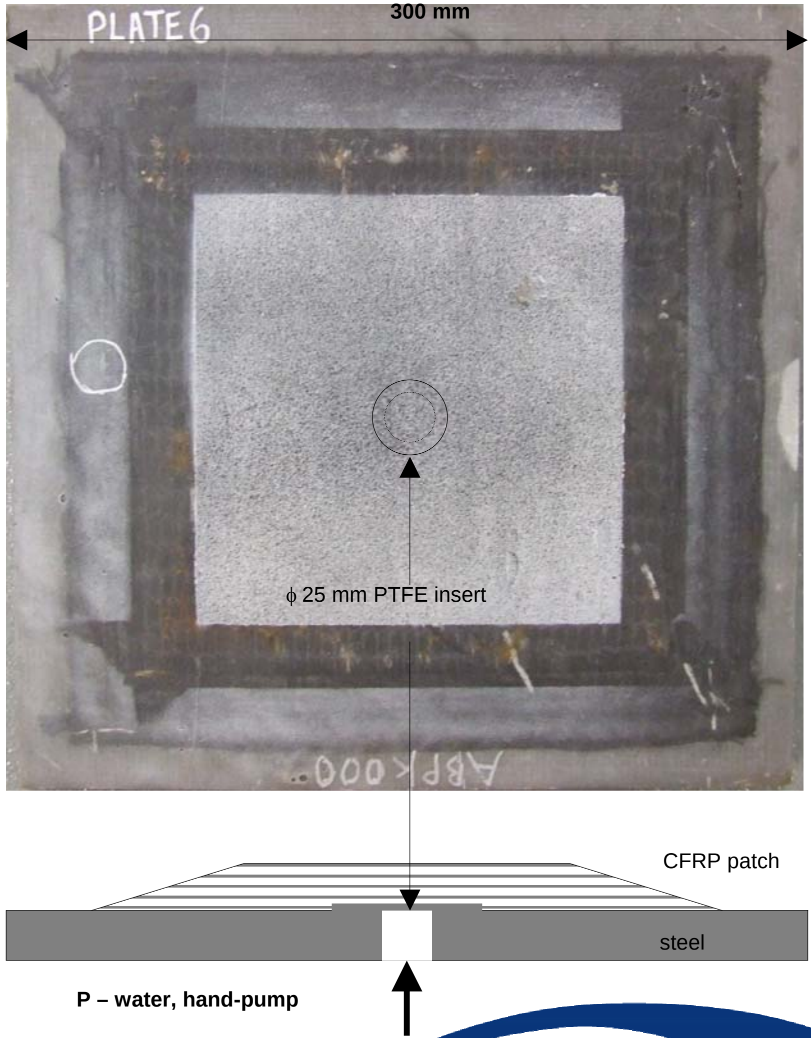
  - 300 mm square, 8 mm thick steel plate

  - central through hole was threaded ¼ inch BSP

  - effective hole diameter of 13 mm

  - central hole covered with 100 μm thick 25 mm diameter PTFE disk to avoid run through of the adhesive and to define an effective de-bond diameter

  - repair laminate - one layer of woven glass and four layers of hand laid quadraxial carbon fibre tow all impregnated with an ambient cure epoxy – effective thickness ~ 6 mm



Experimental set-up

Equipment

- LAVision DIC system
- Cameras: 2 x Imager Compact

(1280 x 1024 pixel)

- 3D set-up
- Hand operated pump
- 2 pressure gauges – voltage out to DIC

Specimen Preparation

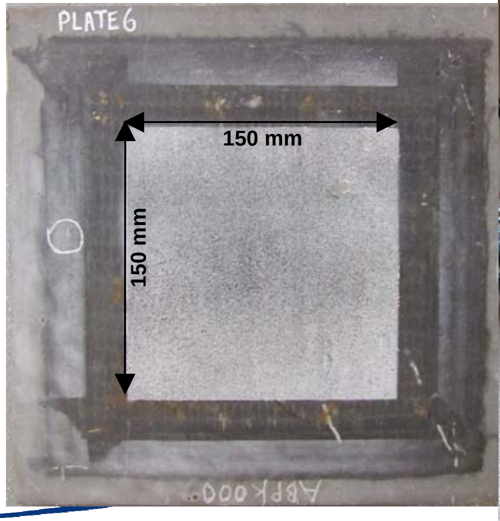
- AOI sprayed with white, grey and black paint

Field of View

- 150 x 150 mm,
- scaling ~ 130 µm/pixel

DIC Analysis

- Cross-correlation between 2 images
- Interrogation window: 128 x 128 to 64 x 64 multi pass, 50 and 75 % overlap
- Surface height calculation and subsequent 3D deformation analysis



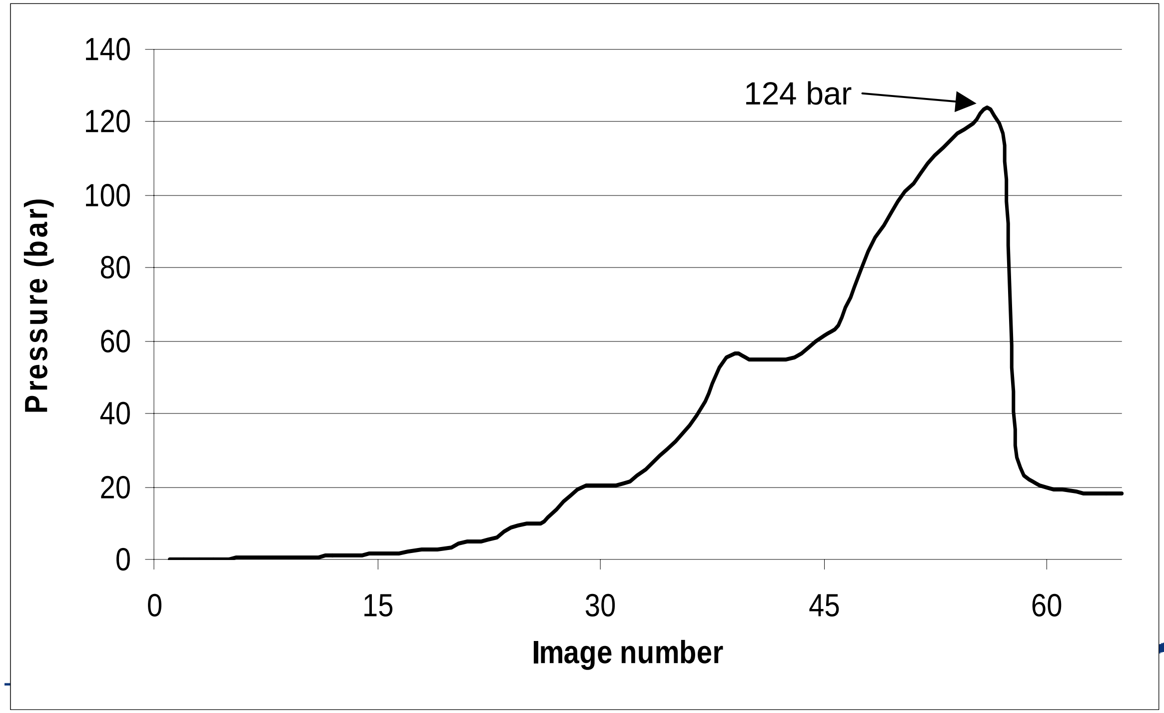
Test procedure

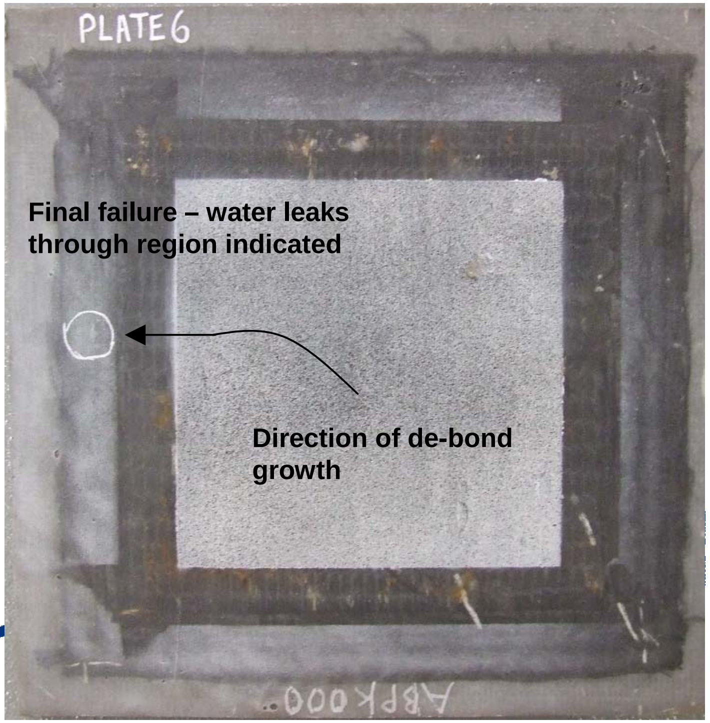
• Samples pressurised to failure using hand-pump – no control over pressure ramp rate!

