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TOWARDS A NEW PARADIGM FOR HIGH-FIDELITY TESTING AND INTEGRATED MULTI-SCALE MODELLING OF COMPOSITE SUBSTRUCTURES AND COMPONENTS

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CIMComp EPSRC Future Composites Manufacturing Research Hub

EPSRC Engineering and Physical Sciences Research Council

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Outline

- Background and motivation
- Aims & objectives – the Vision
- High fidelity substructure testing methodology (demonstrator: wind turbine blade substructure)
- Strain based NDE methodology – TSA & LIDIC integration (demonstrator – aircraft CFRP spar corner)
- Future directions and final comments

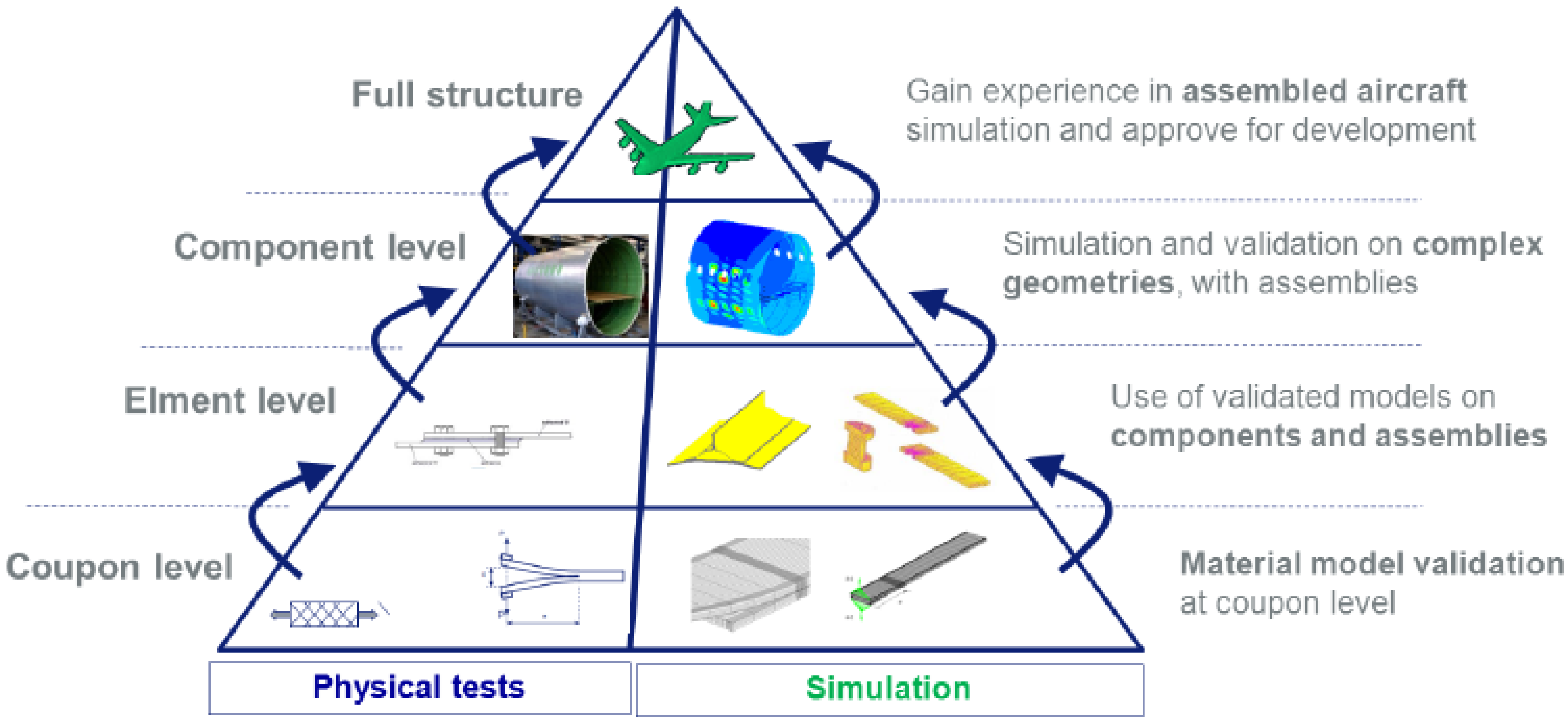
Background and motivation

'Building block' approach OR **'testing pyramid'**

1. **Coupon:** a small test specimen for evaluation of basic laminate properties or properties of generic structural features
2. **Element:** A generic part of a more complex structural member
3. **Detail/Component:** a non-generic structural element of a more complex structural member
4. **Component/Full structure:** major three-dimensional structure - complete structural representation of a section of the full structure (or the full structure)

Background and motivation

'Building block' approach OR **'testing pyramid'**



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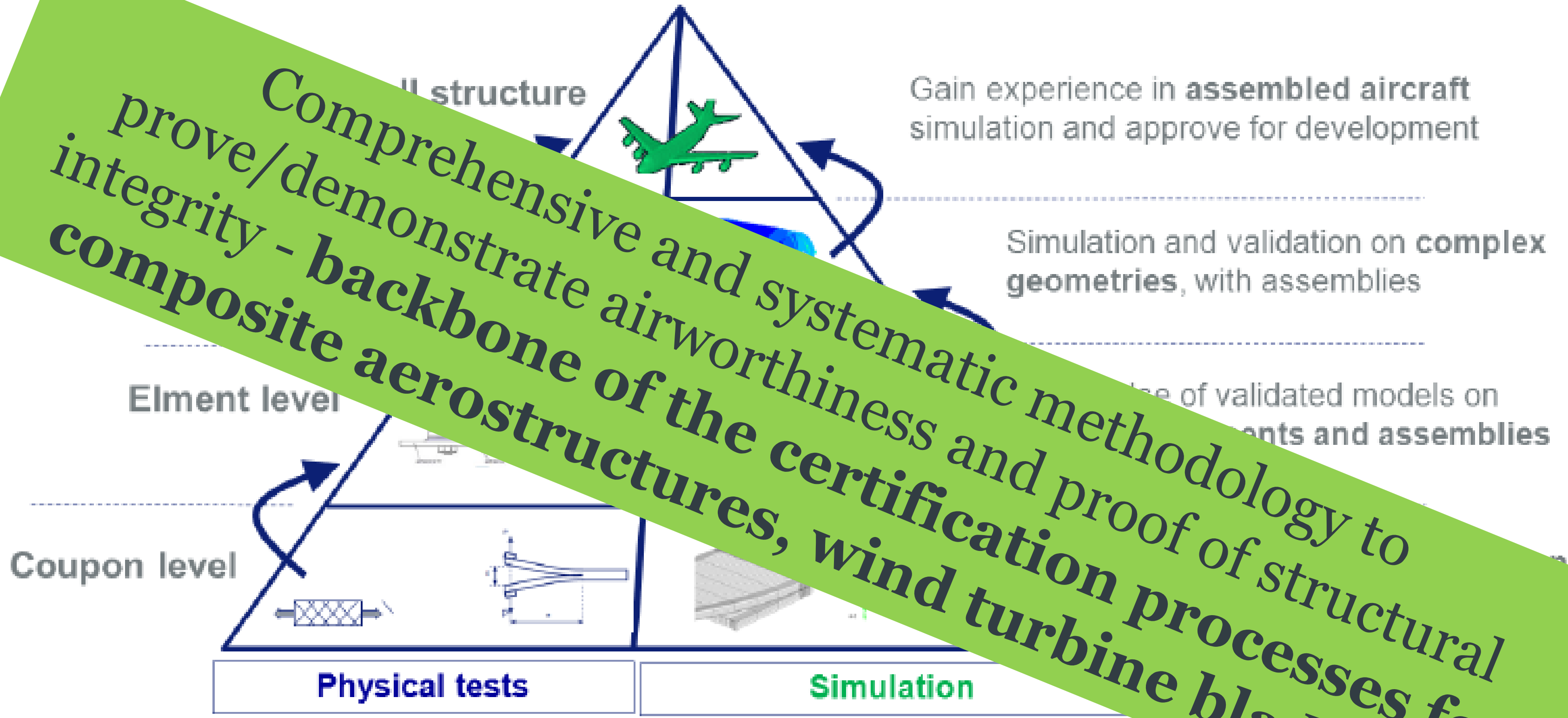

Comprehensive and systematic methodology to prove/demonstrate airworthiness and proof of structural integrity - **backbone of the certification processes for composite aerostructures, wind turbine blades, …**

HOWEVER - building block approach has severe limitations

Evidence

- Conventional failure models are based on inputs derived from coupon tests comprising simple, mainly uniaxial, loading modes and unidirectional materials
- Building block approach:
  - Large number of coupon tests to define ‘allowables’ - relatively few tests at larger scales (elements to full structure)
  - Underlying assumption: material properties from tests at the coupon level can be used to define design allowables at greater length scales
  - Coupon properties do not represent the ‘in-situ’ properties well
- Coupon level failure data does not correlate well with failure behaviour observed on component and substructure levels
- Defects and geometrical artefacts/details are not well-represented in coupon specimens

HOWEVER - building block approach has severe limitations

Evidence

- …ntional failure models are based on inputs derived from … comprising simple, mainly uniaxial, loading modes … materials
- … ‘allowables’ - … full structure)
    - … the coupon … greater length …
    - Coupon properties do n… well
- Coupon level failure data does not correla… behaviour observed on component and substructu…
- Defects and geometrical artefacts/details are not well-represented in coupon specimens

Overly conservative design - large safety factors - significant time and expense testing large numbers of coupons

The building block approach – in its current form – prevents innovative use of composites

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HOWEVER - building block approach has severe limitations

Ev

ilure models are based on inputs derived from
simple, mainly uniaxial, loading modes

Allowable properties as measured on flat laminates in simple stress states have **almost no power to predict the properties of more complex real components** containing a range of internal micro/mesostructural features

'Kevin Potter, University of Bristol & NCC Professor of Composites Manufacuting'

- gre
- Coupon prop
  well

- Coupon level failure data does
  behaviour observed on component a
- Defects and geometrical artefacts/details are not
  represented in coupon specimens

Aims & Objectives – the Vision

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Devise a methodology referred to as ***'integrated high fidelity testing and multi-scale analysis'*** to include:

- Measurement and simulation of complex multiaxial deformation states and the corresponding loading conditions
- Quantitative characterisation of the limit states that lead/contribute to failure on higher (structural) length scale levels
- Output from tests at higher length scales used for updating the computational models
- Validated data for failure under multiaxial stress states - improving predictions of failure models

Laustsen, S., Lund, E., Kühlmeier, L. and Thomsen, O.T. (2013) Development of a high-fidelity experimental substructure test rig for grid-scored sandwich panels in wind turbine blades *Strain*, 50, (2), pp. 111-131. (doi:10.1111/str.12072).

Laustsen, S., Lund, E., Kuhlmeier, L. and Thomsen, O.T. (2014) Failure behaviour of grid-scored foam cored composite sandwich panels for wind turbine blades subjected to realistic multiaxial loading conditions *Journal of Sandwich Structures and Materials*, 16, (5), pp. 481-510. (doi:10.1177/1099636214541367).

Methodology demonstrator: wind turbine blade substructure

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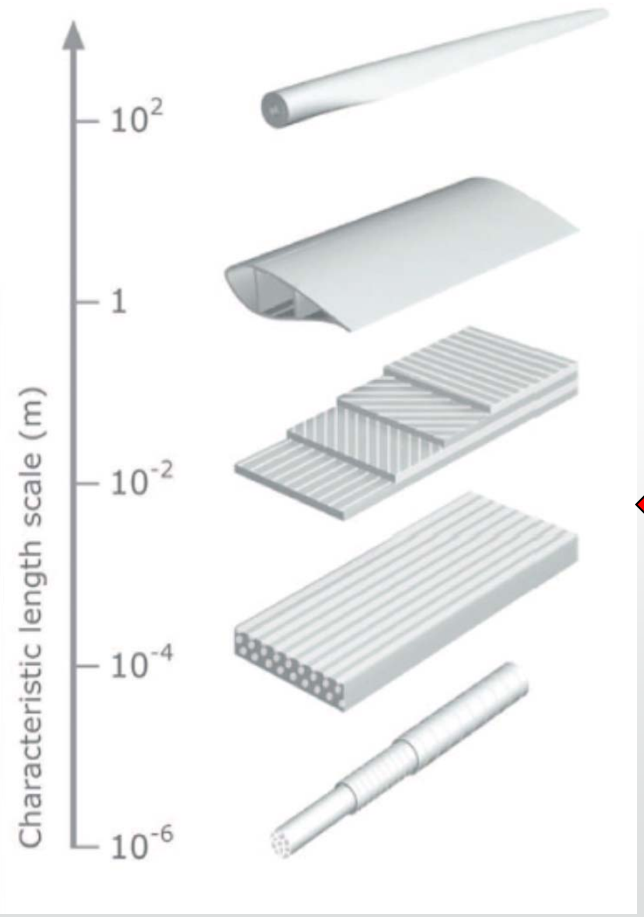
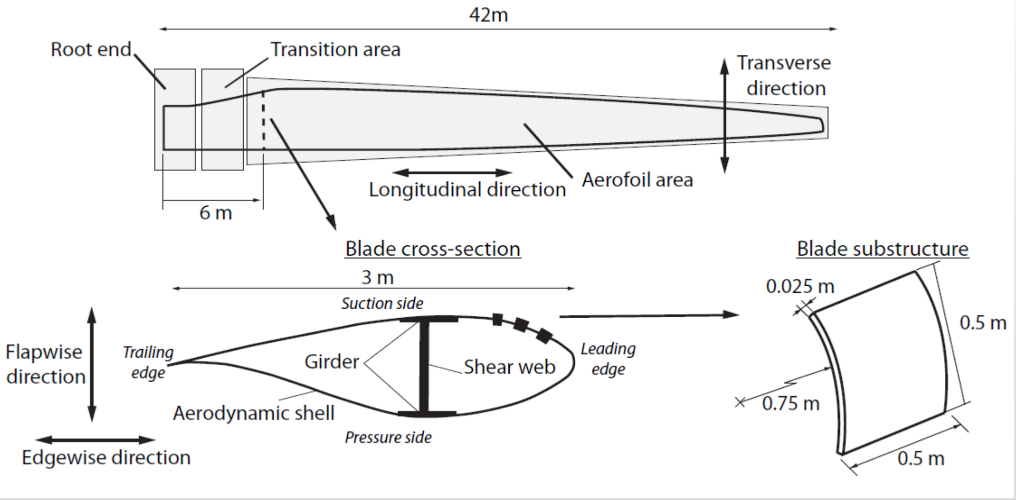
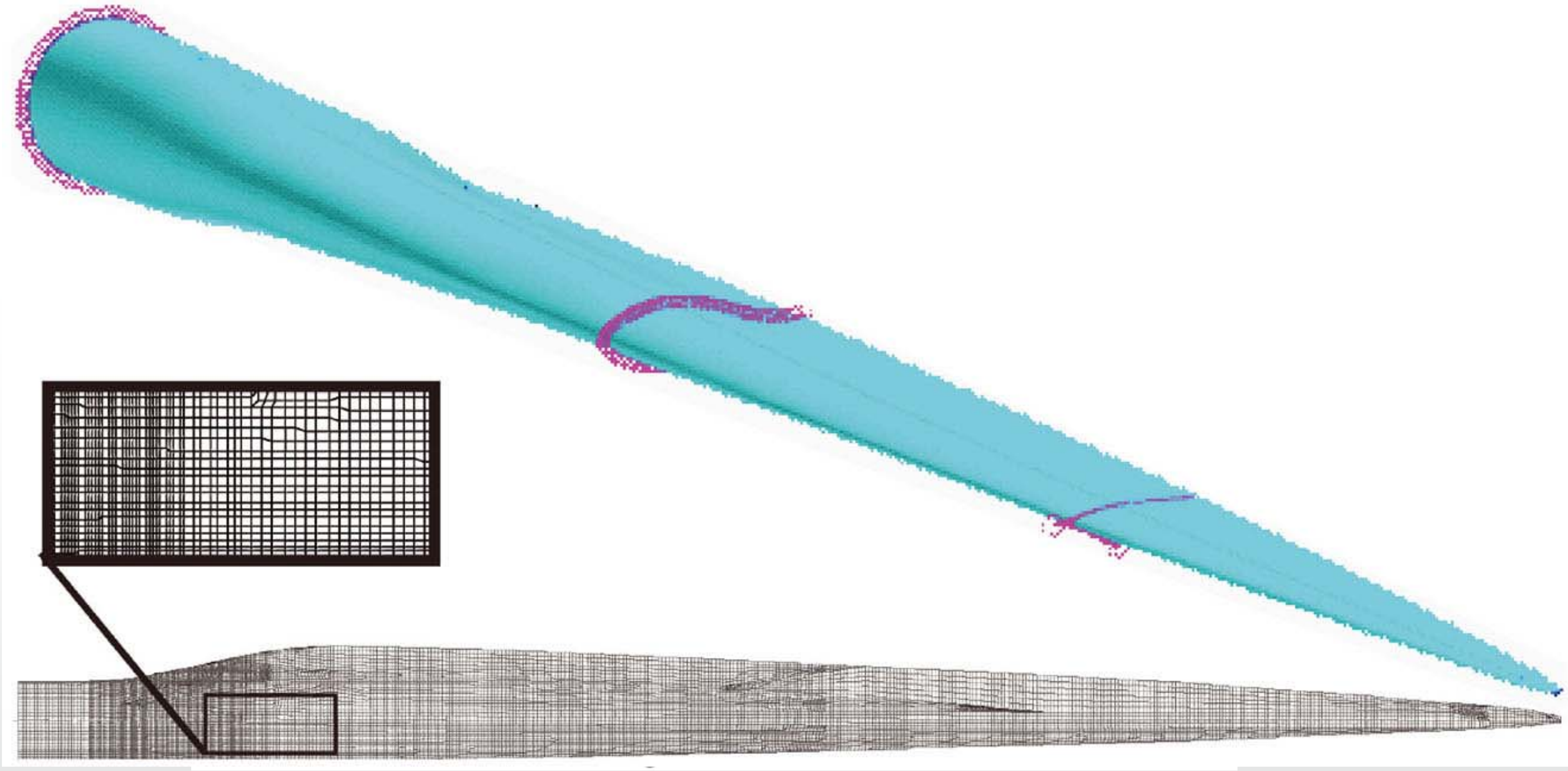
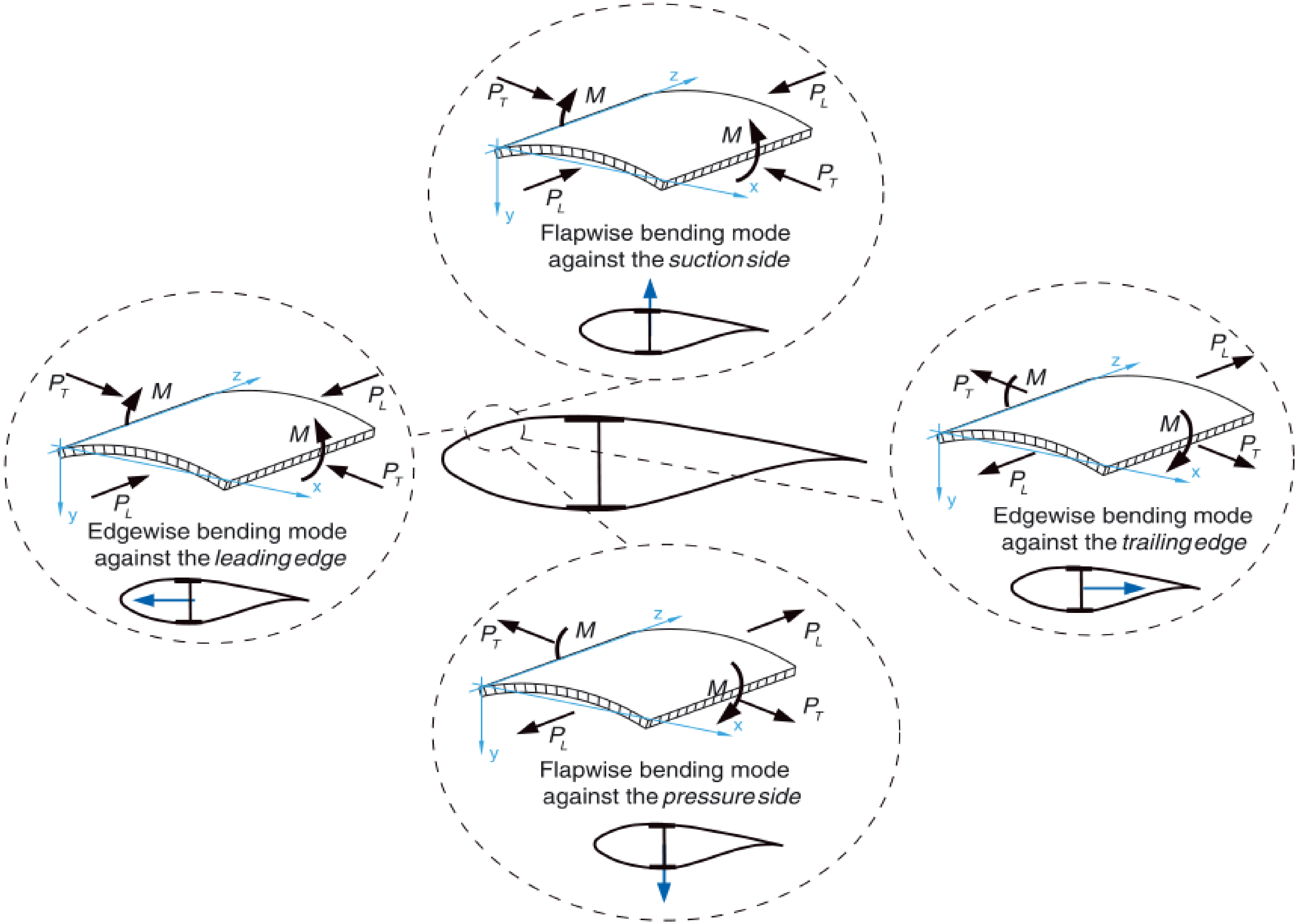