• Images recorded at 1 Hz throughout duration of test

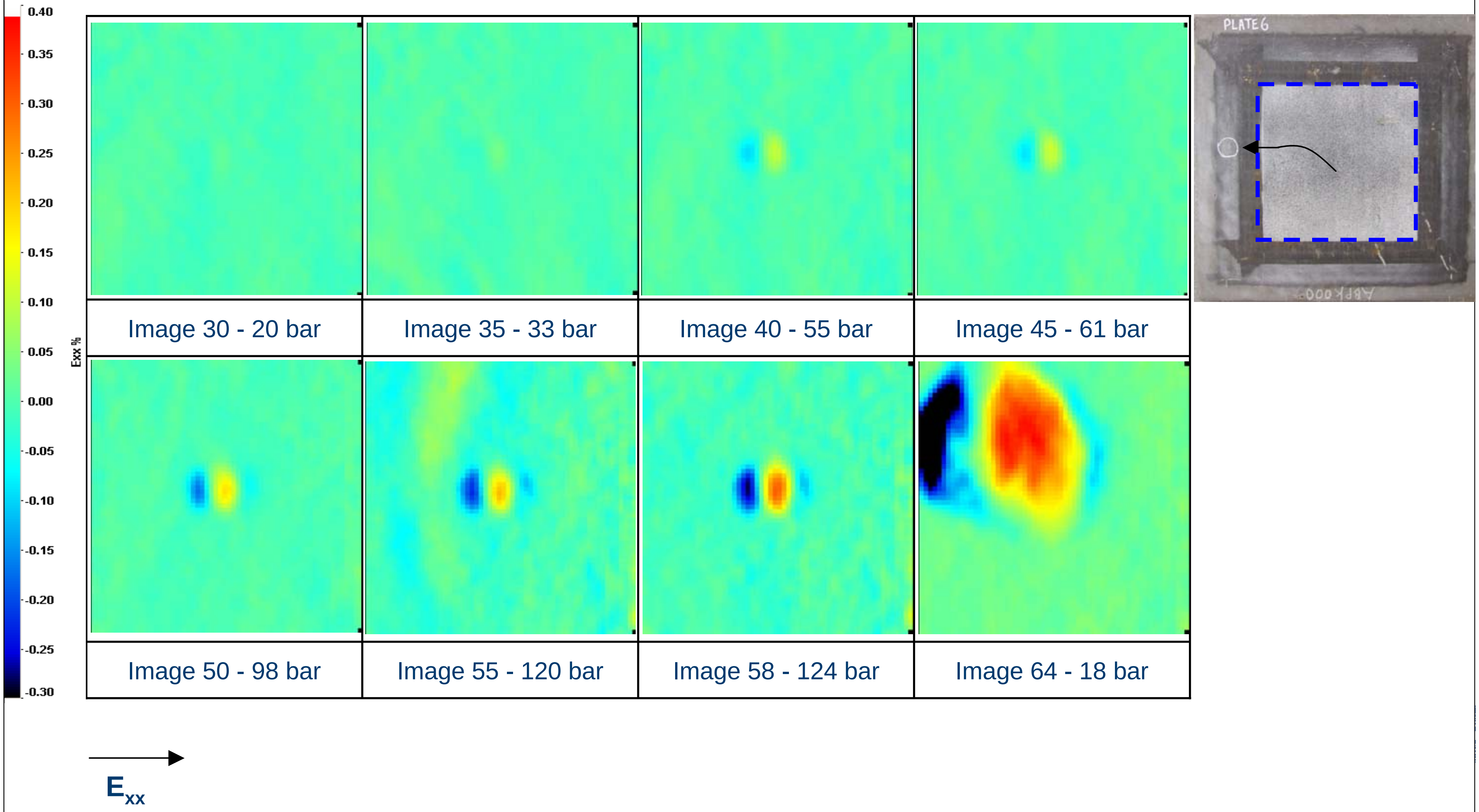
• Pressure recorded as a function of image number