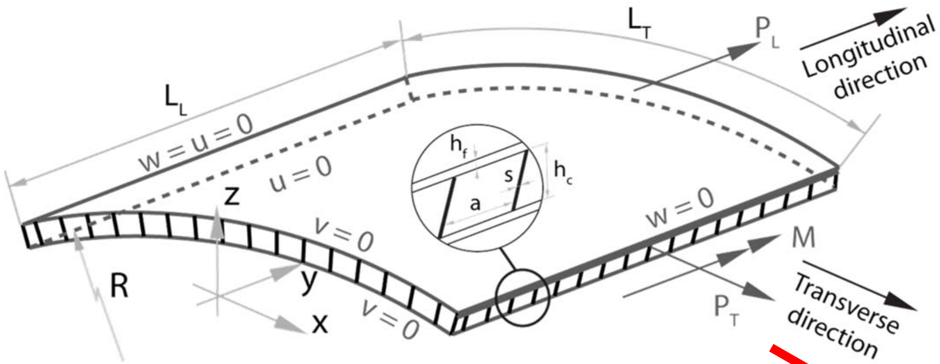
Definition of load and displacement boundary conditions



Geometrically nonlinear FE analysis (solid shell elements)

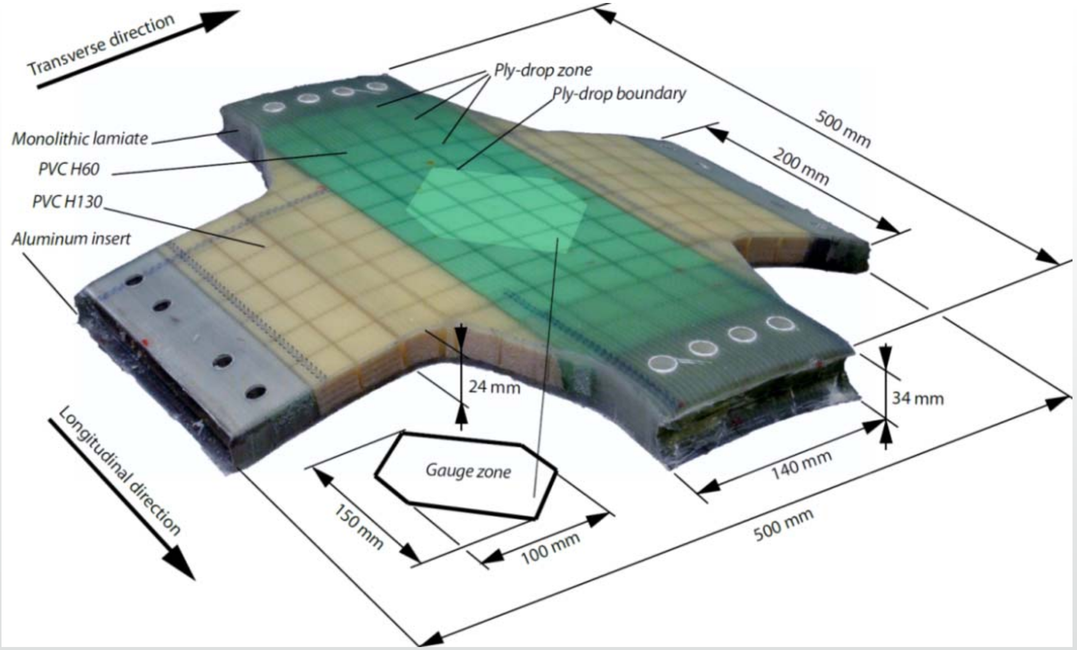

Flapwise bending mode
against the suction side
Edgewise bending mode
against the leading edge
Edgewise bending mode
against the trailing edge
Flapwise bending mode
against the pressure side

Full scale results are translated into local loading conditions



Substructure test specimen

P_L, P_T, M: varied independently



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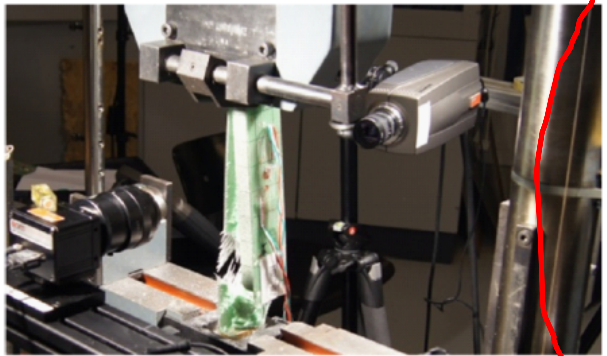
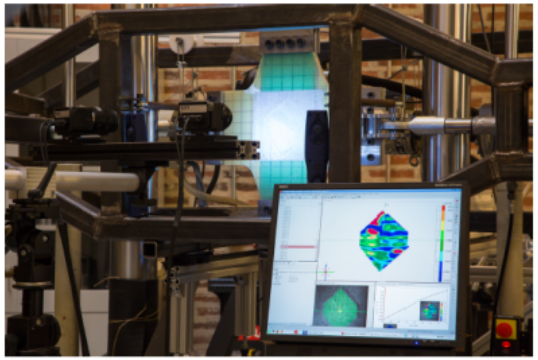
Uniaxial testing of coupon specimen



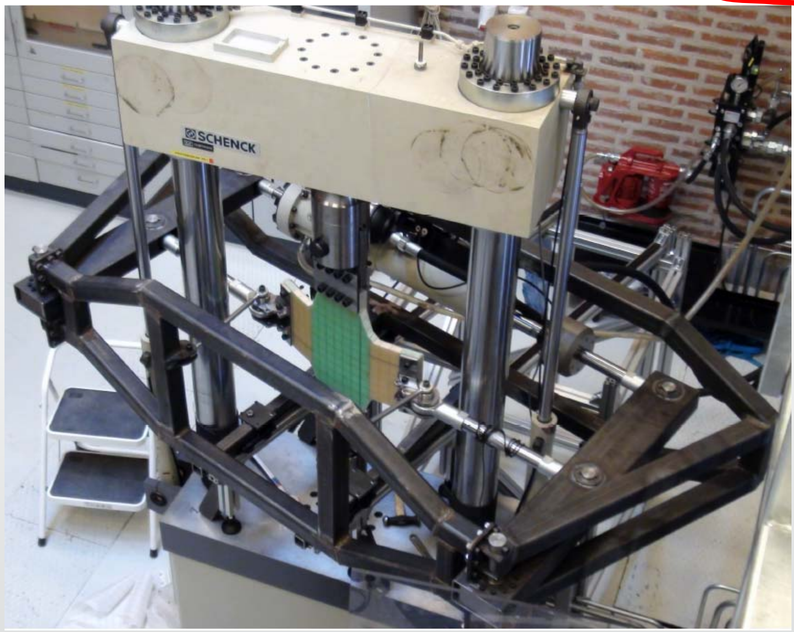
Accurate measurement of high resolution test data

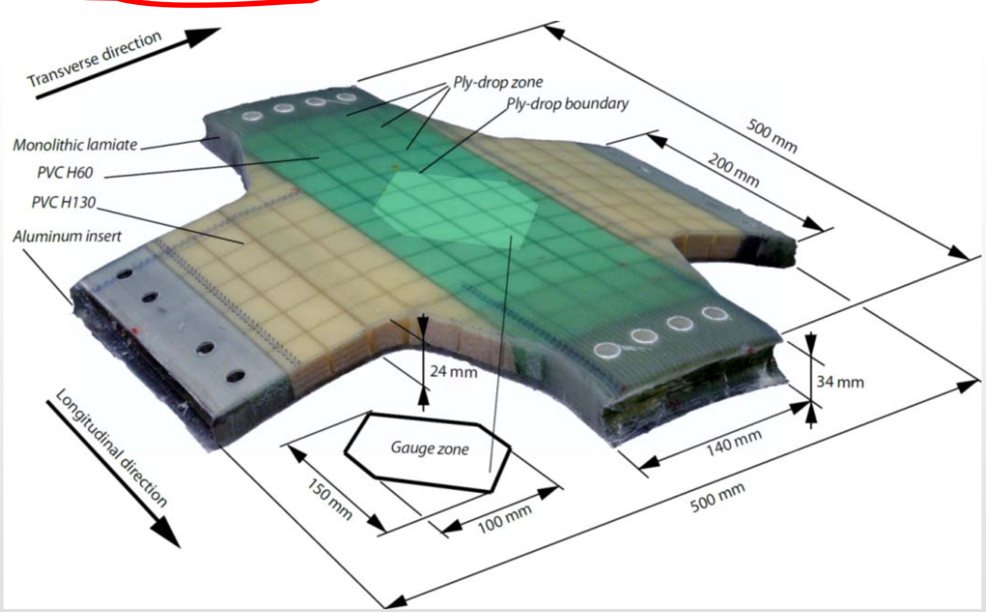
Multiaxial testing of substructure



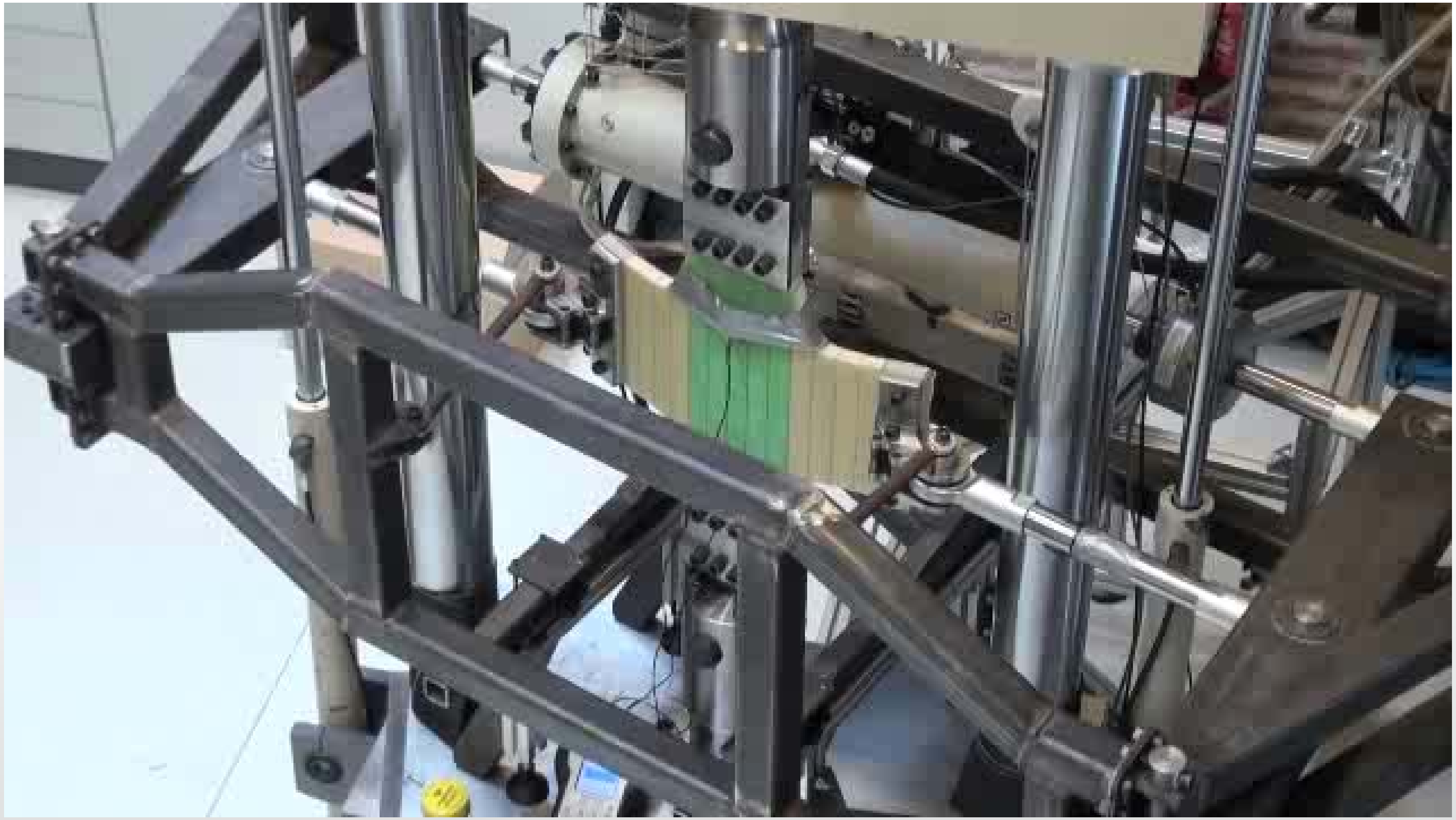
Full scale testing of full scale structure