• Final failure observed at a pressure of 124 bar

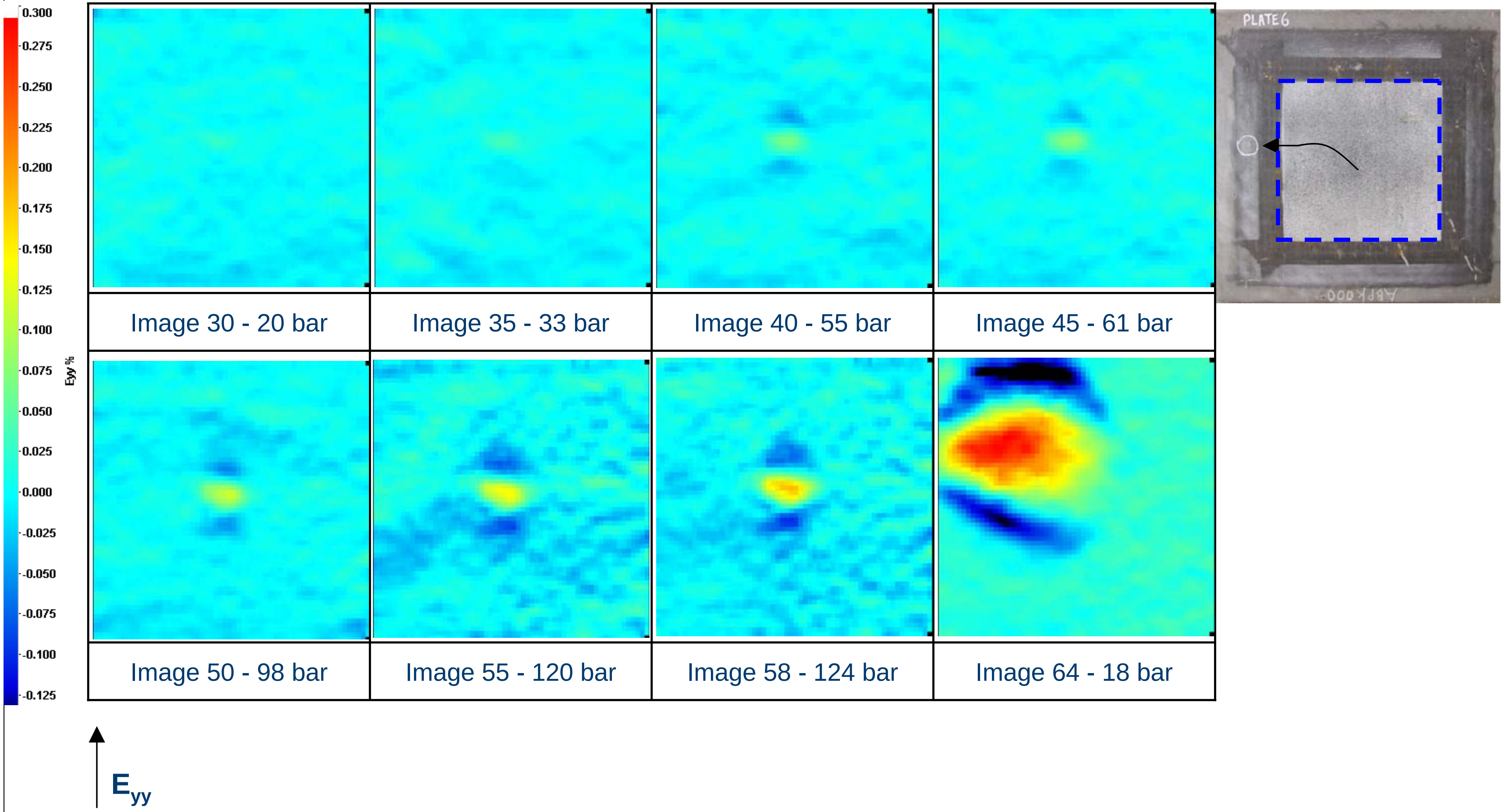




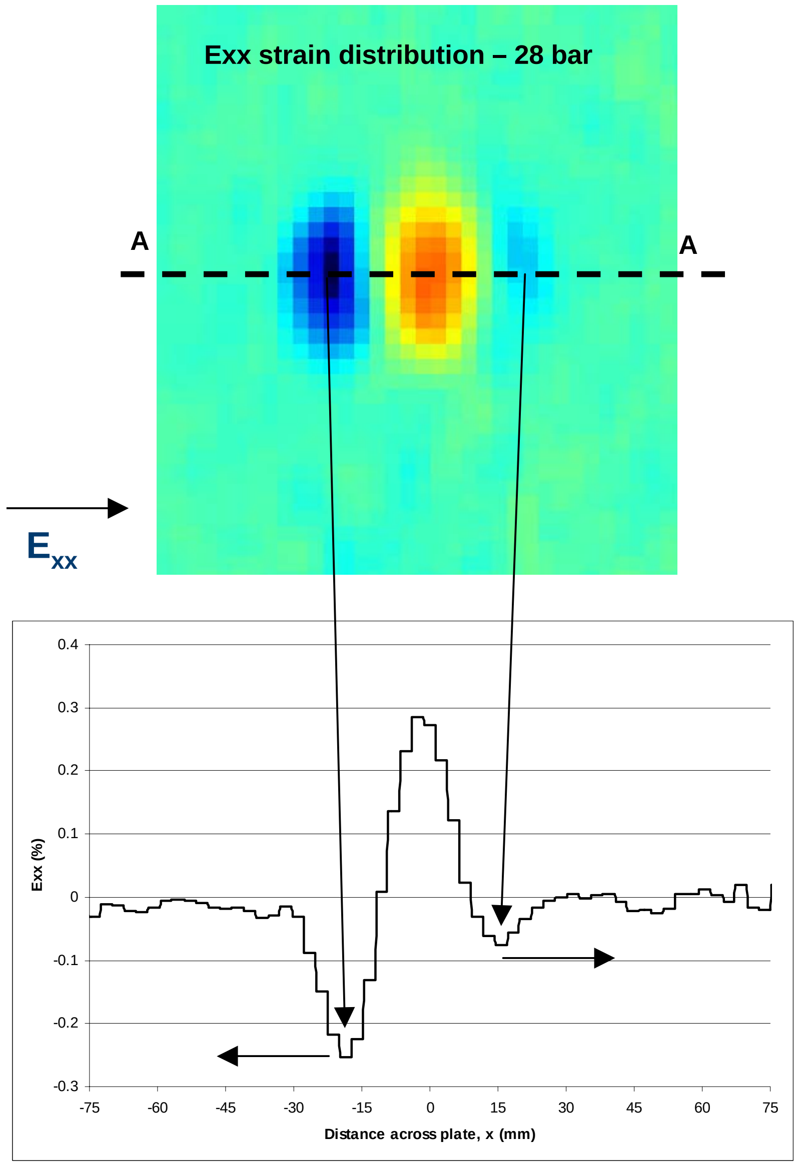
Strain results – E_{xx} 2D



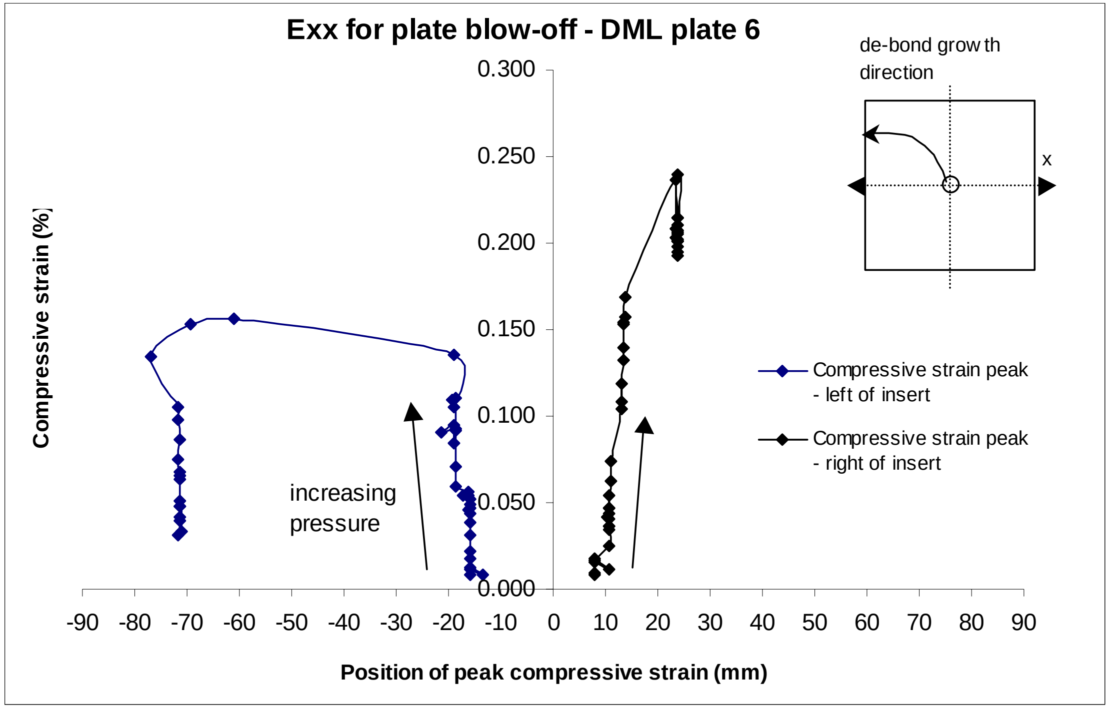
Strain results – E_{yy} 2D

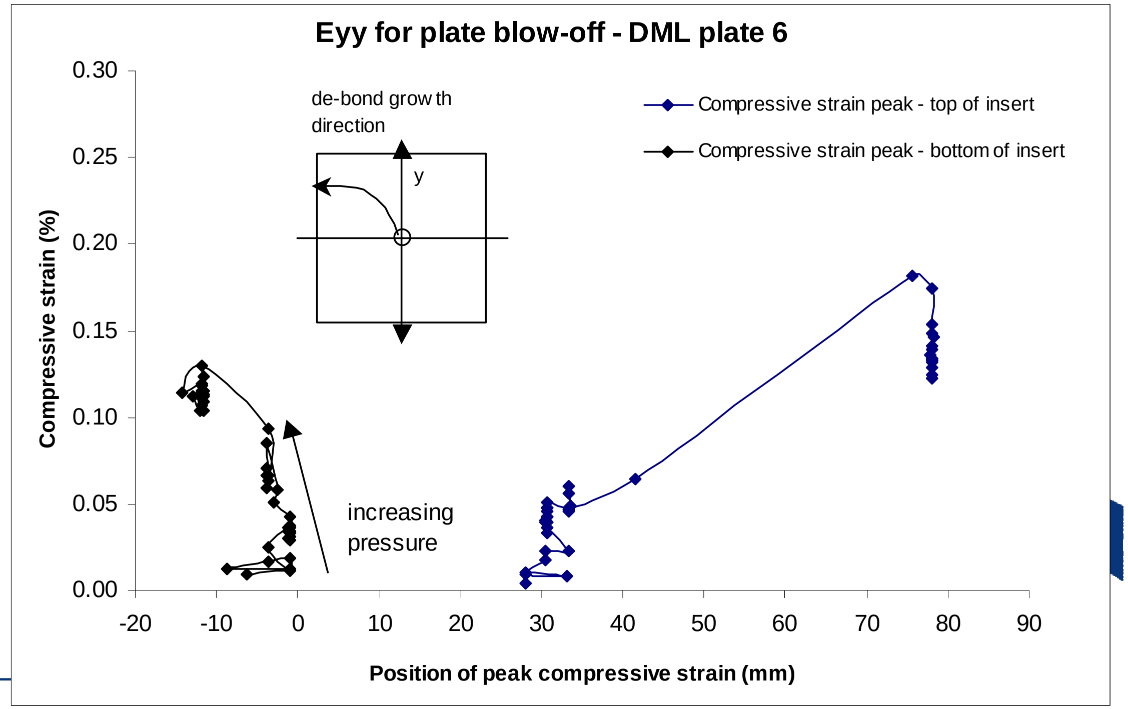


Strain results – 2D



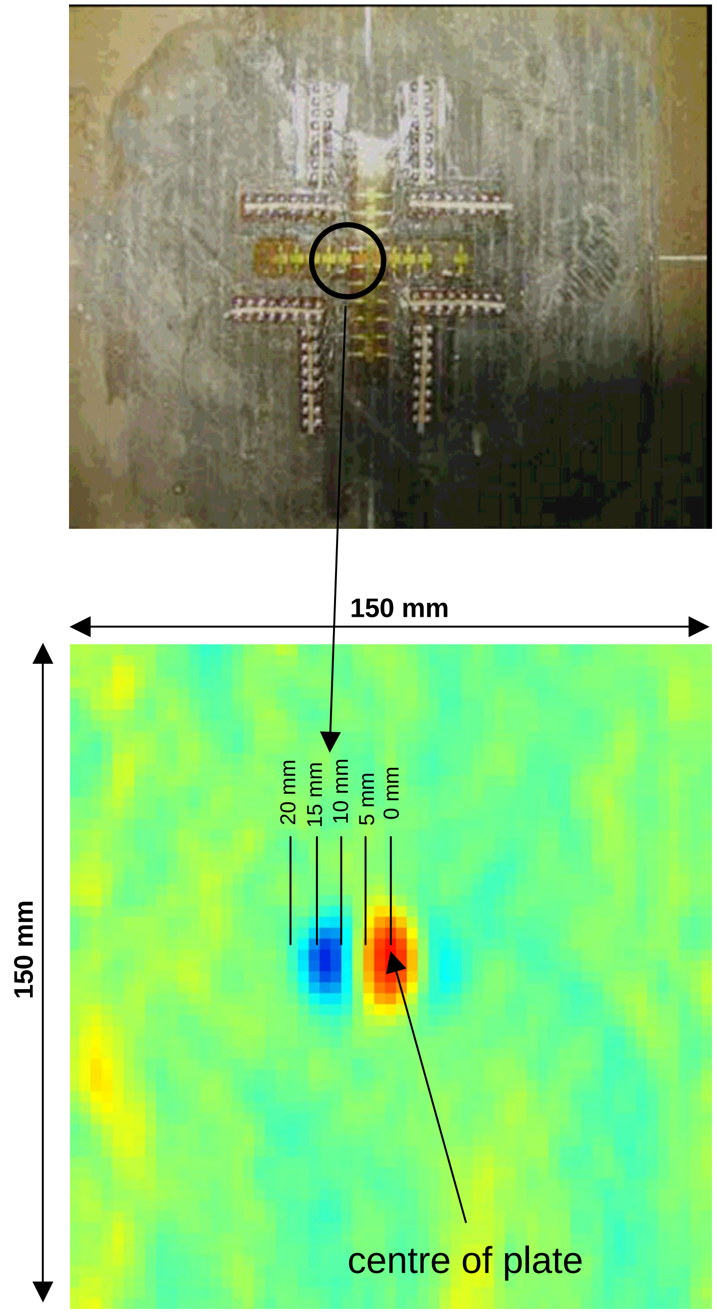
Exx strain profile along AA (28 bar)