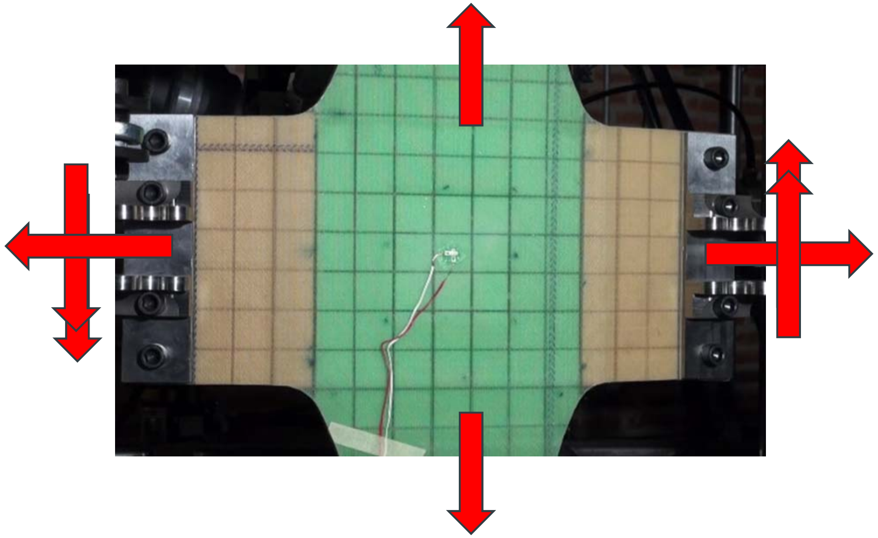
Accurate representation of loading conditions



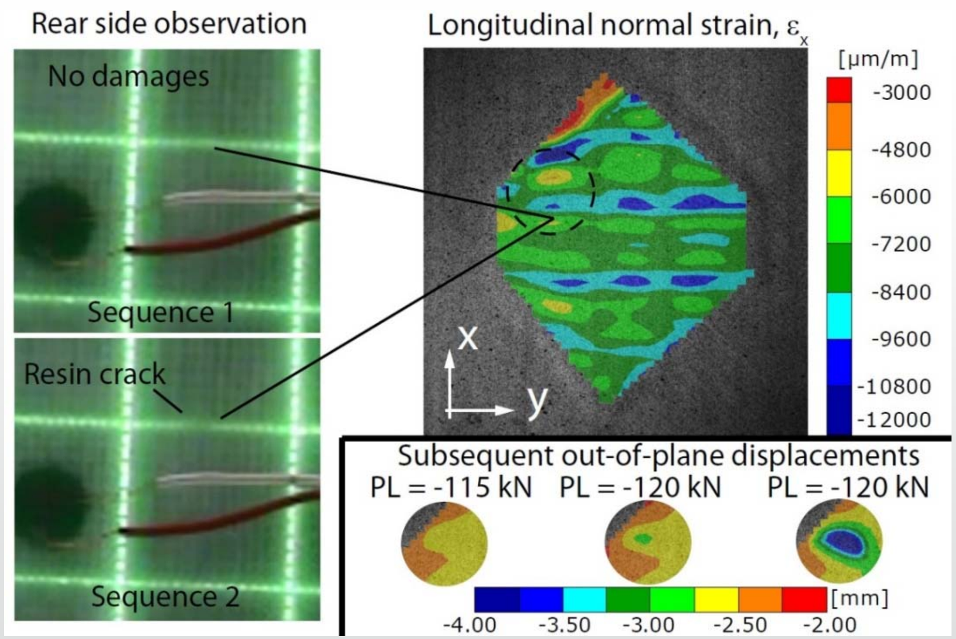


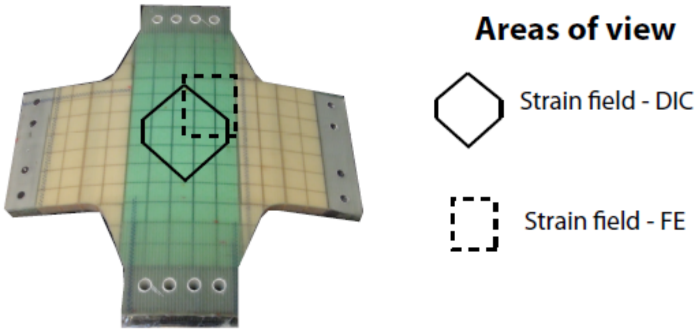
Pulsating biaxial compression loading (cyclic fatigue)

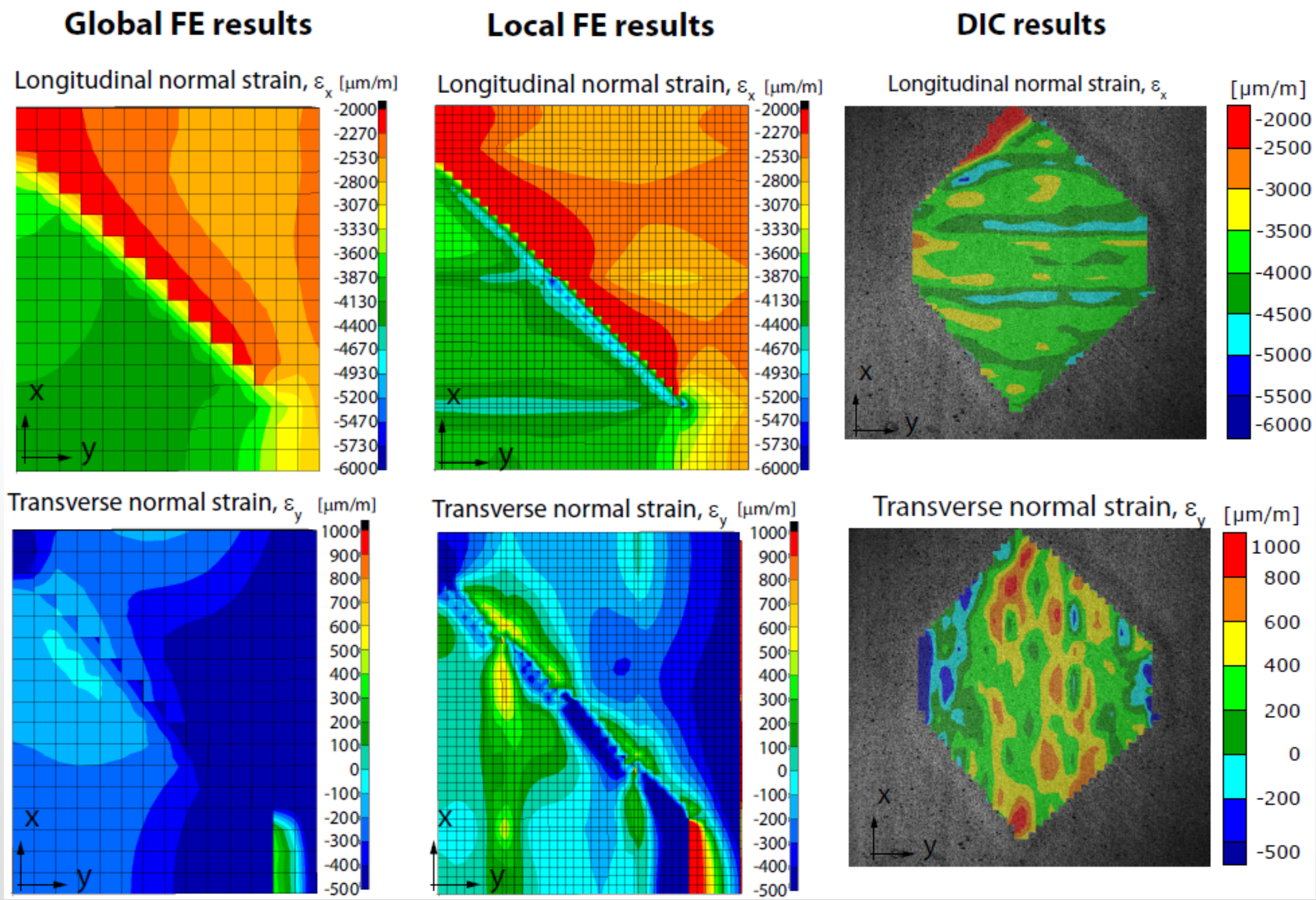




- Failure event recorded by DIC on the front side of the specimen and video recording from the rear side at P_L=-110 kN for the ***biaxial compression load case***
- Out-of-plane face sheet displacement fields within the circular area shown at 3 different load levels/stages

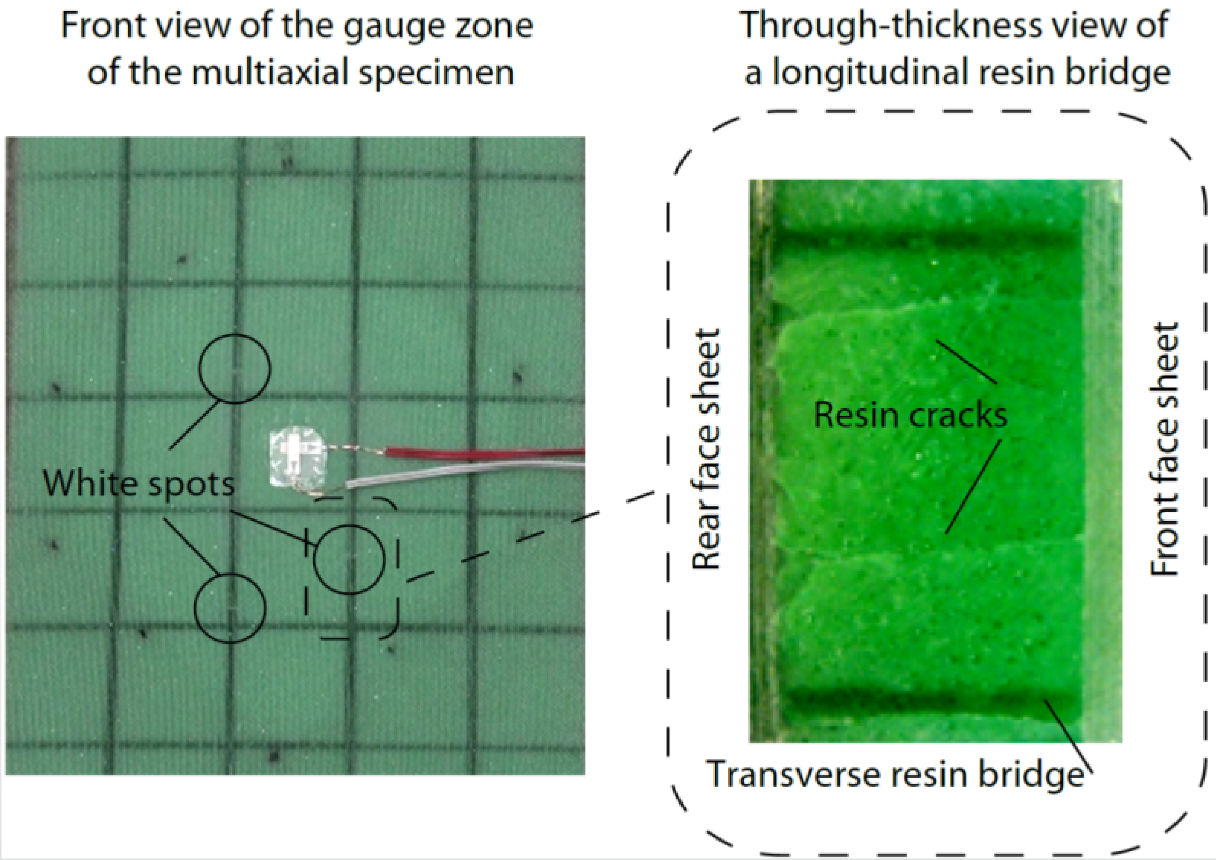






Global and local FE model predictions vs. DIC measurements for the ***biaxial compression case***

Post mortem images showing through-thickness (z direction) cracks in the longitudinal resin bridge when subjected to the ***multi-axial tension load case***.



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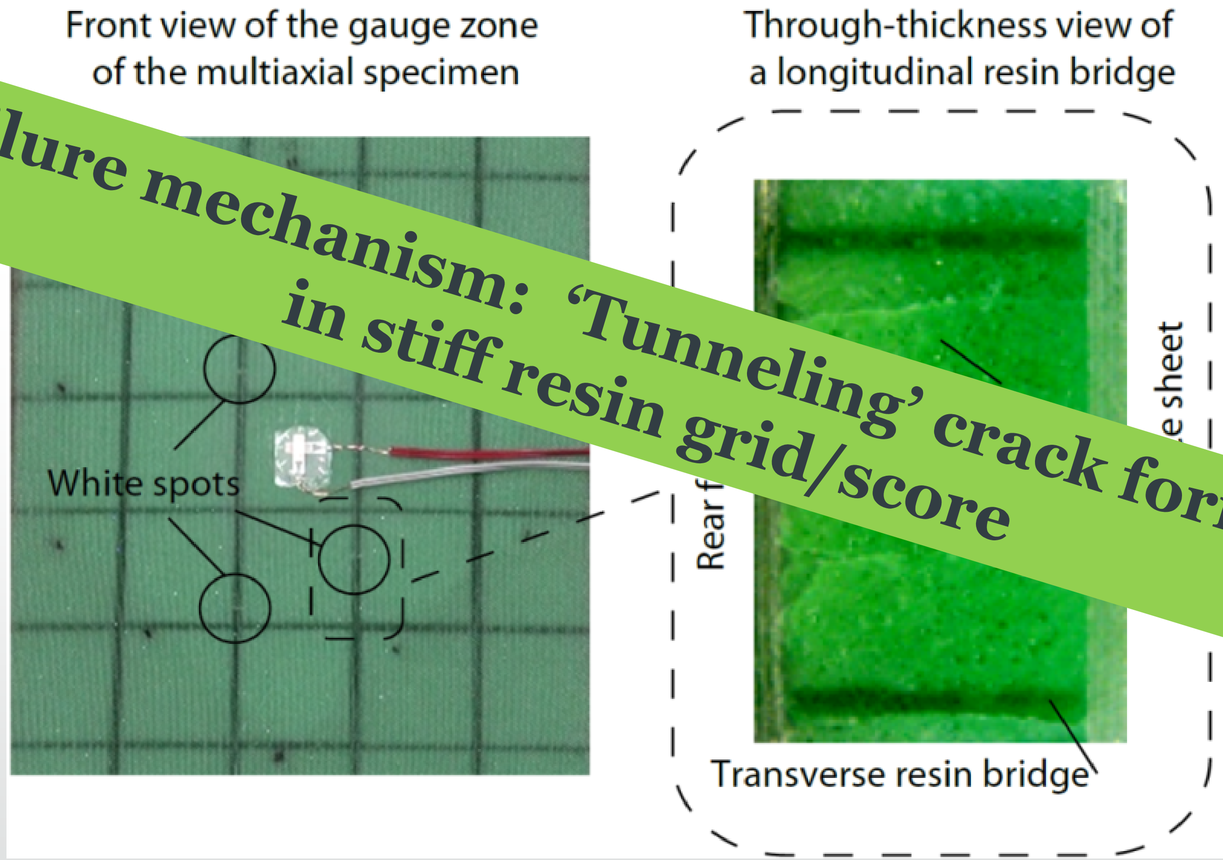

Failure mechanism: ‘Tunneling’ crack formation in stiff resin grid/score

Criterion #1:

- Fracture mechanics approach, where the resin bridge is considered as a brittle layer between two tough substrates ('tunnelling crack' in constrained layer)
- A conservative form of the criterion is suggested, which computes the steady state value of the energy release rate
- The criterion is governed by the maximum principal stress in the resin, σ_p, the width, h, of the resin bridge, the critical energy release rate, Γ_r, of the resin, and the stiffness of the resin $\overline{E} = E/(1-\nu^2)$:

$$\frac{\pi \sigma_p^2 h}{4 \Gamma_r \overline{E}} \geq 1$$

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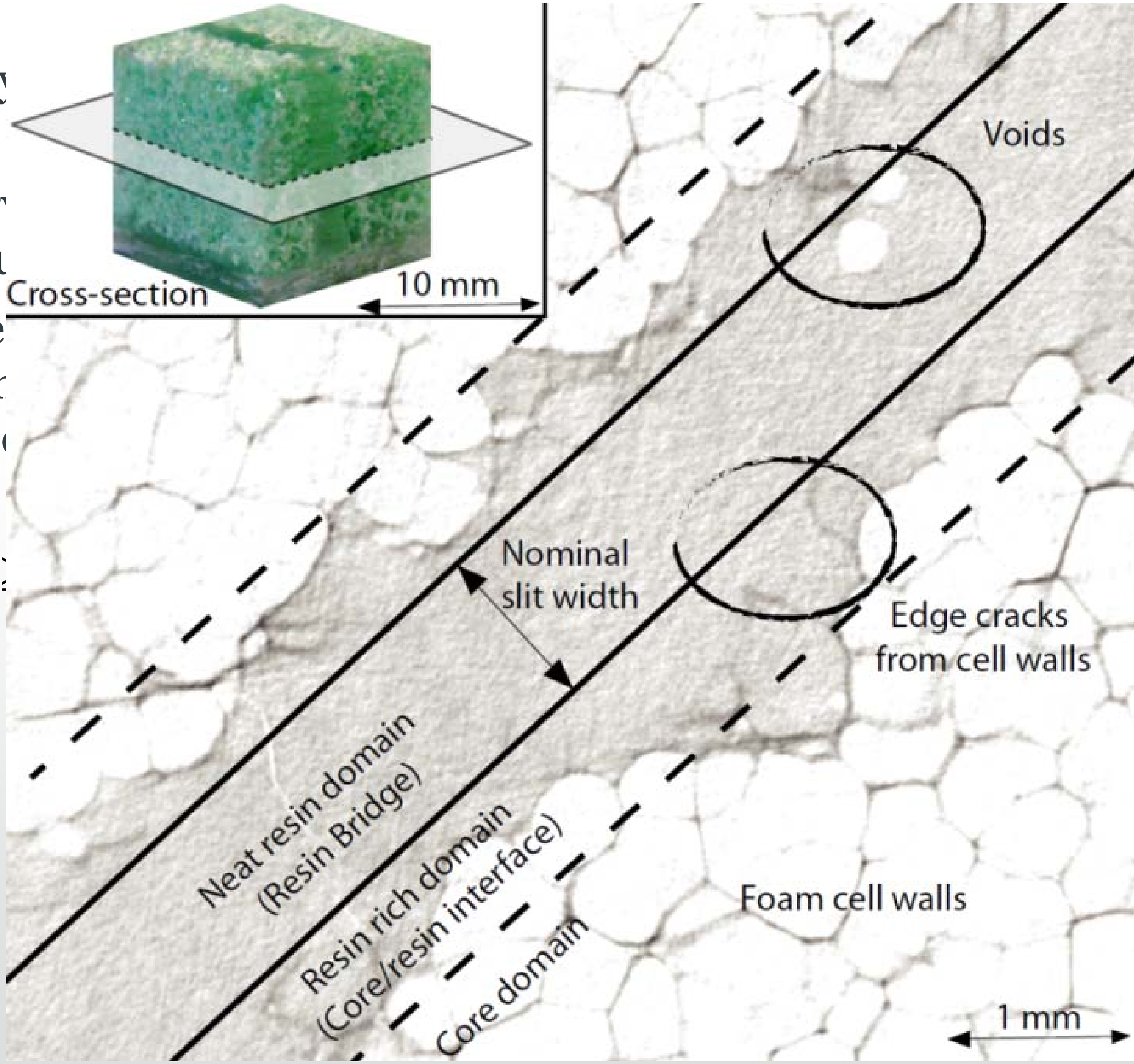
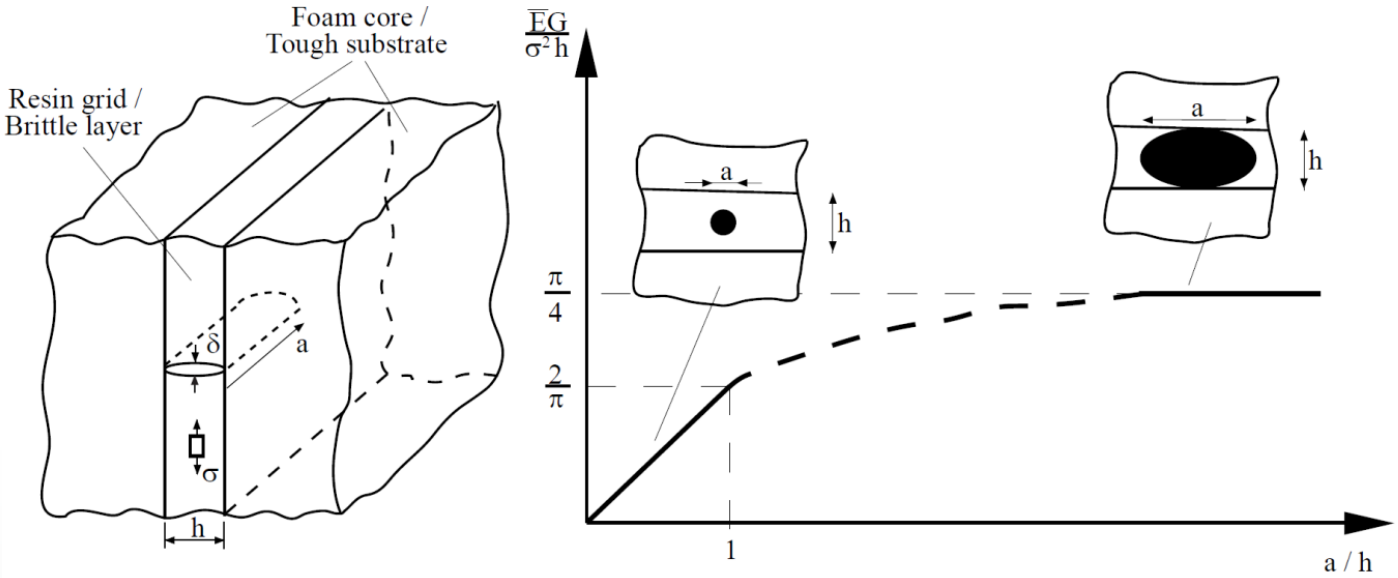
Criterion #1:

- Fracture … ed as a brittle la… onstrained layer)
- A conser… the steady state valu…
- The crite… resin, σ_p, the widt… Γ_r, of the resin, an…

$$\frac{\pi \sigma_p^2 h}{4 \Gamma_r \overline{E}} \ldots$$





- 'Tunnelling crack' criterion is computationally expensive - requires a 3D solid element model of the sandwich structure
- Requires estimates of the effective resin grid width, *h*, which in some cases can be three times higher than the nominal width
- 'Tunnelling crack' criterion may be mostly useful for identifying the parameters governing the 'resin grid' failure phenomenon rather than serving as a practical tool for failure prediction

Criterion #2:

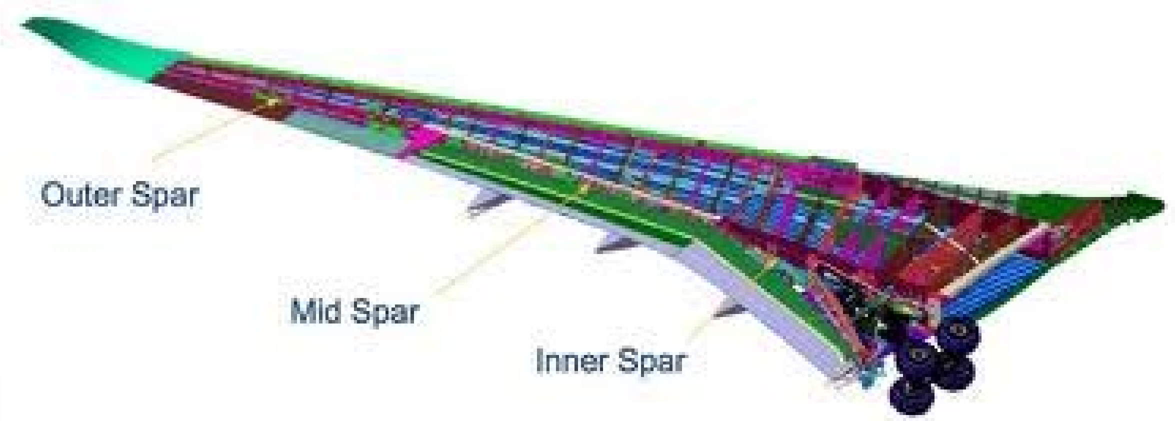
- To accommodate 'issues' with 'tunnelling crack' criterion a 'point strain' criterion was proposed as a simple alternative:

$$\frac{\varepsilon_p}{\varepsilon_{ult,t}} \geq 1$$

- Ultimate strain ($\varepsilon_{ult,t}$) input derived from uniaxial tension test of the sandwich structure, and the computed principal strain (ε_p) in the resin bridge (FE model / shell or 'solid')
- Influence on the fracture strength of the resin-core interface and resin system is implicitly taken into account

- Both 'failure criteria': Reasonable correlation with obtained experimental data revealed– prediction ~ ±10% of mean experimental value

Strain based NDE methodology – TSA & LIDIC integration – Demonstrator: CFRP spar corner



Aim and objectives

Devise a high fidelity means of obtaining local strain/stress data to inform model-based prognostics to define how a given defect will evolve under service load

- Demonstrate the viability of the experimental methodology providing the data necessary for a model based prognosis system
- Demonstrate the approach at a sub-structural level
- Demonstrate high-fidelity modelling capability – onset of failure of composite sub-structure with embedded defect

Modelling of CFRP spar with wrinkle defect

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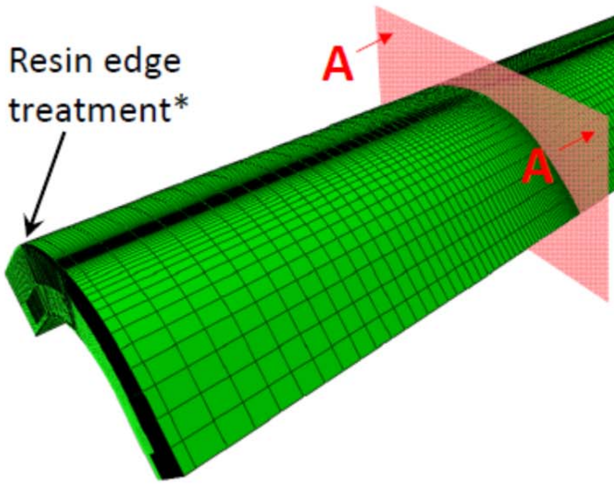
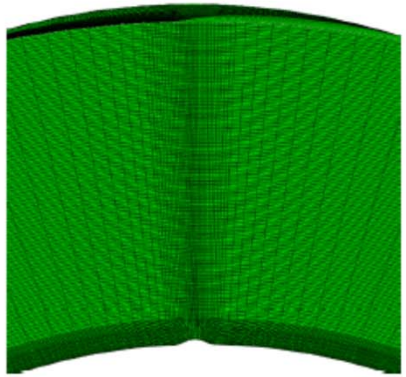
Resin edge treatment*

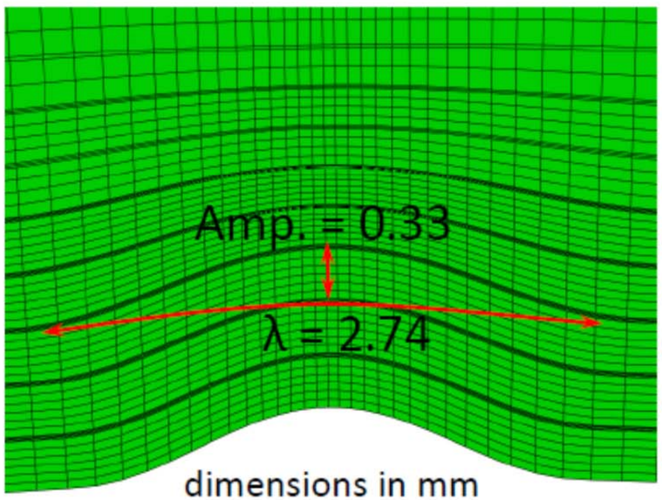


Resin edge treatment*

Wrinkle modelled as cosine wave, with mesh fidelity heavily biased to wrinkle region

A - A

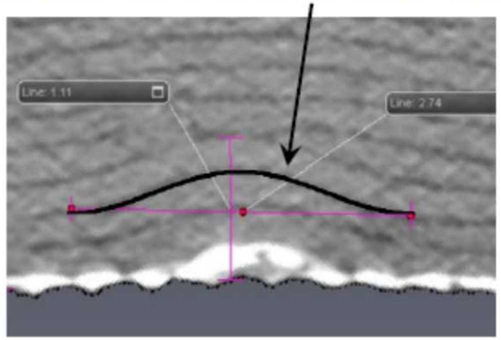




dimensions in mm

Ply	
78	-45°
79	+45°
80	-45°
81	+45°
82	0°
83	90°
84	-45°
85	+45°

Cosine wave overlaid on CT scan



*Fletcher, et al. Resin treatment of free edges to aid certification of through thickness laminate strength. Composite Structures 2016; 146: 26-33.

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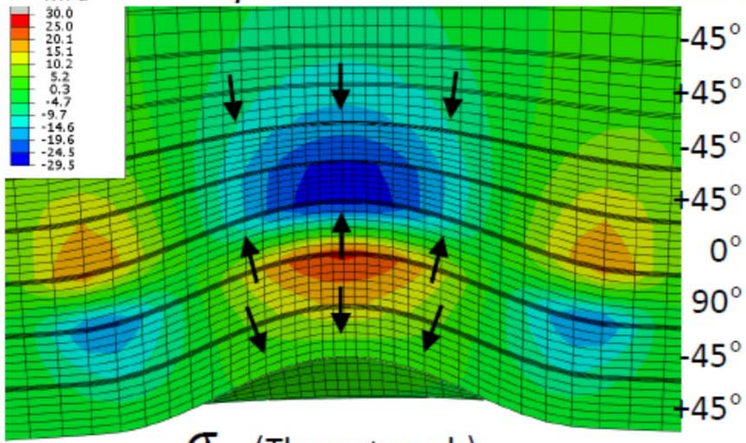
Stress concentrations

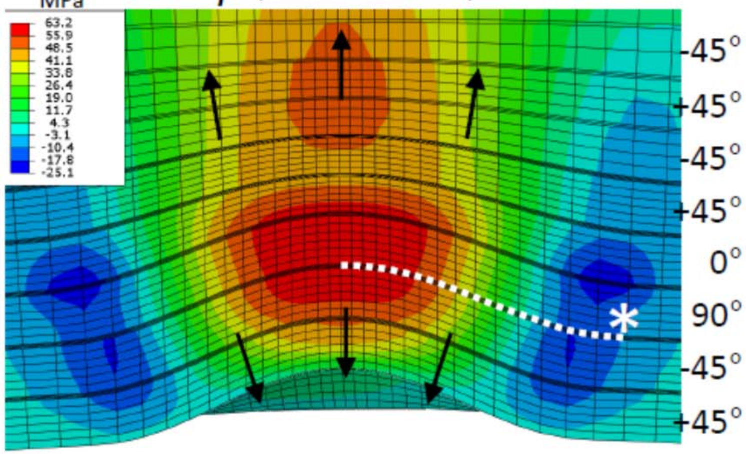
σ_r (Therm only)

90° fibres run in the θ direction

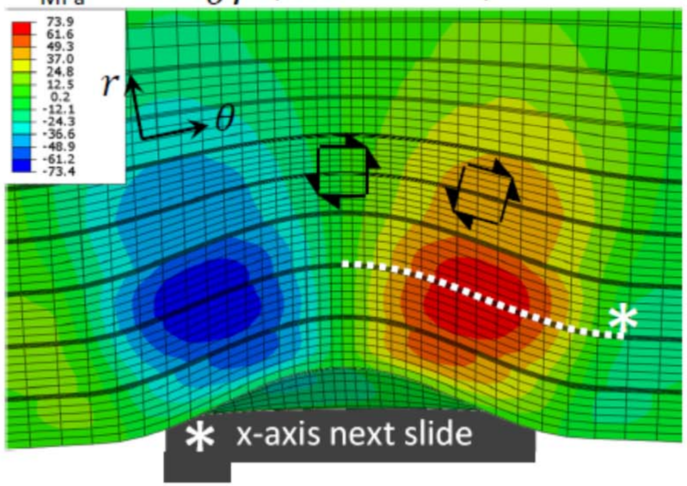


- Cooldown 180 → 20°C
- Then 45 kN applied (~test failure)
- Residual thermal stresses alleviate σ_r above 90° ply and increase it below
- Peak σ_r at max amplitude
- Peak $\tau_{\theta r}$ at max slope

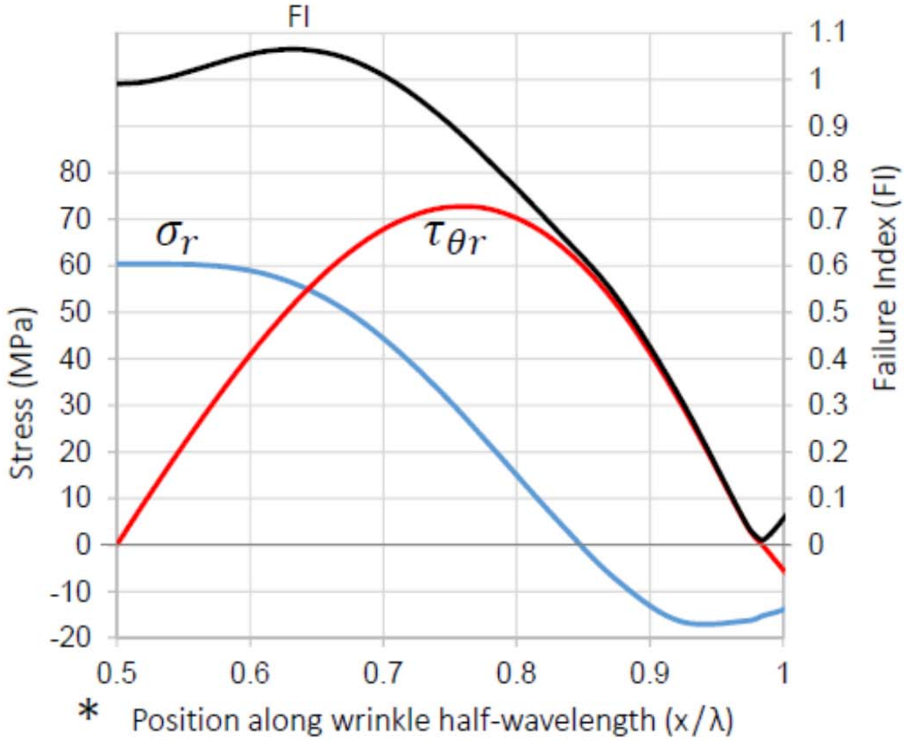
σ_r (Therm+mech)



$\tau_{\theta r}$ (Therm+mech)



Model Predictions



$$\text{FI} = \sqrt{\left(\frac{\sigma_{33}^{+}}{s_{33}}\right)^2 + \left(\frac{\tau_{13}}{s_{13}}\right)^2 + \left(\frac{\tau_{23}}{s_{23}}\right)^2}$$

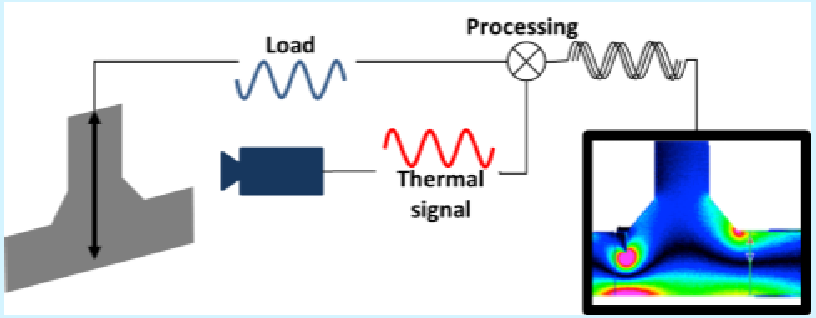
- At 45 kN, FI = 1.06 (left figure)
- At 43 kN, FI = 1 (predicted failure)
- Pristine specimen (no wrinkle) predicted to fail at 88 kN

Potential for virtual testing in future

- Developing bespoke FE solver in *dune**.
- Uses iterative solver >10 times faster than direct solvers for large problems.
- Scales well over 100s of processors.
- Accuracy compares well with Abaqus.