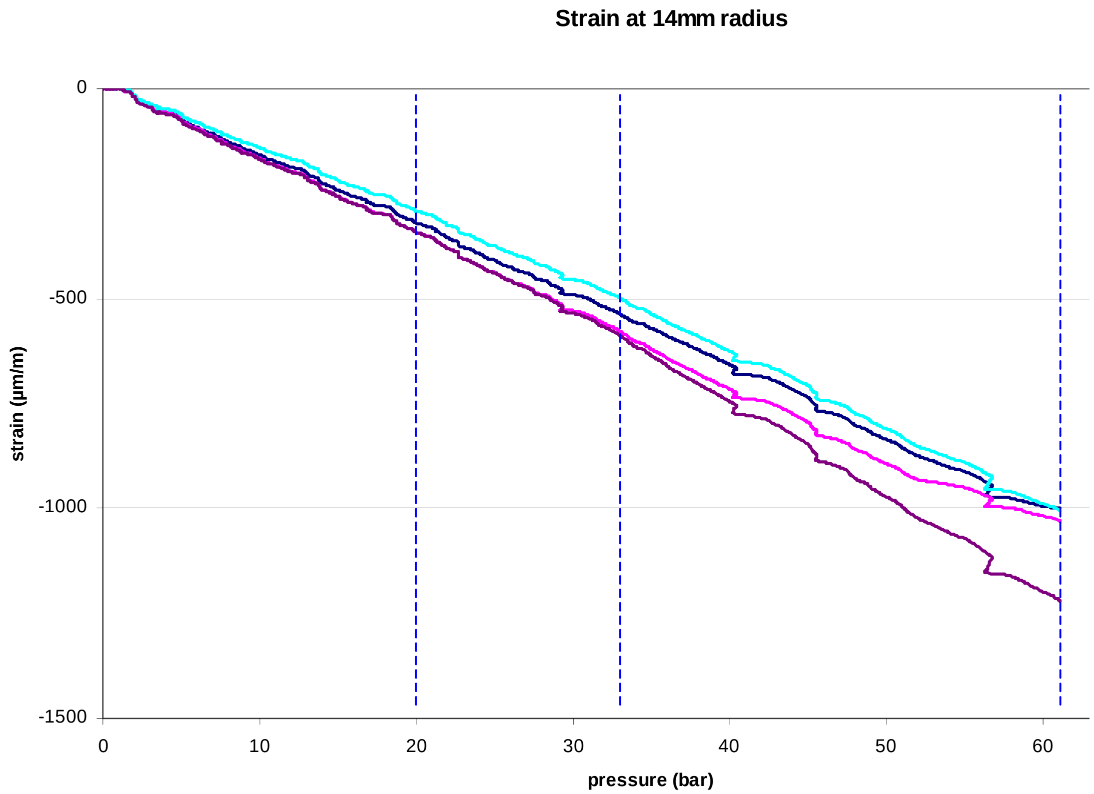




Strain gauge vs. DIC data

Strain gauges in XY array bonded to repair laminate

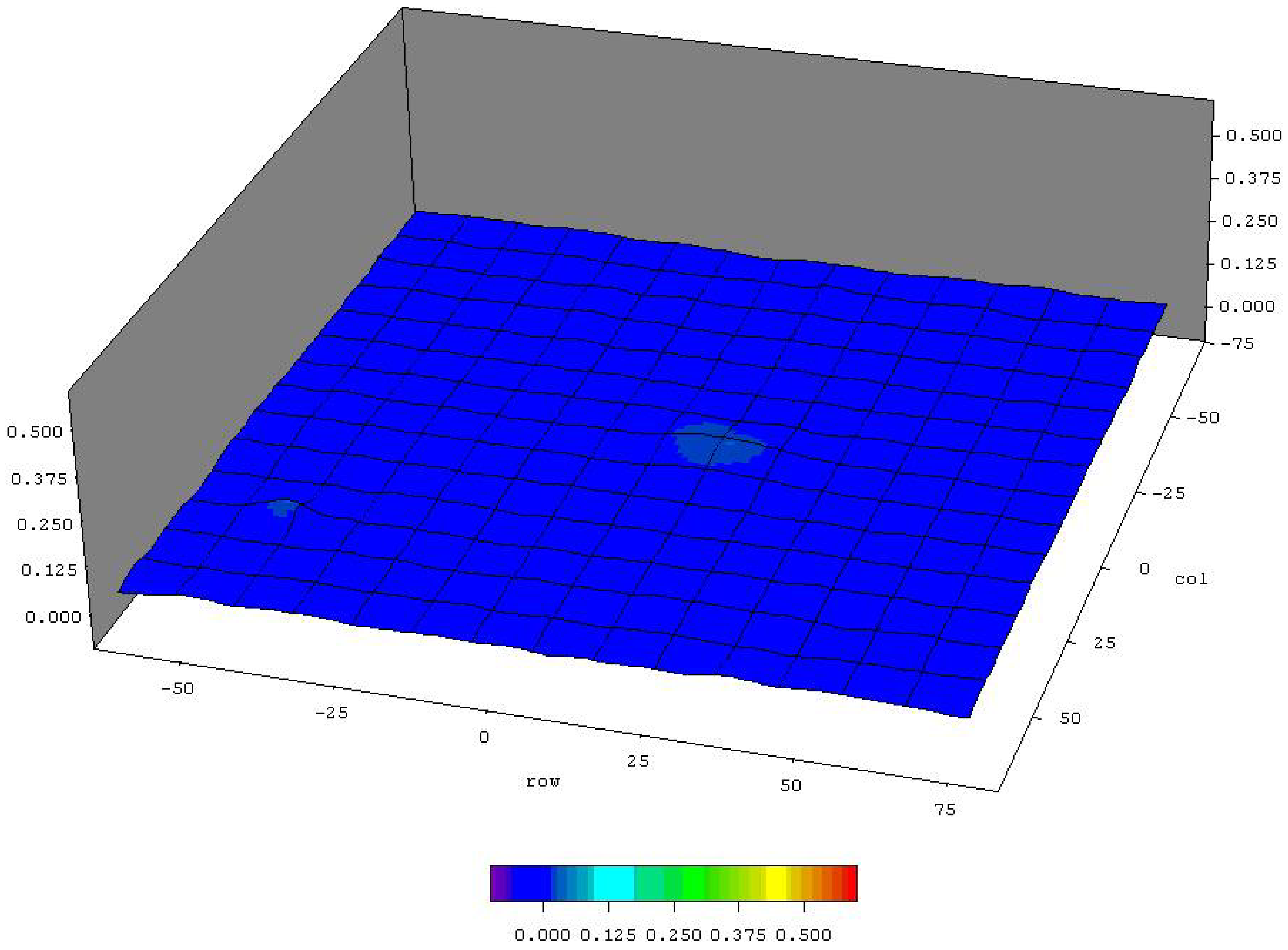




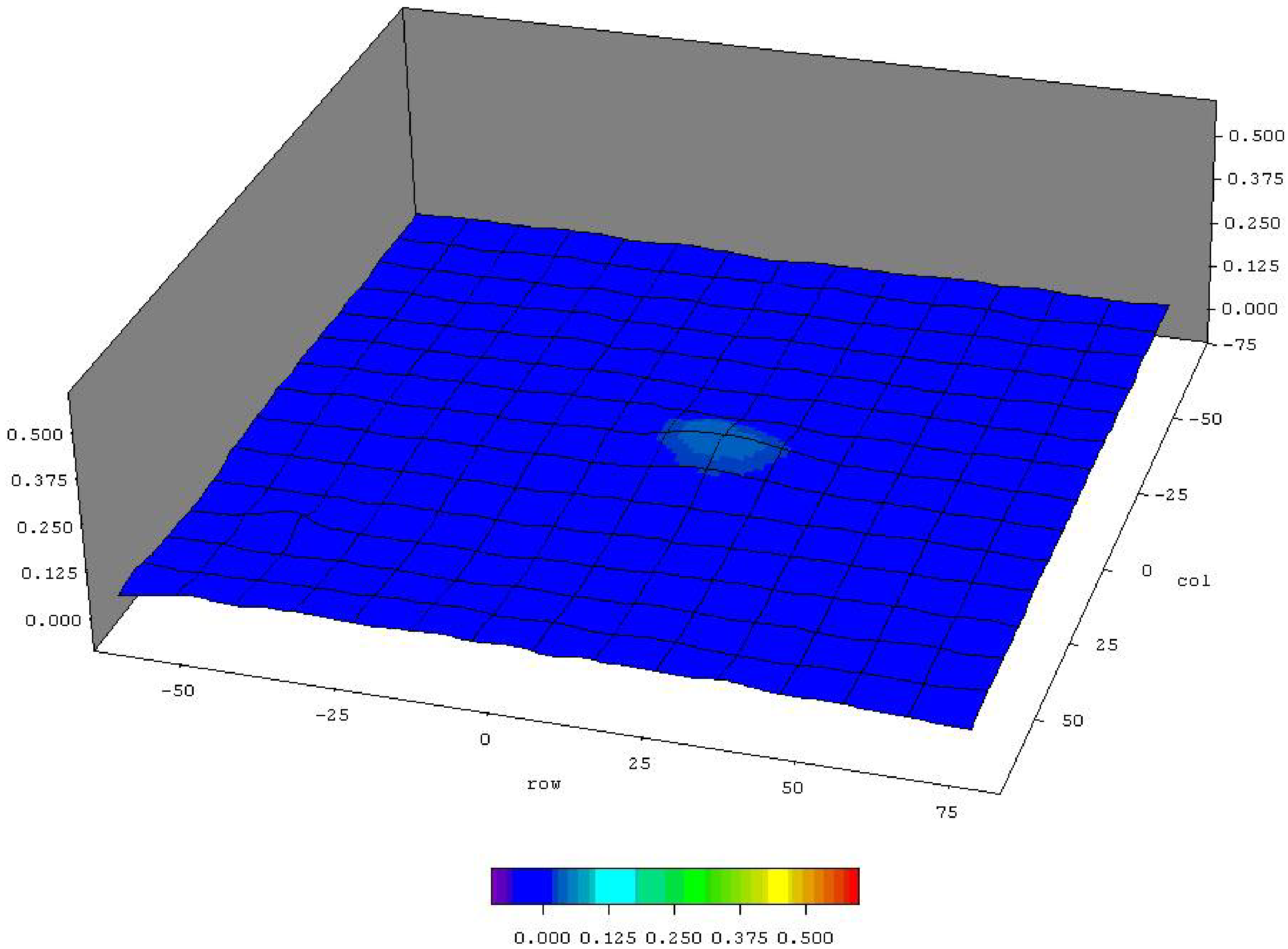
Comparison of Exx (%) from strain gauges and DIC at 14 mm radius