Experimental technique

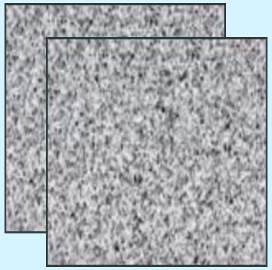
Thermoelastic stress analysis (TSA)



$$\Delta T = -\frac{T}{\rho C_p}\left(\alpha_1 \Delta\sigma_1 + \alpha_2 \Delta\sigma_2\right)$$

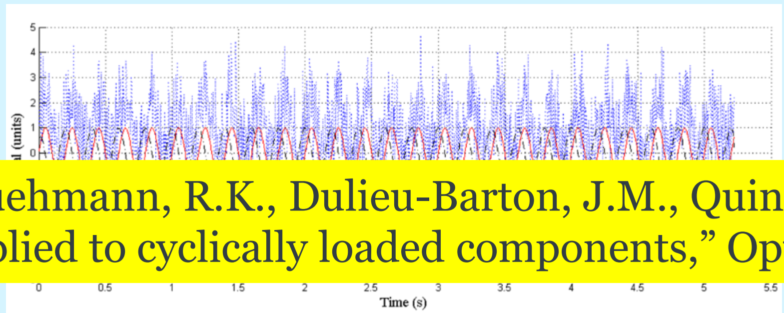
⇒ Provides a stress metric

Digital Image Correlation (DIC)



Uses surface contrast to track displacements between two images to provide the component strains ε_x, ε_y and ε_{xy}

TSA uses lock-in processing to extract ΔT from a noisy signal



Lock-in DIC (LIDIC)

Uses lock-in processing to extract strains during cyclic loading so DIC and TSA are performed simultaneously to provide $\Delta\varepsilon_x$, $\Delta\varepsilon_y$ and $\Delta\varepsilon_{xy}$ and ΔT

Fruehmann, R.K., Dulieu-Barton, J.M., Quinn, S., and Tyler, J.P., "Digital image correlation applied to cyclically loaded components," Optics and Lasers in Engineering. 2015.

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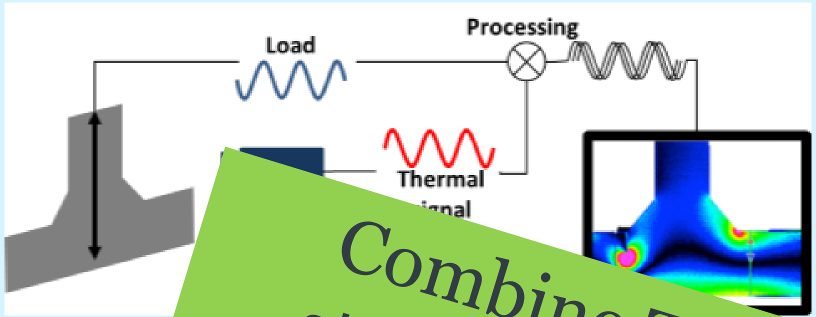
Experimental technique

Thermoelastic stress analysis (TSA)



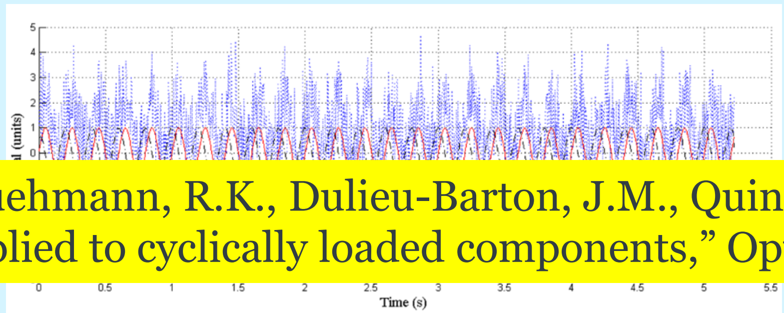
Provid…

Digital Image Correlation (DIC)

Uses surface contrast to track displacements between two images to provide the component strains ε_x, ε_y and ε_{xy}

Combine TSA and DIC to provide stresses and strains resulting from damage

TSA uses lock-in processing to extract ΔT from a noisy signal



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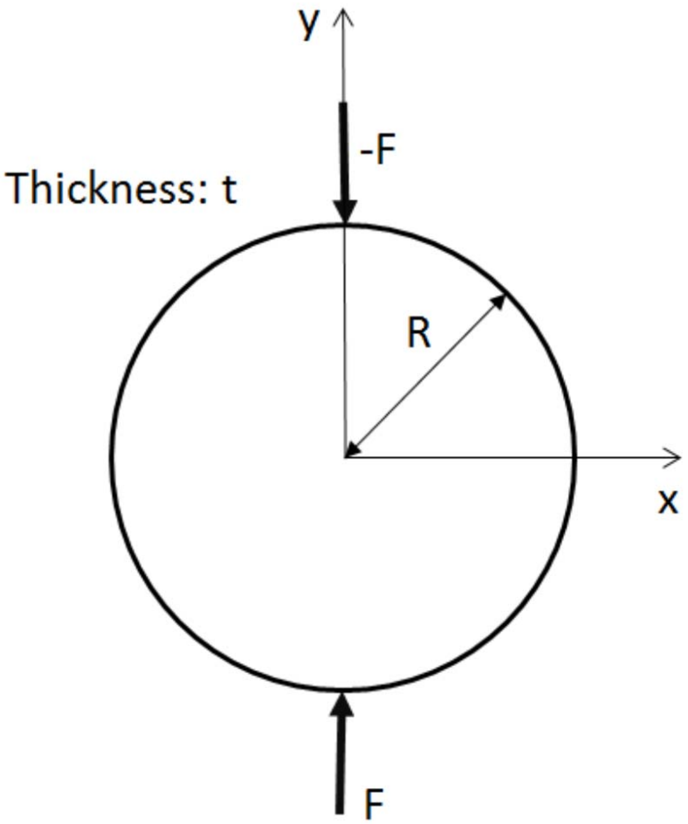
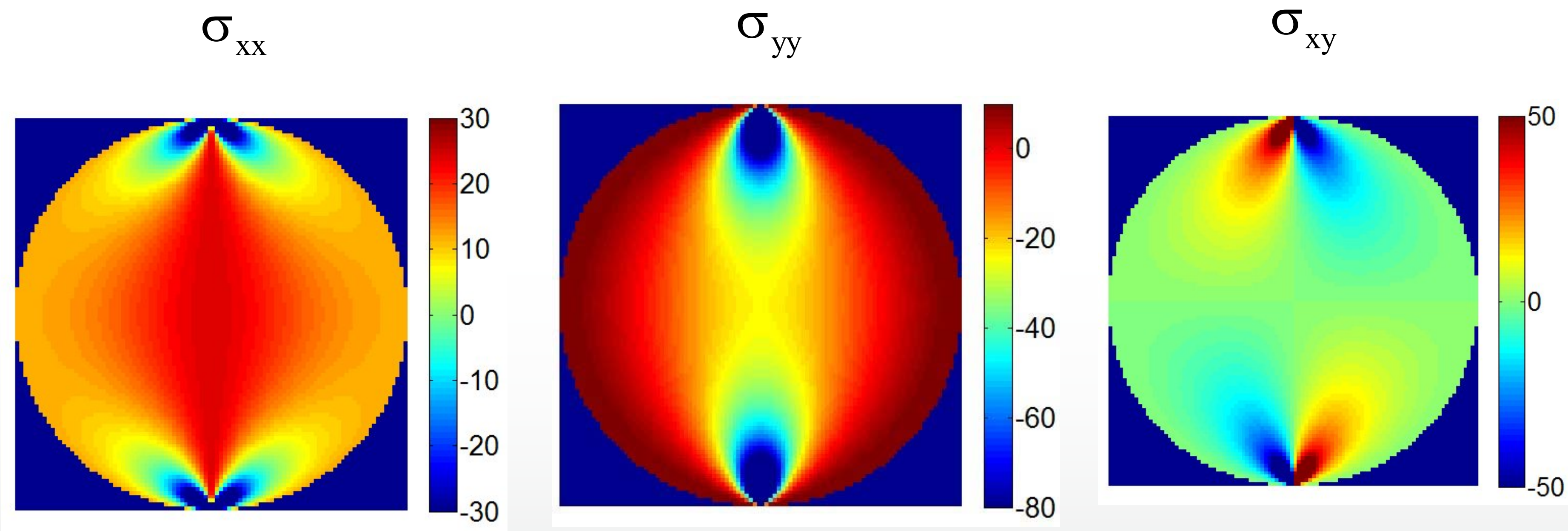
Brazilian disc theory- validation

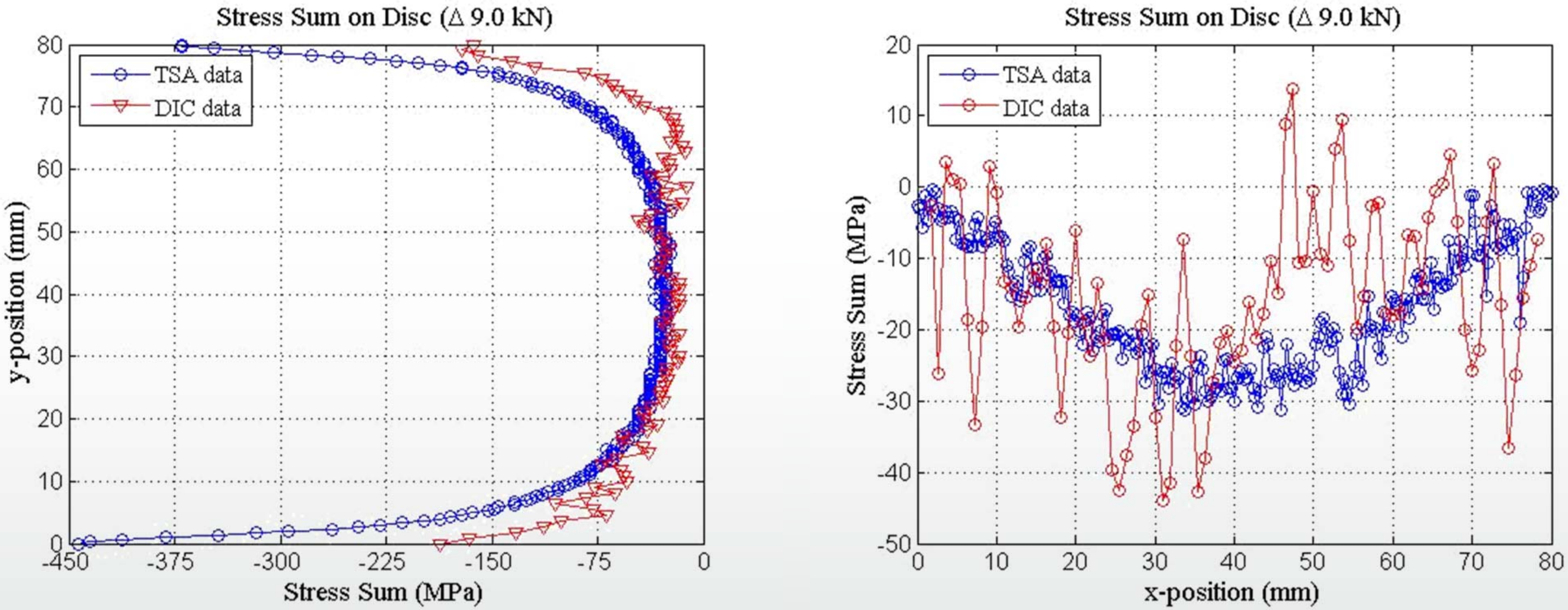


$$\begin{cases} \sigma_{xx} = \dfrac{F}{\pi t R} - \dfrac{2F}{\pi t} \dfrac{(R-y)x^2}{\left[x^2+(R-y)^2\right]^2} - \dfrac{2F}{\pi t} \dfrac{(R+y)x^2}{\left[x^2+(R-y)^2\right]^2} \\ \sigma_{yy} = \dfrac{F}{\pi t R} - \dfrac{2F}{\pi t} \dfrac{(R-y)^3}{\left[x^2+(R-y)^2\right]^2} - \dfrac{2F}{\pi t} \dfrac{(R+y)^3}{\left[x^2+(R-y)^2\right]^2} \\ \sigma_{xy} = \dfrac{2F}{\pi t} \dfrac{(R-y)^2 x}{\left[x^2+(R-y)^2\right]^2} - \dfrac{2F}{\pi t} \dfrac{(R+y)^2 x}{\left[x^2+(R+y)^2\right]^2} \end{cases}$$

Stresses (MPa)

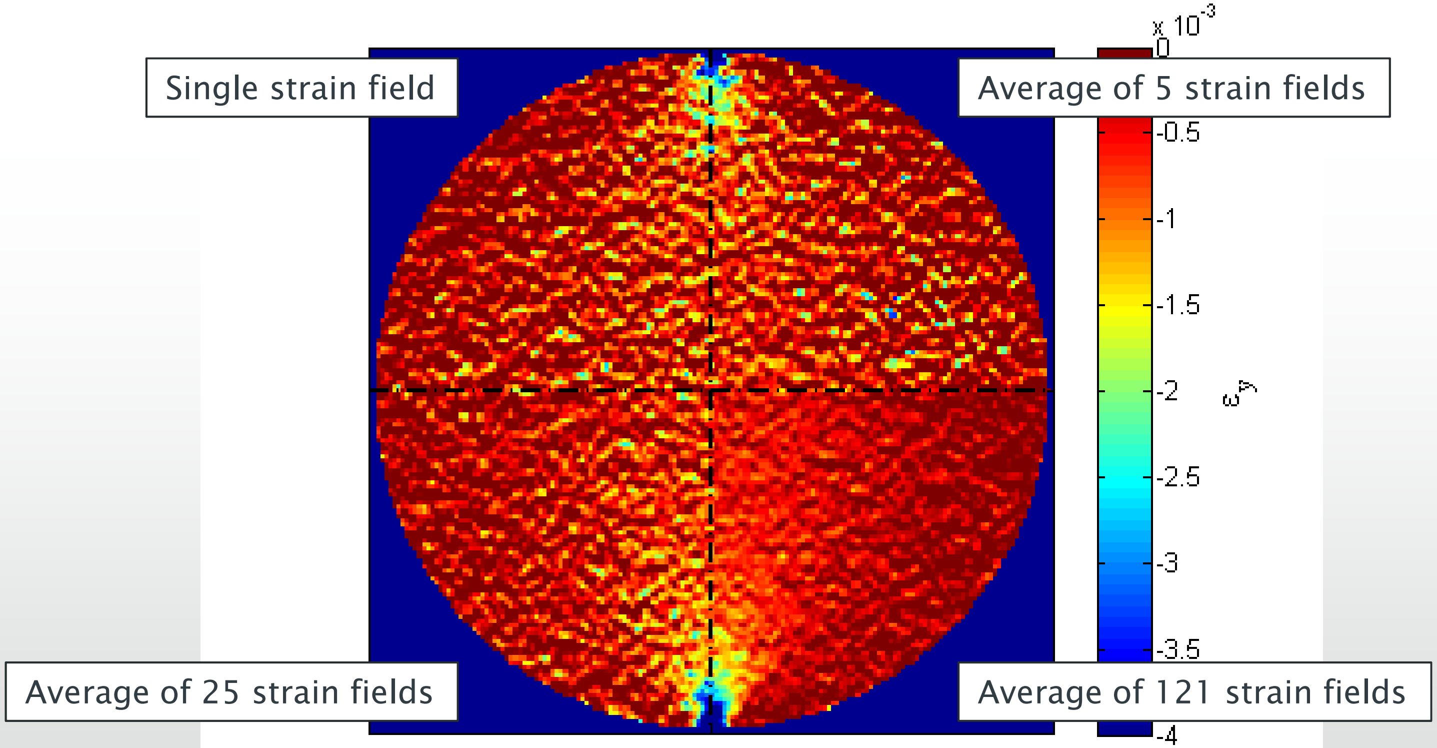


Brazilian Disc – comparison of DIC and TSA



DIC over multiple images

22 images from a quasi static test were combined in all 121 permutations, and the average of all the resulting strain fields was used.