Pressure (bar)	Strain gauge	DIC
20	0.26	0.22
33	0.51	0.43
62	1.1	0.94

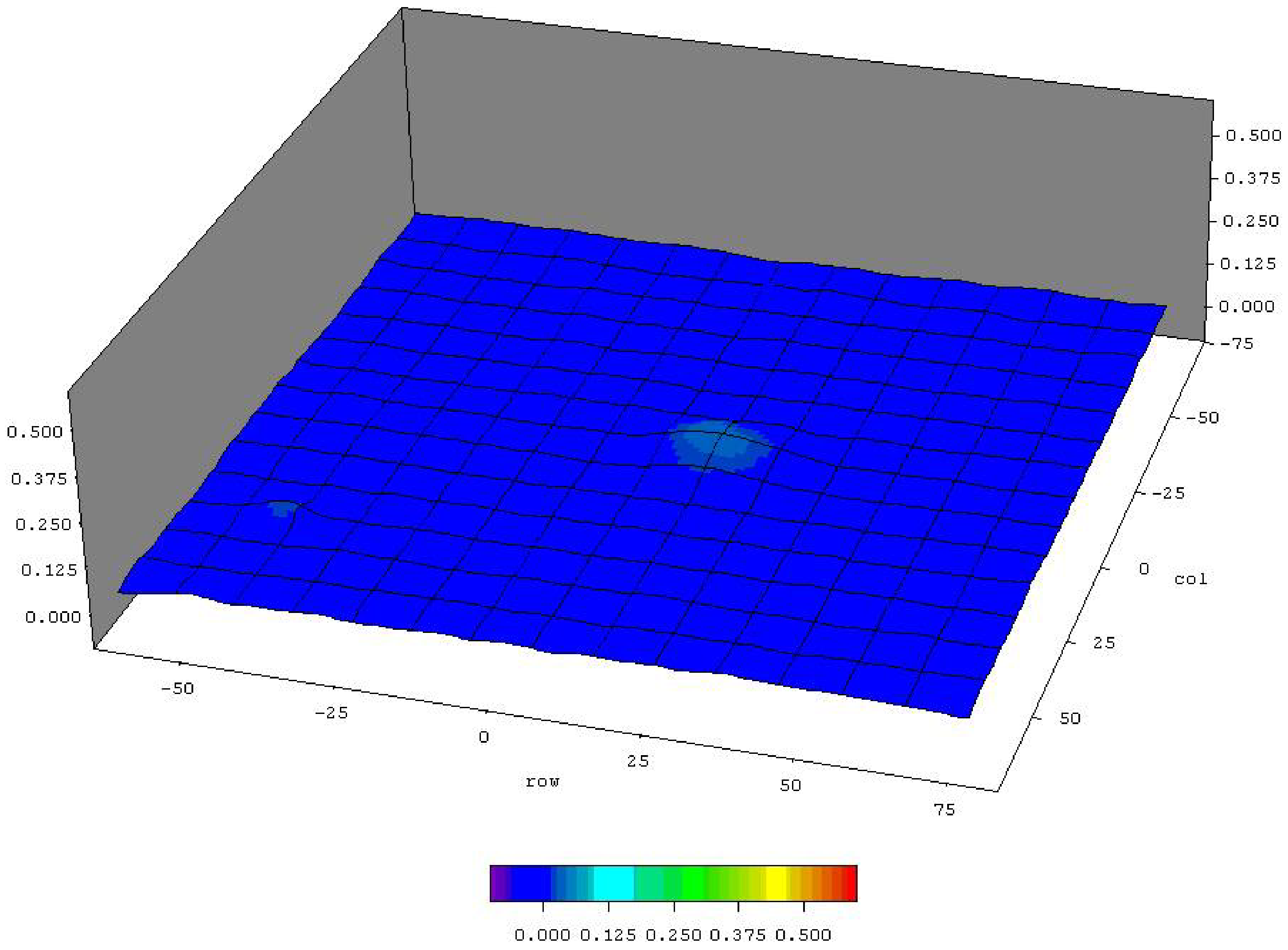
3D results: 55 bar V_z= 0.039 mm (theoretical = 0.05 mm)



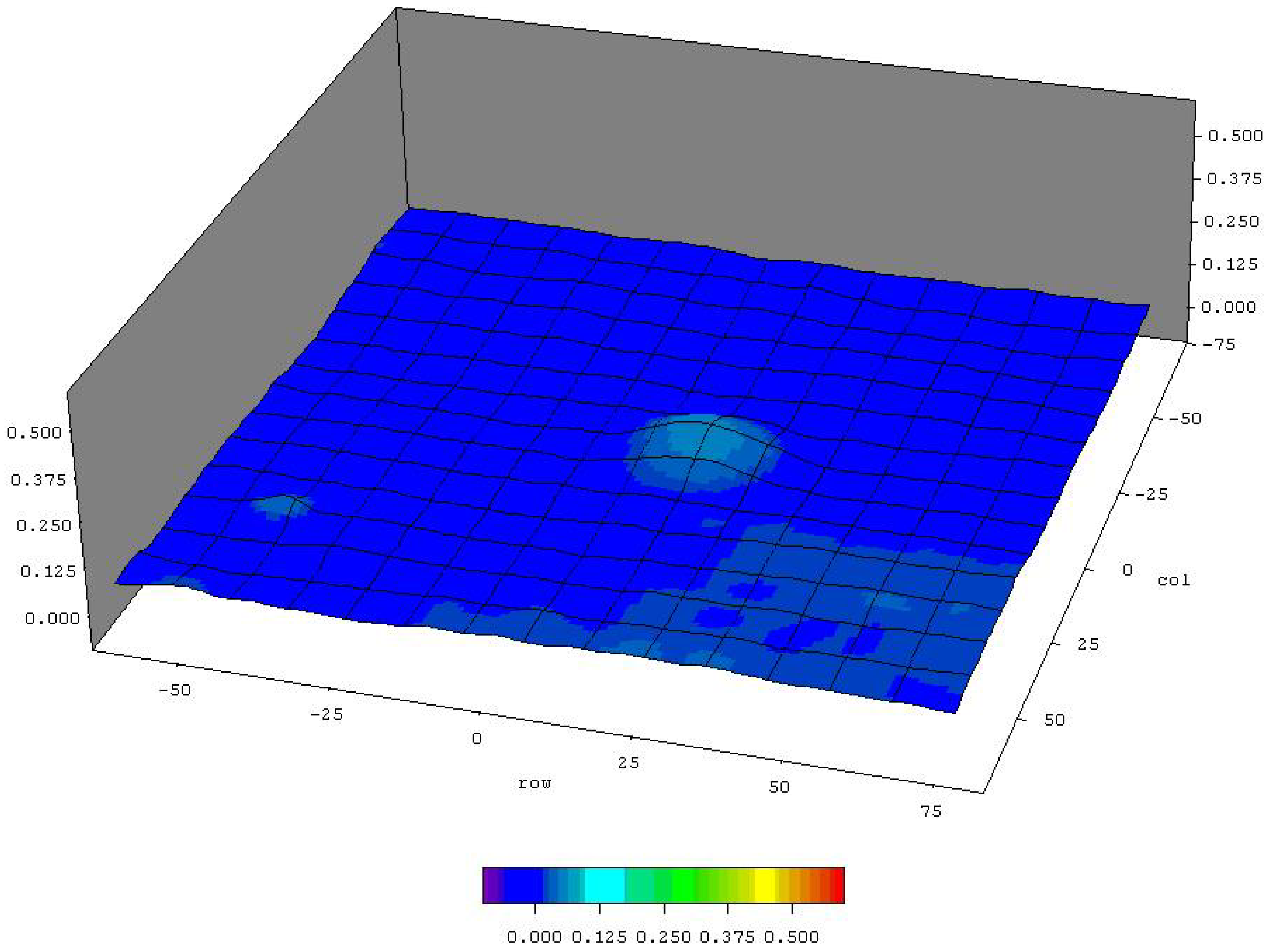
3D results: 61 bar V_z= 0.042 mm (theoretical = 0.06 mm)



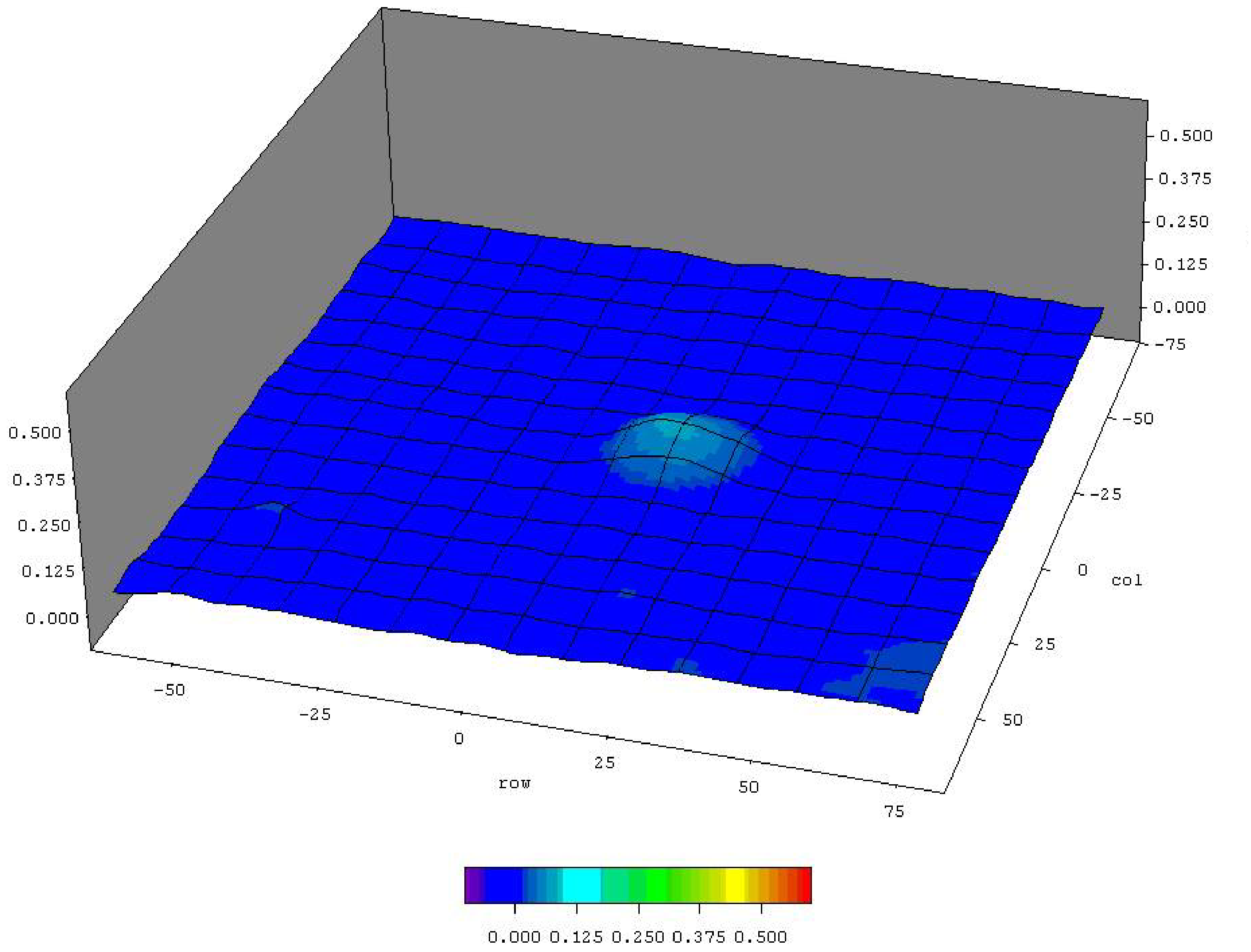
3D results: 98 bar V_z= 0.074 mm (theoretical = 0.12 mm)



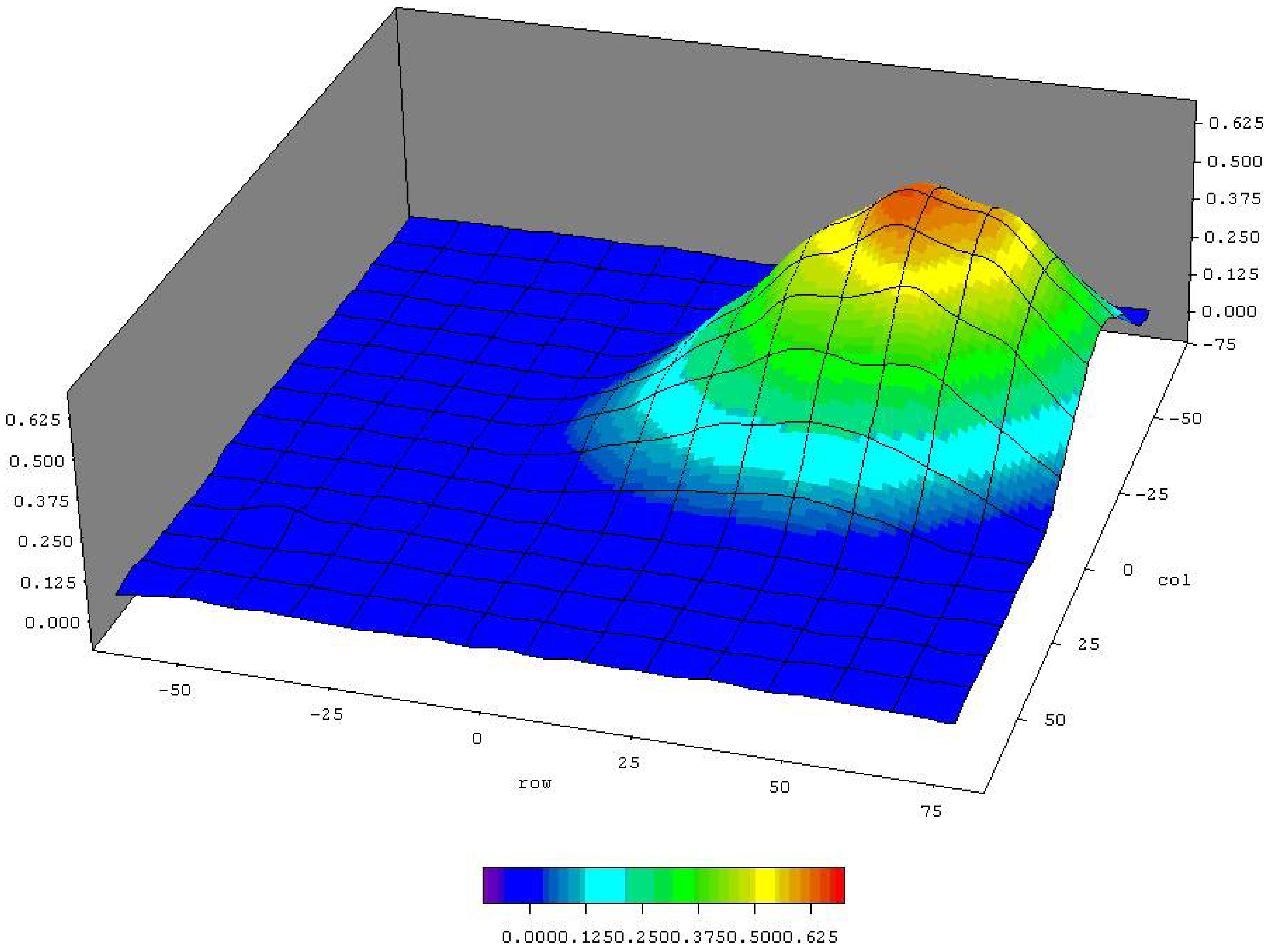
3D results: 120 bar V_z= 0.076 mm



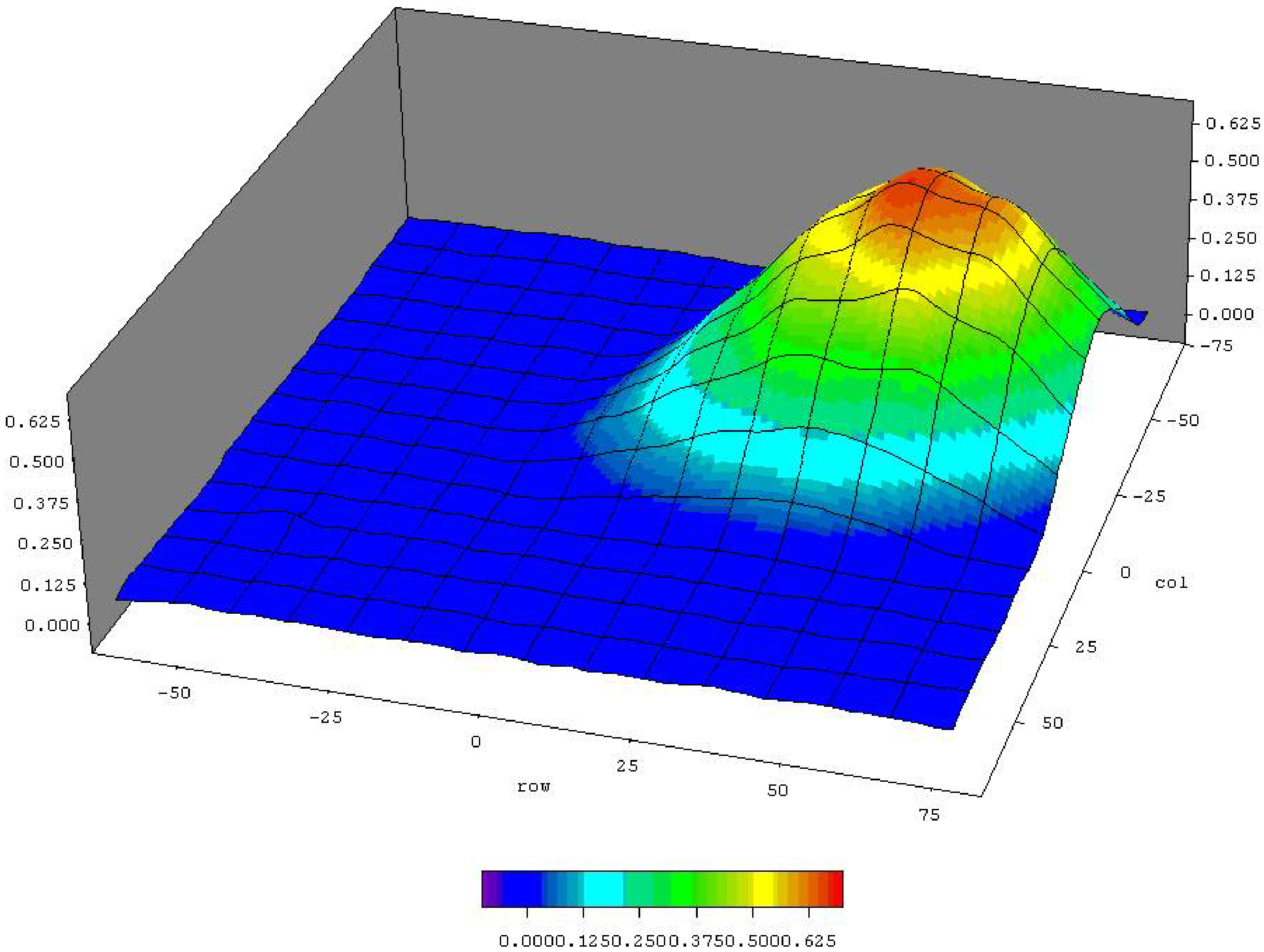
3D results: 124 bar V_z= 0.122 mm



3D results: 50 bar V_z= 0.514 mm



3D results: 28 bar V_z= 0.518 mm



Conclusions

- DIC successfully applied to over-wrap plate blow-off tests
- Able to track approximate positions of compressive strain in the vicinity of the de-bond front – hence direction of growth
- Stable de-bond growth observed for only ~2-3 mm – then catastrophic propagation leading to failure
- DIC and strain gauge data in fair agreement
- Out-of-plane deformation measured using 3D DIC – approximate agreement with theoretical predictions – small displacements

Application 2

Damage monitoring in thick tensile coupons

Why test thick composites?

- Increasingly thick composite material sections are seeing use in a number of application areas e.g. marine, aerospace etc.
- Also seeing increased use in safety critical, primary structures
- Understanding and measurement of thick section behaviour is crucial
- For thick sections, focus has tended to be on the through-thickness properties
- Often neglected in-plane properties and the effect of physical size of test specimens on measured data
- Extensive development work undertaken on thin section test methods
- Very little for thick sections – no standards
- Approach has been to use thin section data for design or adapt thin section test methods for use with non-standard, large specimen geometries
- Key question – are data from thin section tests equivalent to thick section properties?