Lock-in processing in TSA

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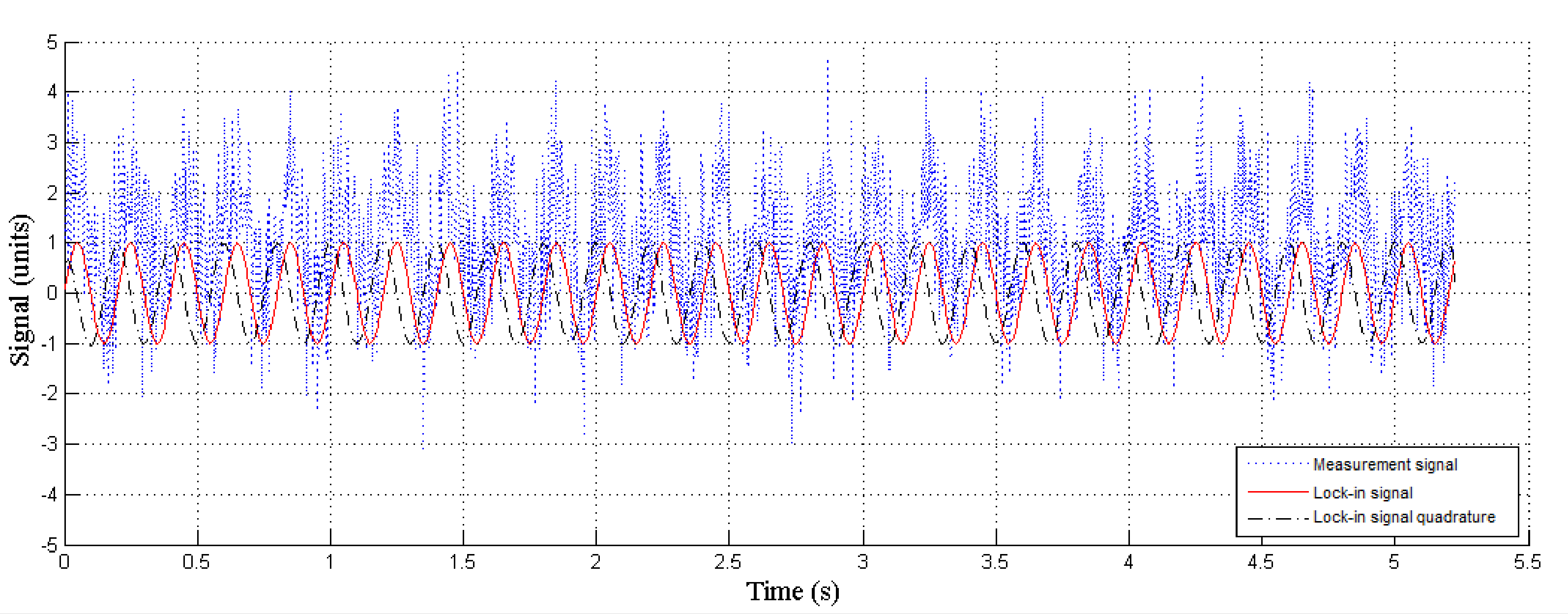
- Example of a typical noisy measurement signal in TSA.
  - Noise and signal are of similar amplitude.
- A reference signal is obtained that contains only the frequency of interest.
  - The reference signal is split into a sine and cosine part.



Lock-in processing

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- The measurement and reference signals are combined to give the amplitude and relative phase angle.

$$X = \frac{1}{N/2}\sum_{i=1}^{N} \underbrace{f(t_i)}_{\text{Measurement signal}} \underbrace{r_s(t_i)}_{\text{Reference signal sine and cosine parts}}$$

Measurement signal

Reference signal sine and cosine parts

$$Y = \frac{1}{N/2}\sum_{i=1}^{N} f(t_i) r_c(t_i)$$

$$A = \sqrt{X^2 + Y^2}$$

Application to DIC

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Challenges:

- Low recording rates (Nyquist condition)
  - Camera specifications:
    - Sensor: Sony ICX655, 2452 x 2056 pixels
    - Sensor pitch: 3.45 µm
    - Maximum frame rate: 9 Hz
    - Image bit depth: 8 – 12 bit
- Large data quantities (short recording lengths)
- Long recording durations (static scene assumption)

Lock-in DIC

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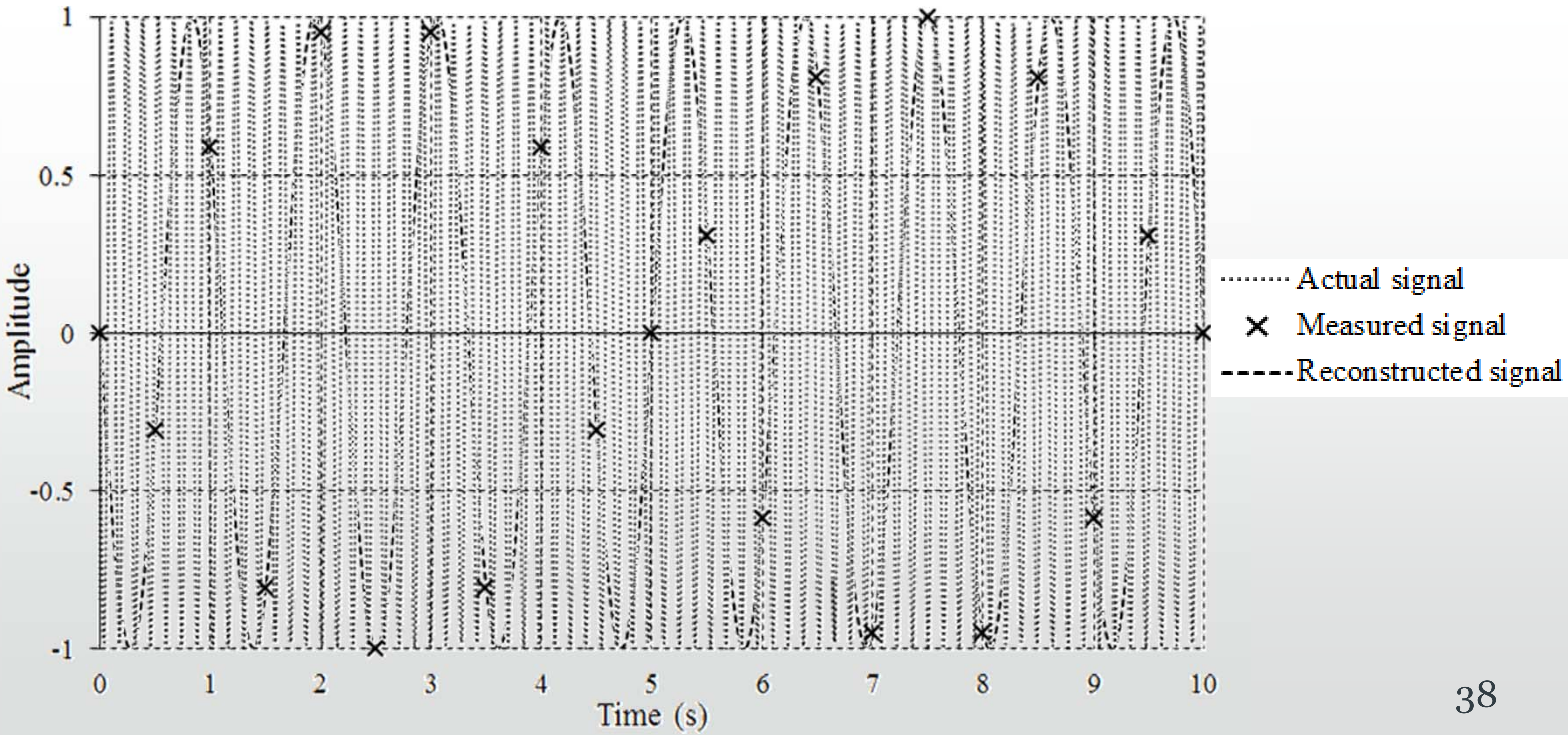
- Example:
  - Signal frequency: 7.1 Hz
  - Recording frequency: 2.0 Hz
  - Reconstructed signal: 0.9 Hz



Lock-in DIC

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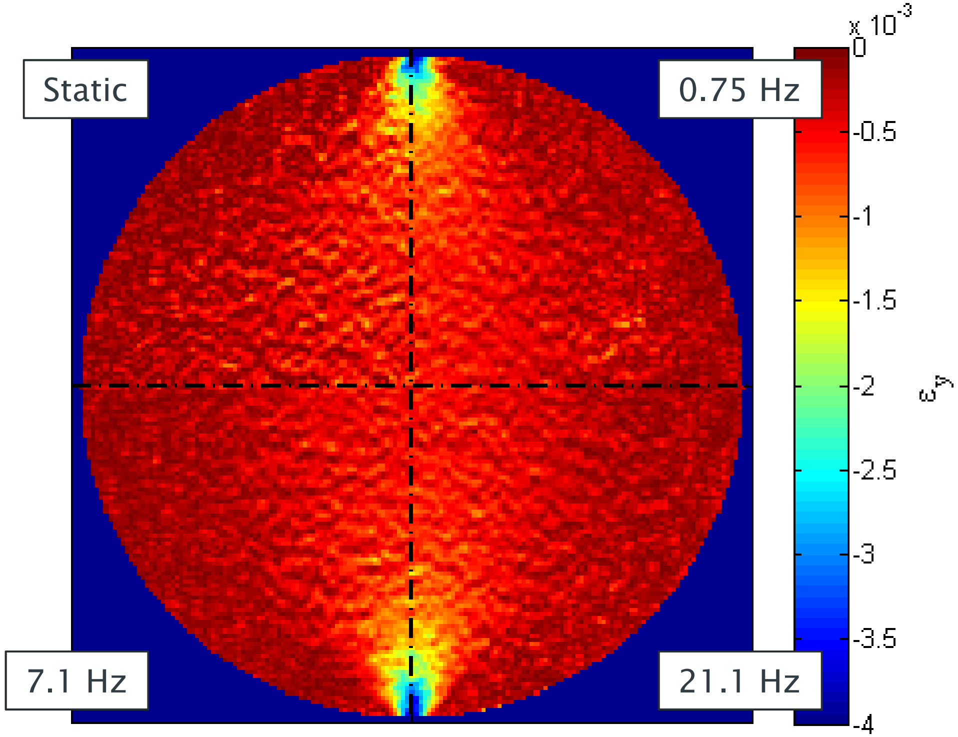
- Visual comparison between quasi-static 121 images and dynamic



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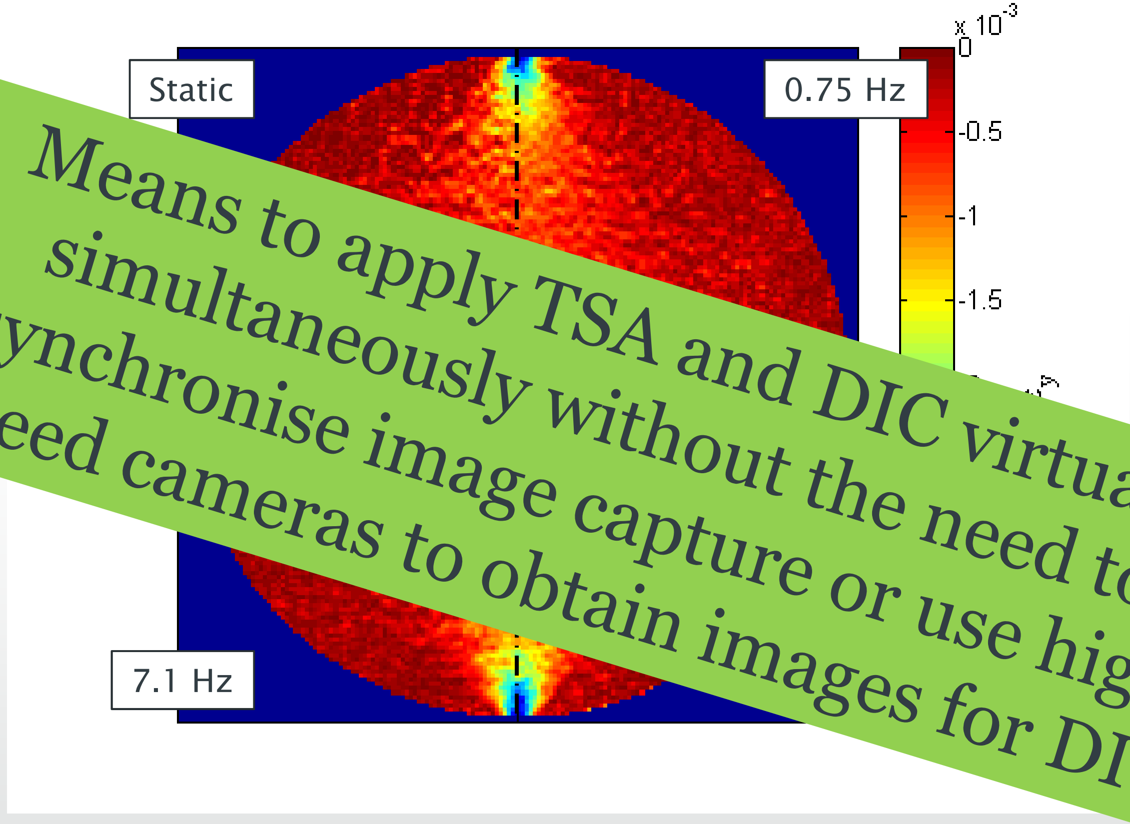

Means to apply TSA and DIC virtually simultaneously without the need to synchronise image capture or use high speed cameras to obtain images for DIC

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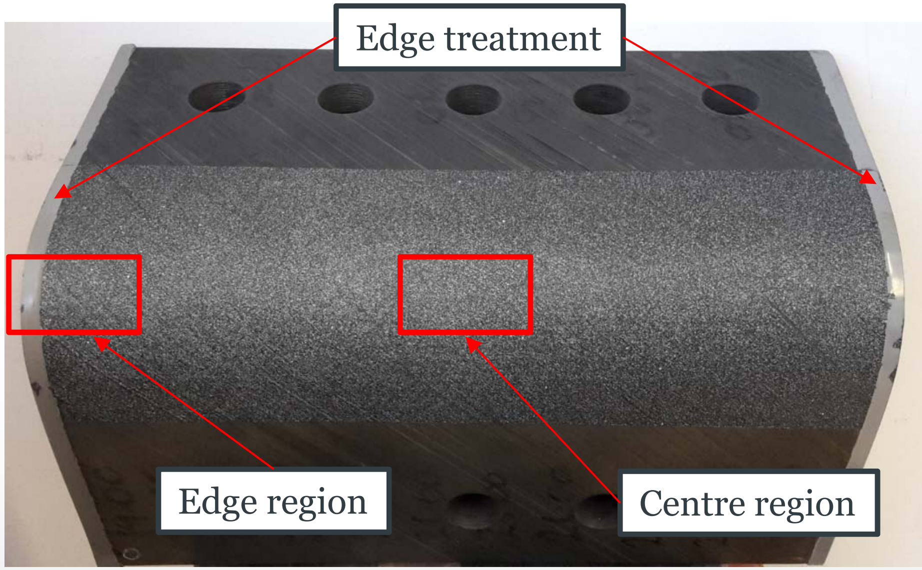
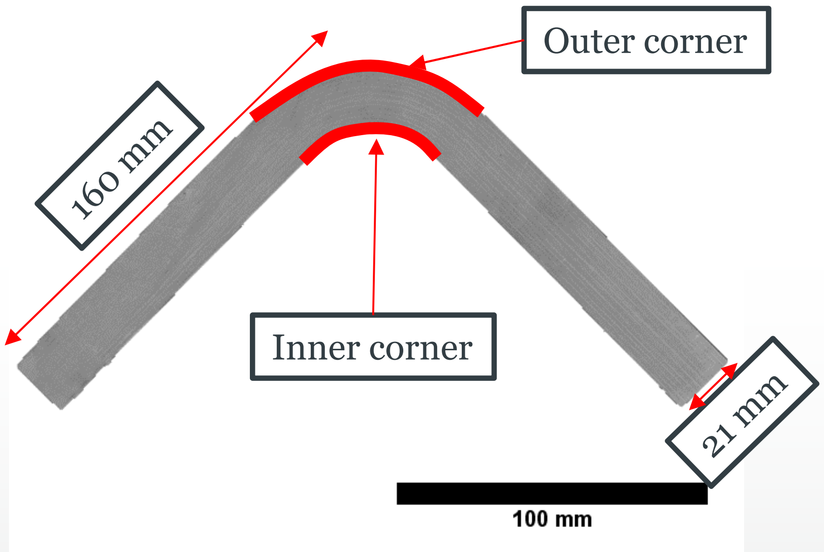
The test component