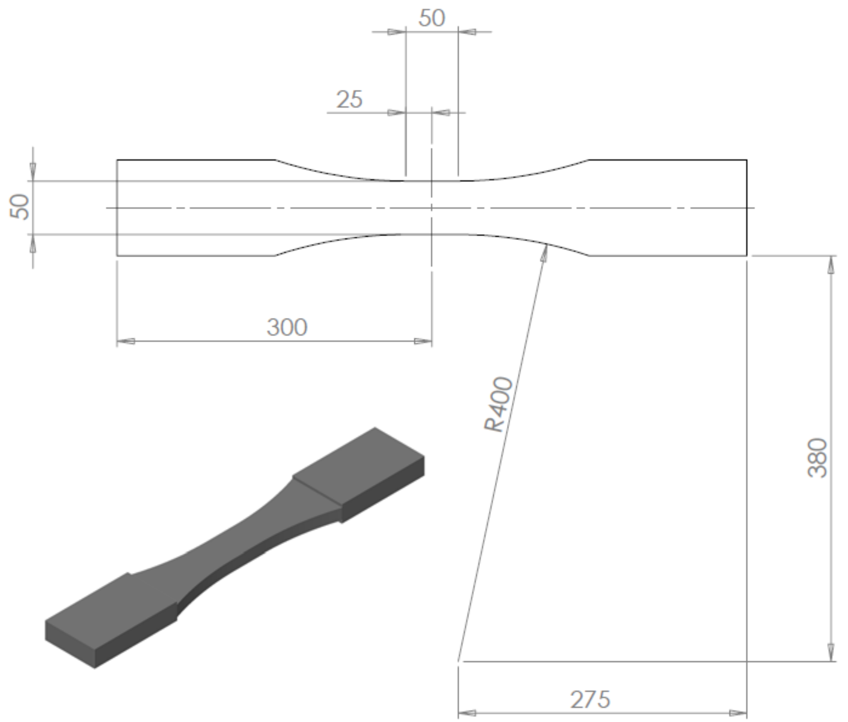
Thick tension specimen testing

- Standard tensile testing undertaken according to ISO 527-4
  - QI lay-up $(+45°/0°/-45°/90°)_s$
  - 250 x 25 x ~2.5 mm thick
  - Baseline 'thin' tensile properties
- Thick laminates for tensile testing:
  - $(+45°/0°/-45°/90°)_{8s}$ – distributed – sub-laminate scaling
  - **$(+45°_8/0°_8/-45°_8/90°_8)_s$ – blocked – ply level scaling**
- Nominal thickness of ~19-20 mm (cured ply thickness ~0.3 mm)
- Chose n=8 to provide a 'worst' case blocked lay-up to compare with distributed lay-up

NPL National Physical Laboratory

Thick section coupon preparation - tension

- 3 coupons extracted from 300 x 600 mm panels
- Water jet cutting used to extract specimens
- Grit blasted and end-tabbed
- Post machining – splitting observed in specimens cut from blocked laminate…..



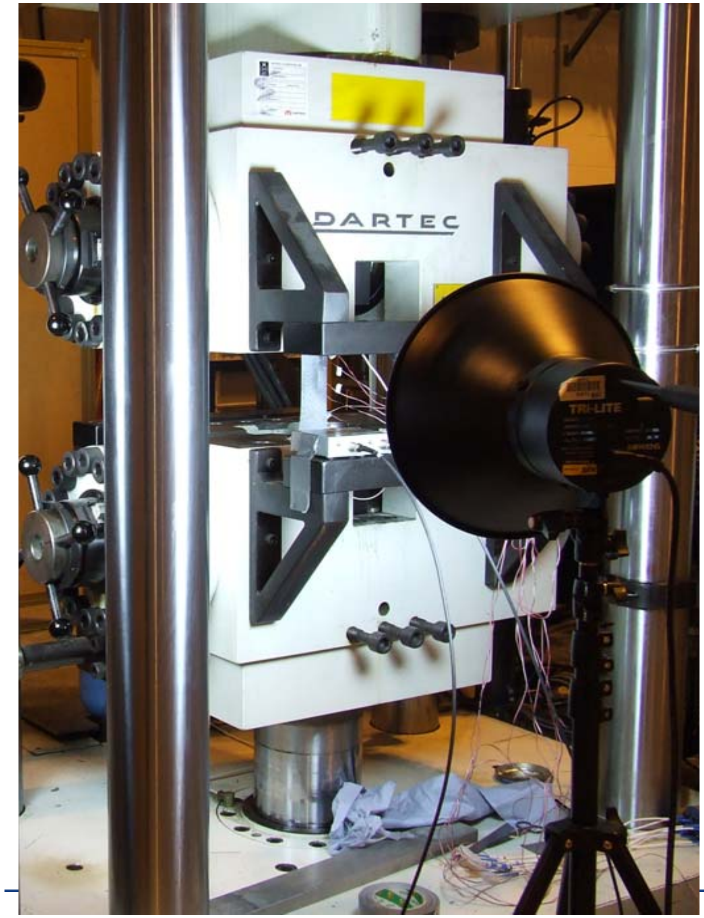
Ply splitting in thick, blocked laminate - +45° ply visible…

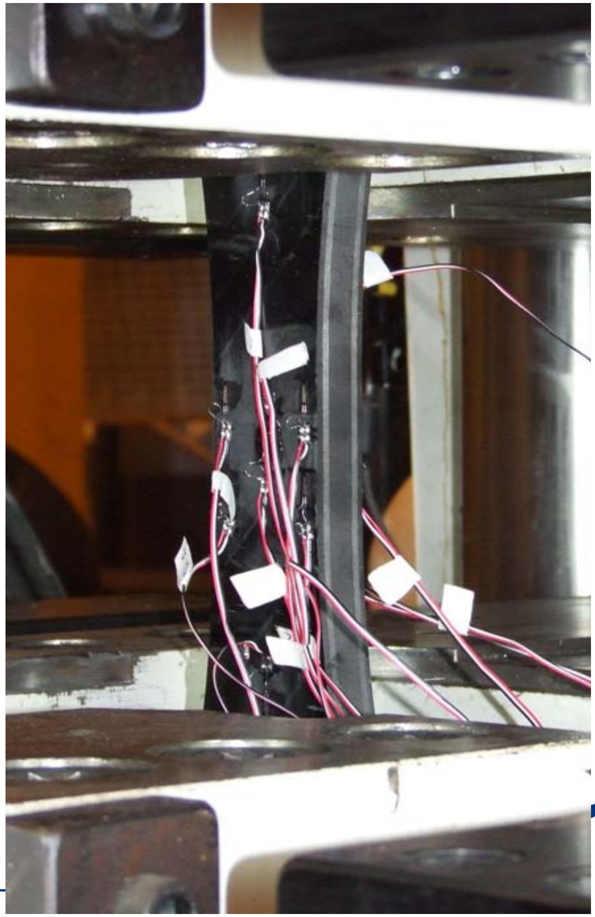
also present in -45°, 90° and 0° ply blocks

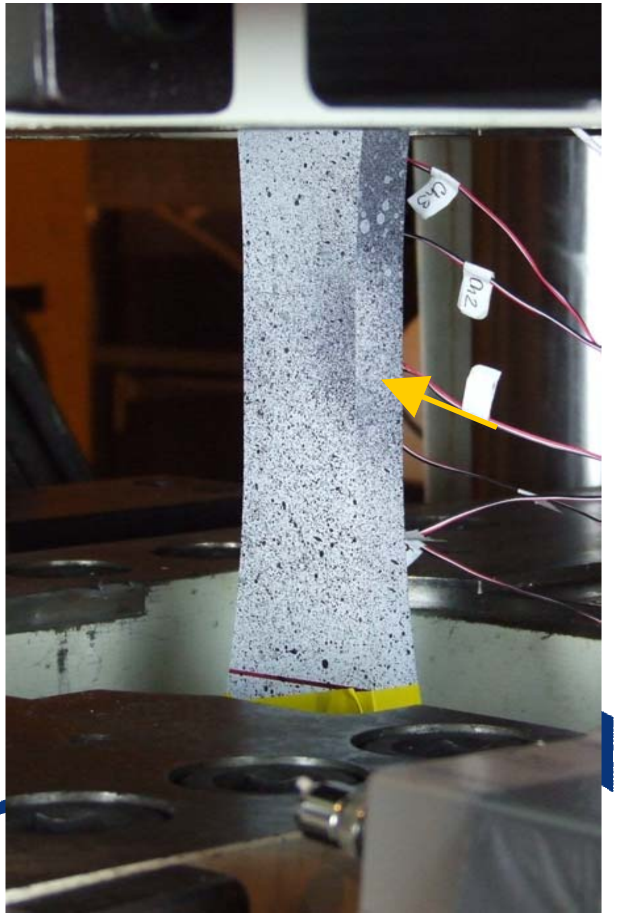
Due to residual stress (formed during cure and cool down) acting on thick ply blocks and interlaminar stresses at free edges

Thick section coupons – tension testing

- 2 MN Dartec
- Specimens loaded to failure at 2 mm/min
- Load, crosshead displacement and strain (gauges and digital image correlation)
- Images recorded using 1 Megapixel camera – analysed using LAVision® system

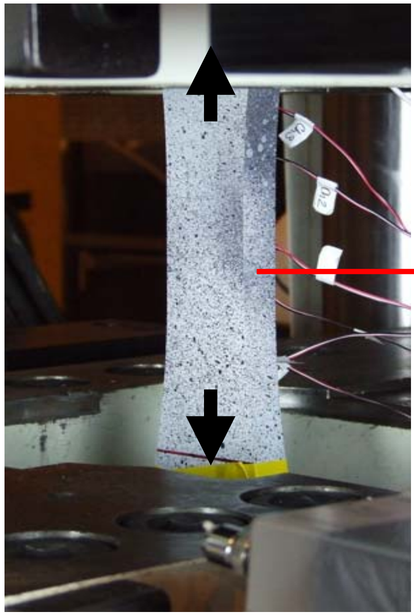


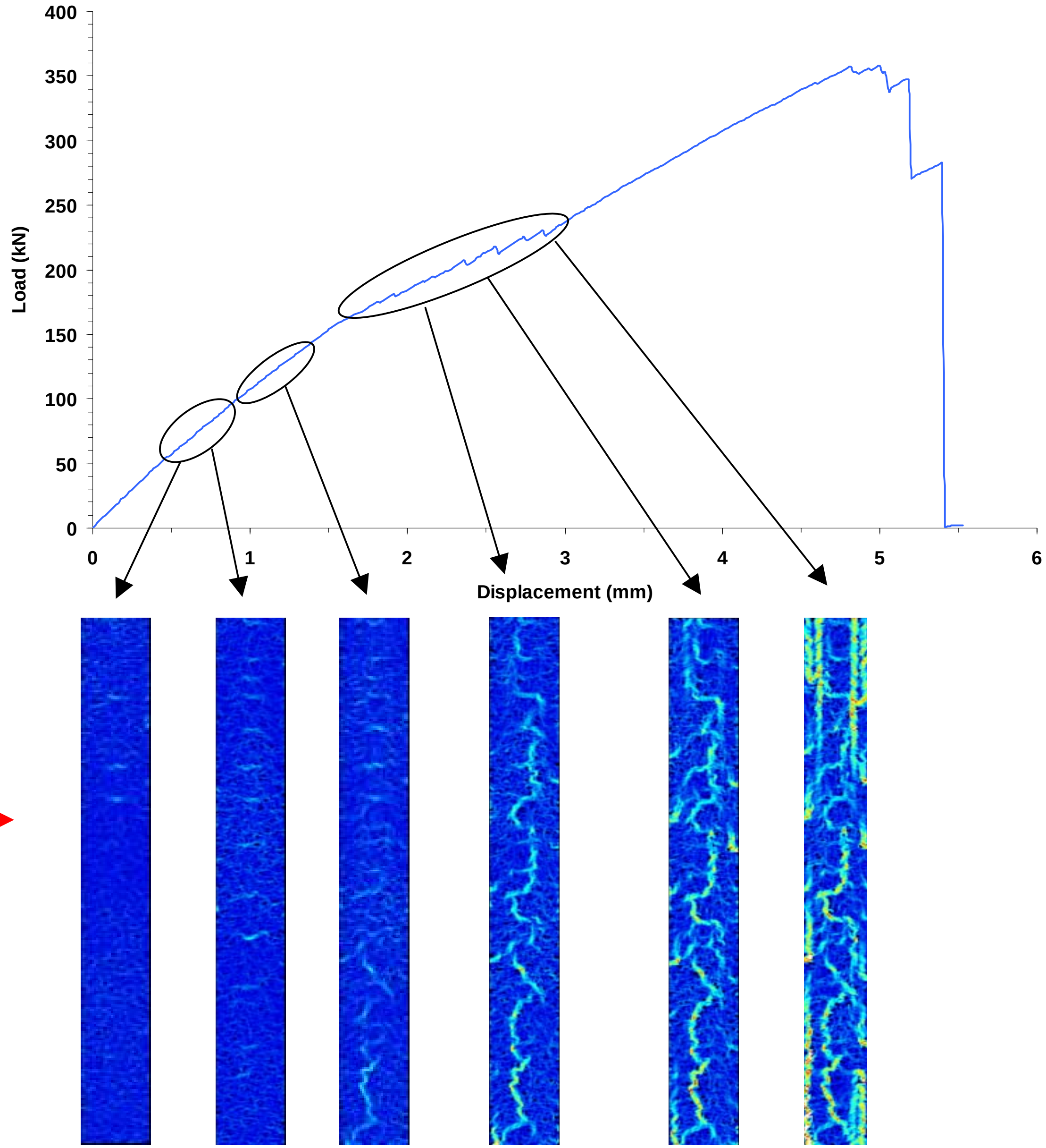




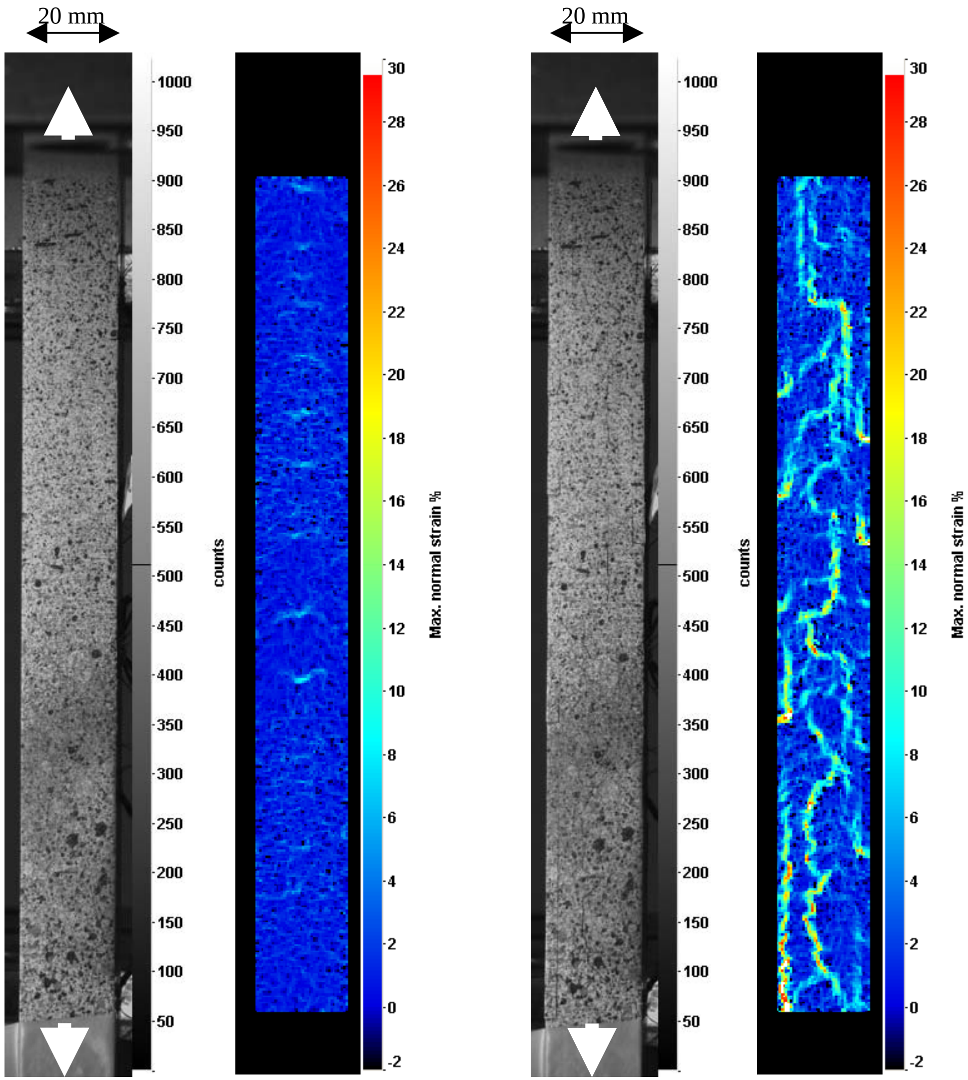
Thick section coupons – tension DIC results

- DIC monitoring on edge of sample
- Damage progression for blocked laminate
- Strains plotted are maximum normal strains across cracks and delaminations





Thick section coupons – tension DIC results

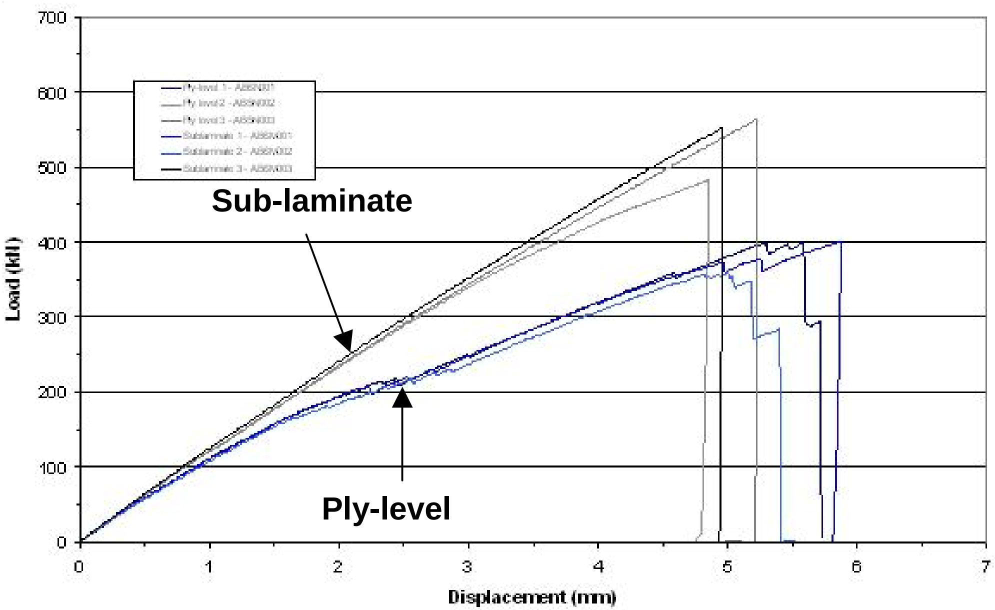


(a) Formation of ply cracks in central 90° plies

(b) Damage progression consisting of extensive cracking of +45°, 90° and -45° plies plus delamination

Thick section coupons – tension testing results

Lay-up details		Nominal Thickness (mm)	Modulus (GPa)	Poisson's ratio	Strength (MPa)
Standard (thin)	$[+45°/0°/-45°/90°]_s$	2.5	44.2 ± 0.6	0.35 ± 0.03	551 ± 22
Distributed (thick)	$[+45°/0°/-45°/90°]_{8s}$	20	45.6 ± 0.5	0.33 ± 0.01	540 ± 44
Blocked (thick)	$[+45°_8/0°_8/-45°_8/90°_8]_s$	20	34.6 ± 5.7	0.52 ± 0.10	392 ± 25



Conclusions

- DIC successfully used for monitoring the formation of damage on the edge of thick laminates
- Possible to see the opening of existing ply cracks in the 90° central ply block
- Significant knock down in tensile strength observed in blocked QI lay-up compared to thin and thick 'distributed' lay-ups
- If blocking plies then there is a requirement to characterise the tensile performance

Acknowledgements

- Colleagues at ESR Technology (Richard Lee/Simon Frost), Doosan Babcock (David Hayward)
- NPL colleagues Mr Richard Shaw, Dr Bill Broughton and Dr Graham Sims
- Gurit Holdings AG for material supply
- UK Government’s Department for Innovation, Universities and Skills (DIUS) for project funding and the Technology Strategy Board (TSB)