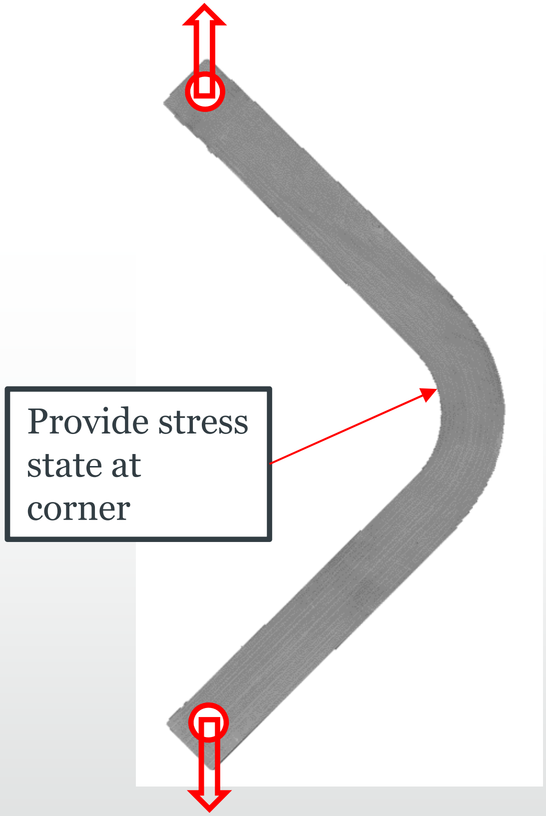


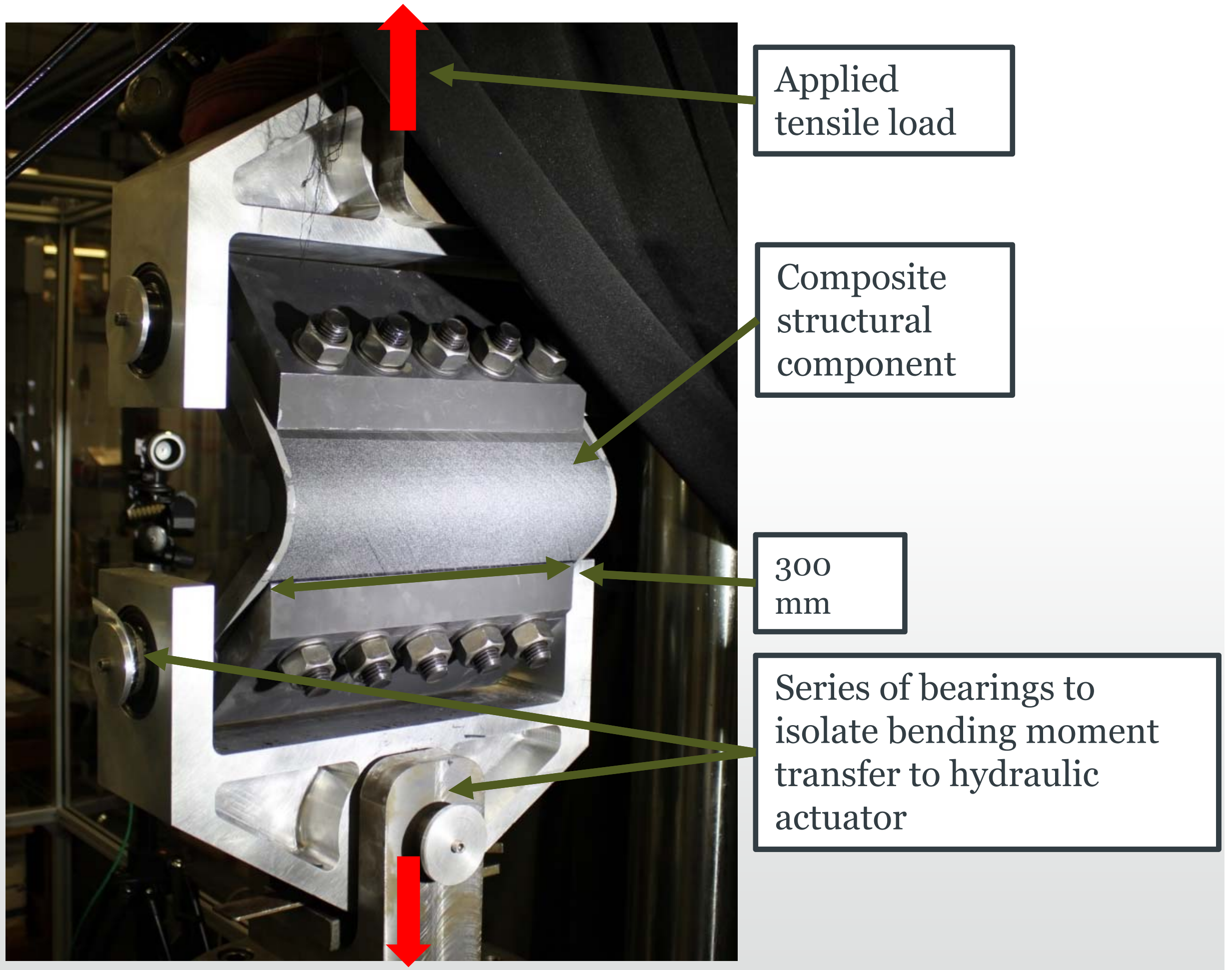
300 mm

Surface preparation: thin layer of matt black paint for TSA
Fine white speckle for DIC (~6 speckles per mm)

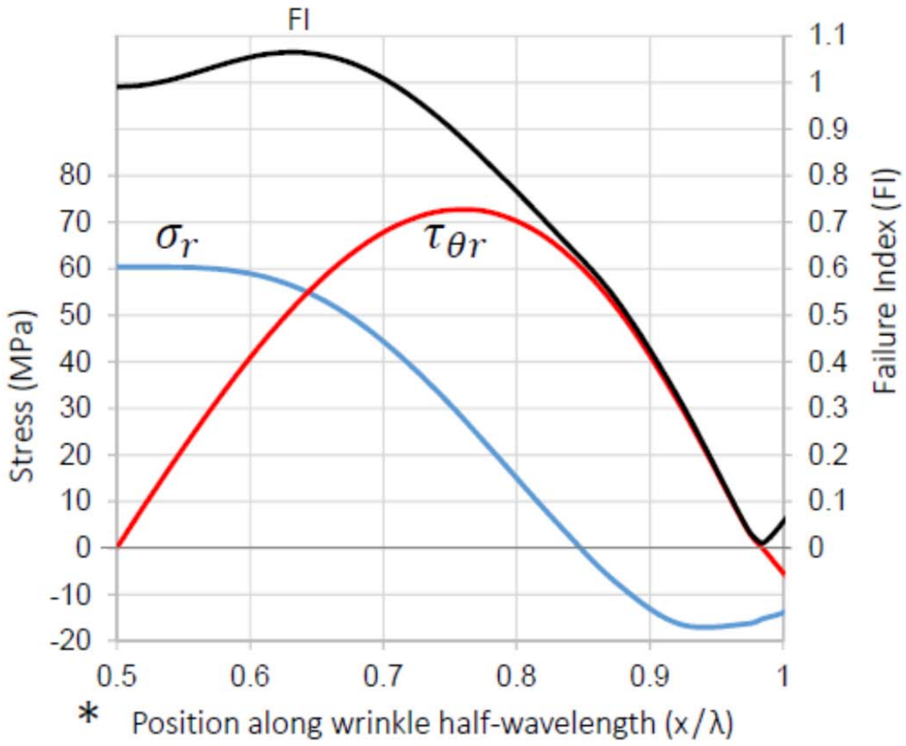
T.A. Fletcher et al., Resin treatment of free edges to aid certification of through thickness laminate strength. Composite Structures 146 (2016) 26-33

Loading test rig in test machine





Model Predictions



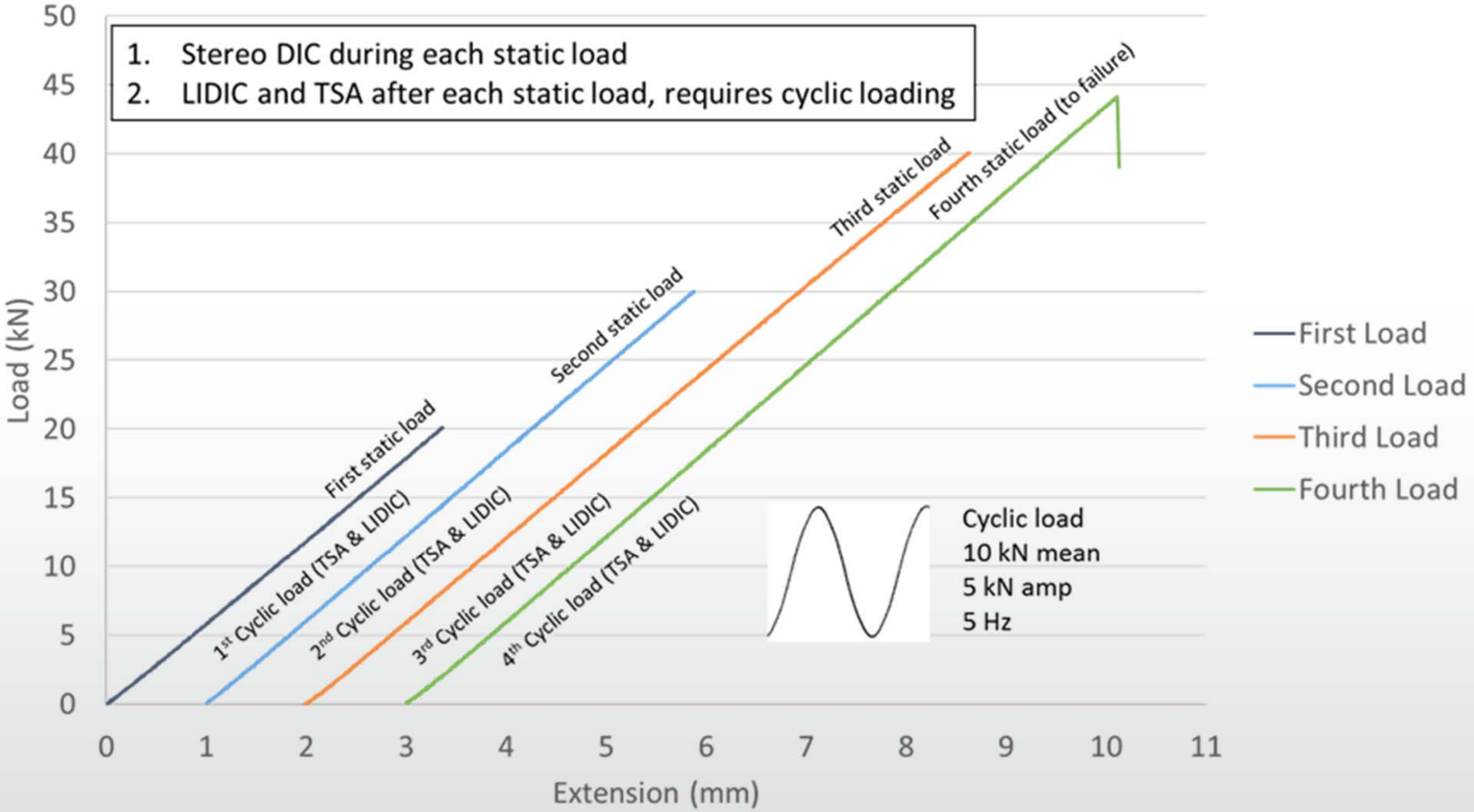
$$FI = \sqrt{\left(\frac{\sigma_{33}^{+}}{s_{33}}\right)^2 + \left(\frac{\tau_{13}}{s_{13}}\right)^2 + \left(\frac{\tau_{23}}{s_{23}}\right)^2}$$

- At 45 kN, FI = 1.06 (left figure)
- At 43 kN, FI = 1 (predicted failure)
- Pristine specimen (no wrinkle) predicted to fail at 88 kN

Potential for virtual testing in future

- Developing bespoke FE solver in *dune**.
- Uses iterative solver >10 times faster than direct solvers for large problems.
- Scales well over 100s of processors.
- Accuracy compares well with Abaqus.

Wing spar loading



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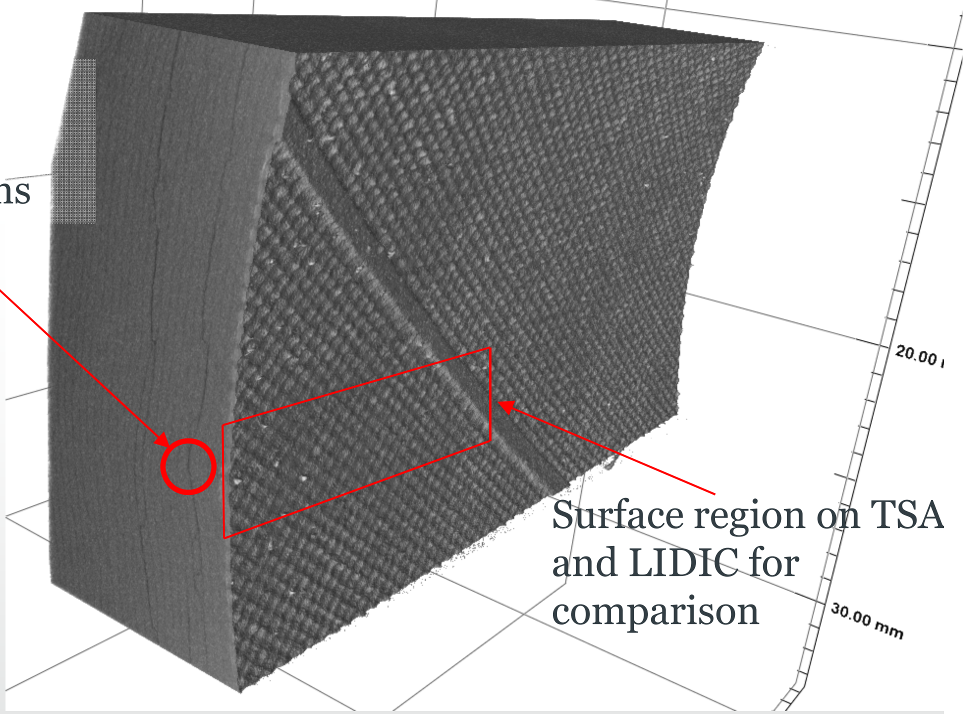
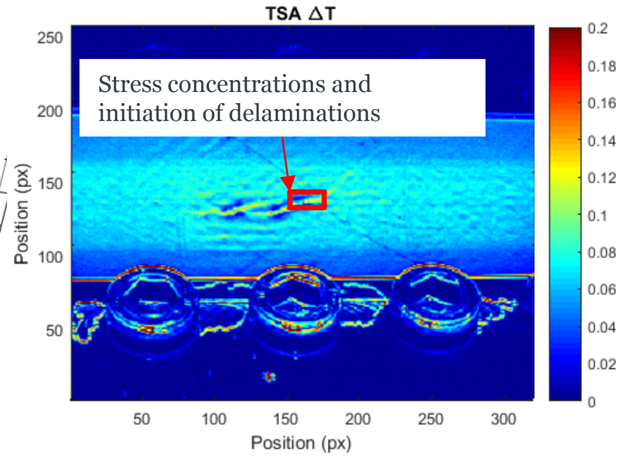
Results

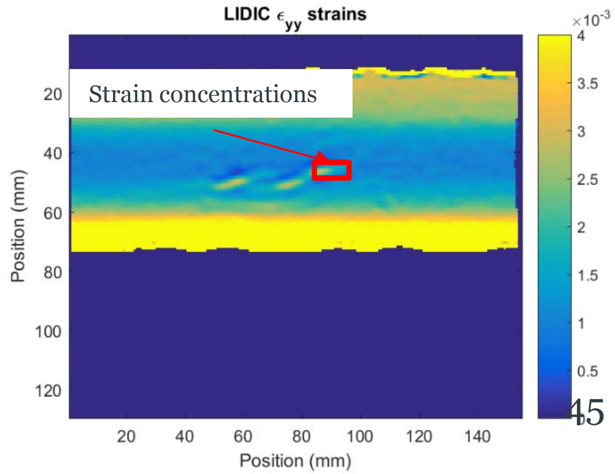
X-ray CT scan after failure, 3D rendering: centre location

Subsurface winkle & delaminations

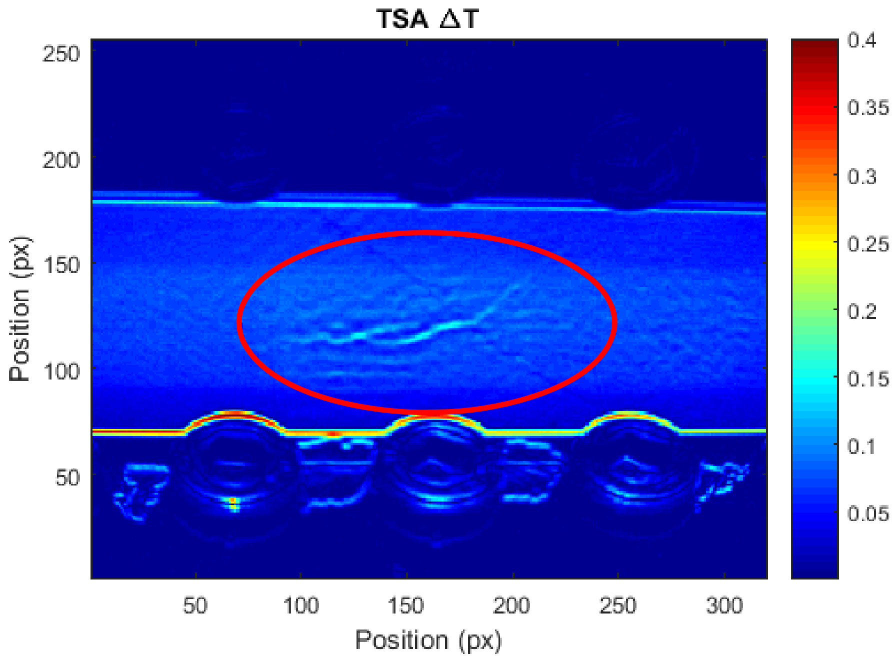


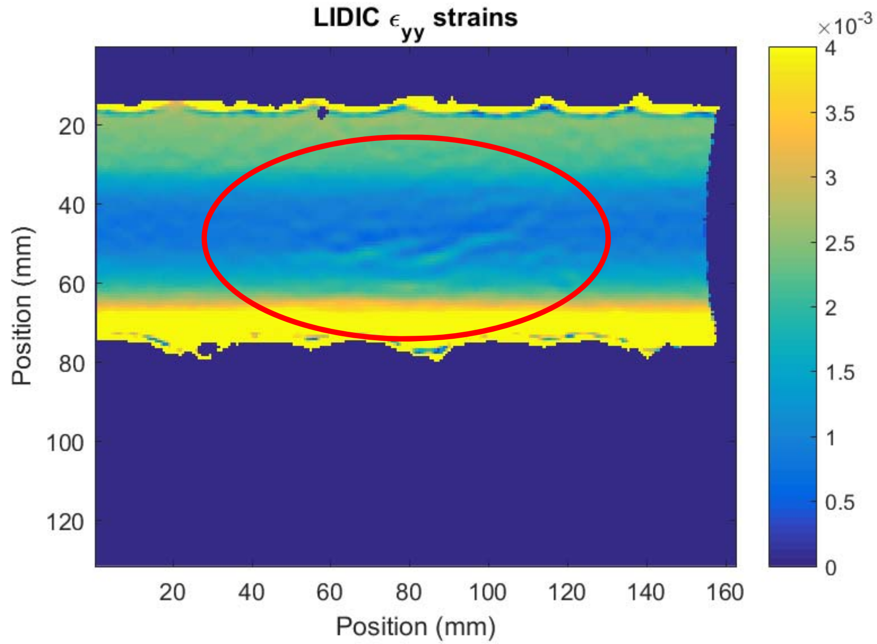
Surface region on TSA and LIDIC for comparison





TSA and LIDIC comparison: after first (20kN) load





Wrinkle detected in both TSA and LIDIC

Mean load: 10 kN; Amplitude: 5 kN; 5 Hz

TSA: Inner corner after 1st, 2nd, 3rd and 4th load (delamination failure at 45 kN)

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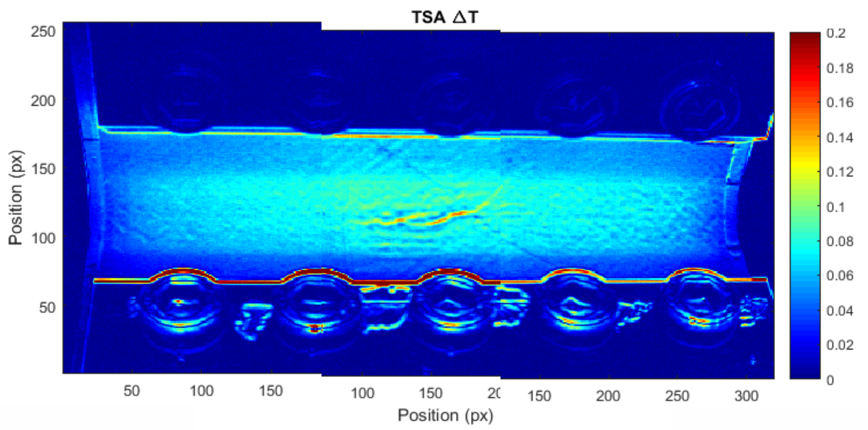
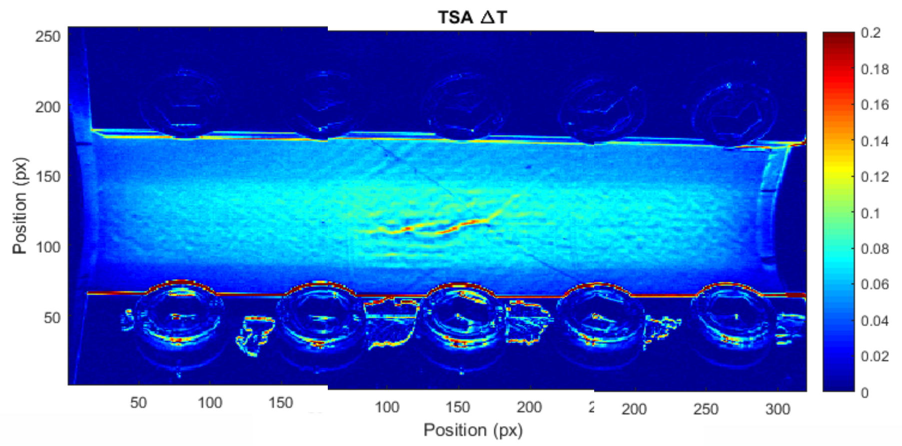
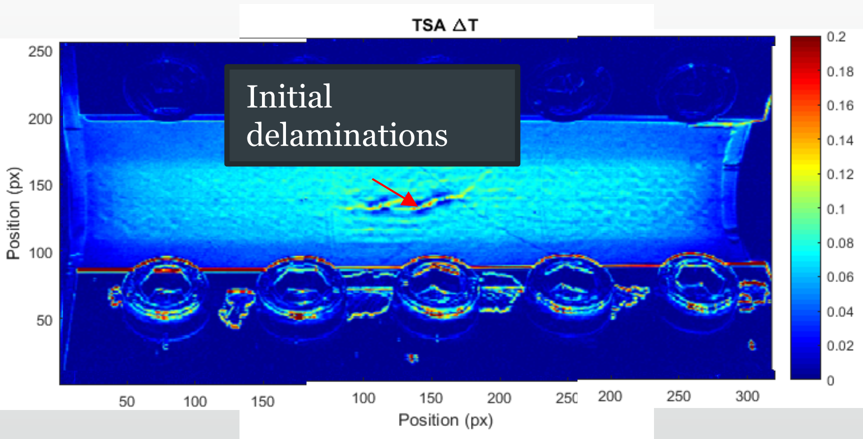
After 1st load



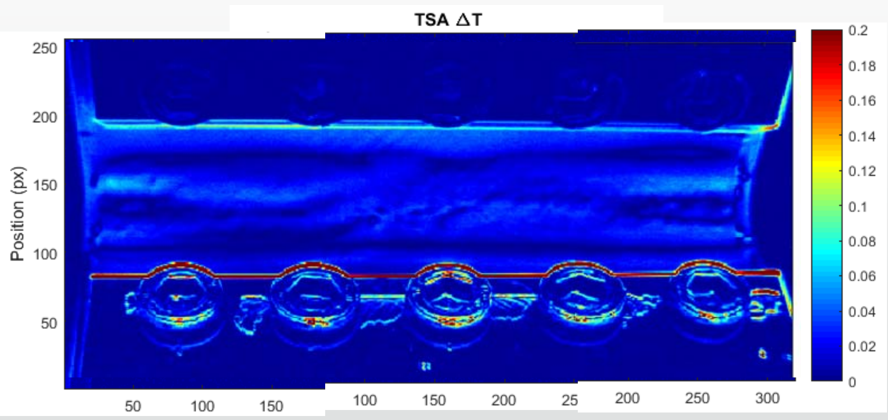
After 2nd load



After 3rd load



After 4th load



TSA: Inner corner after 1st, 2nd, 3rd and 4th load (delamination failure at 45 kN)

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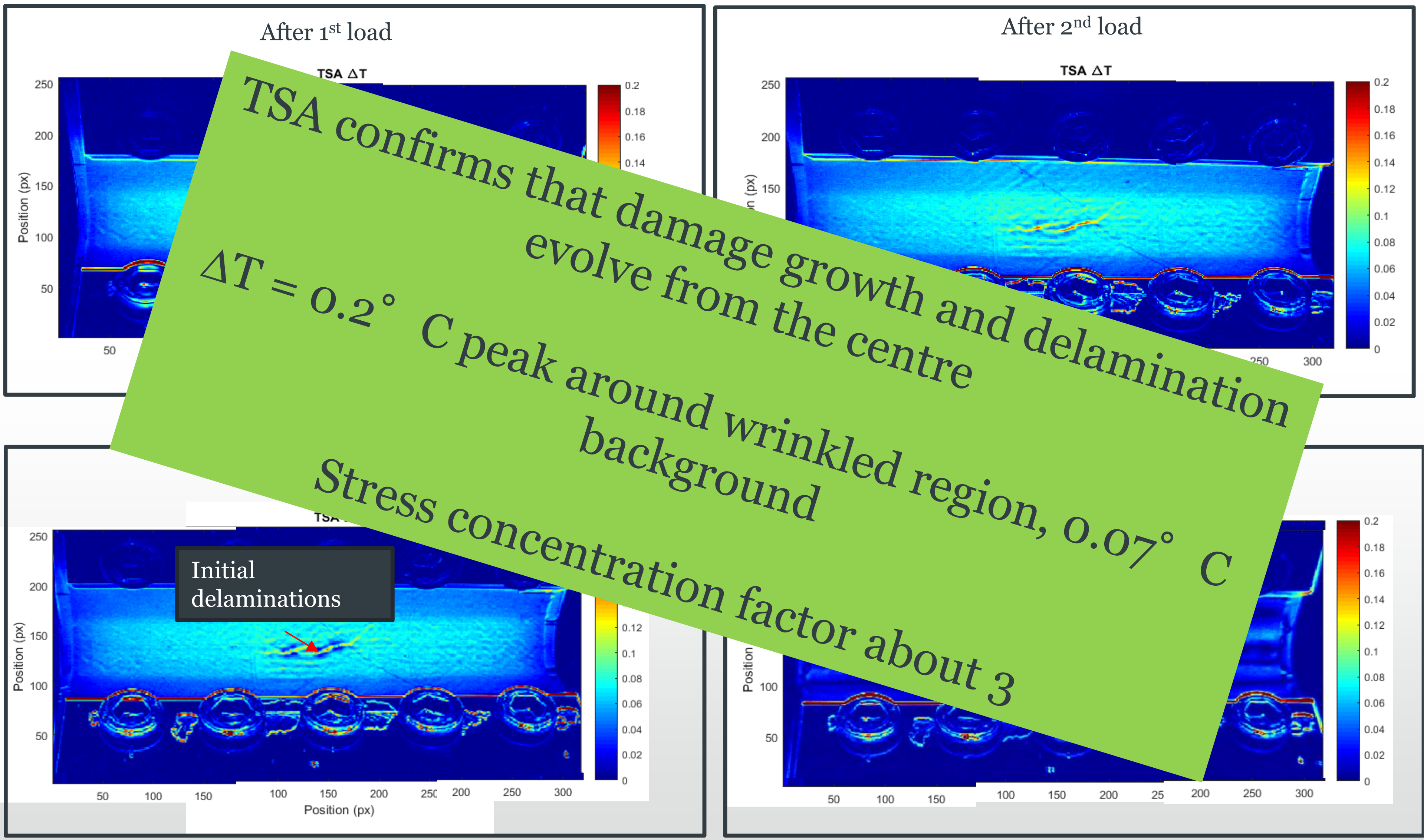

TSA confirms that damage growth and delamination evolve from the centre

ΔT = 0.2° C peak around wrinkled region, 0.07° C background

Stress concentration factor about 3

ε_{yy} after load steps 1-4 – inner surface of specimen

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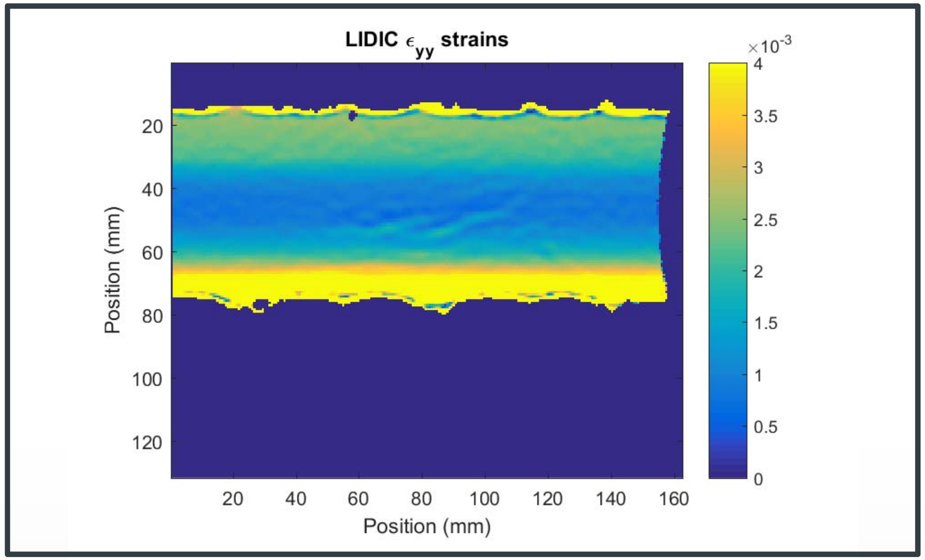
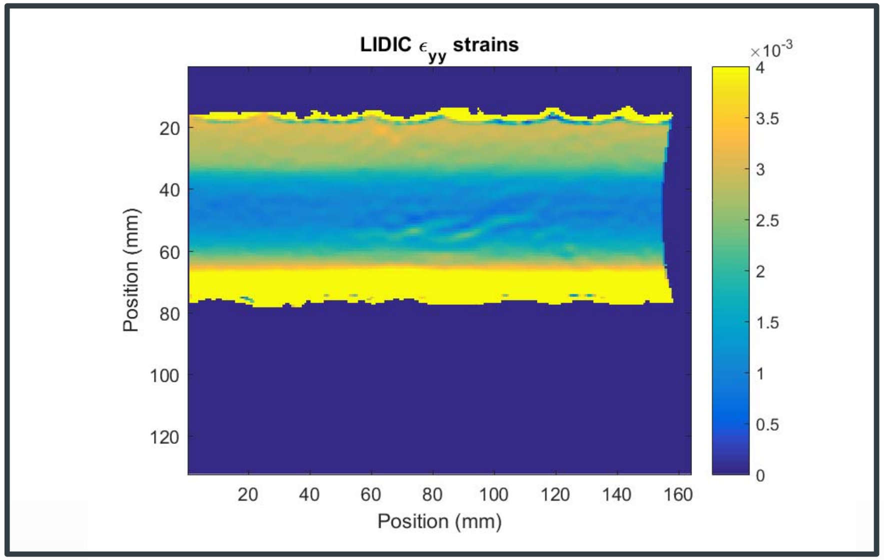
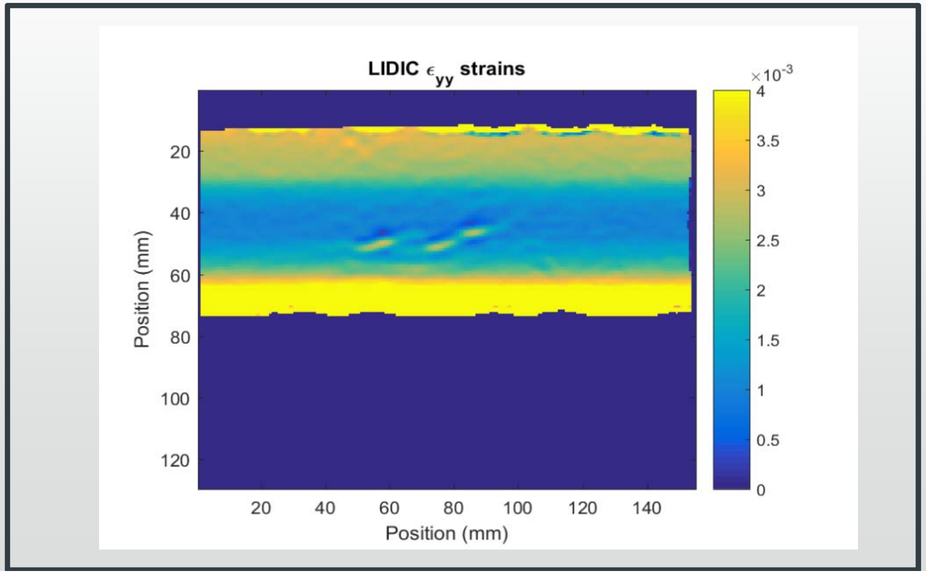
After 1st load



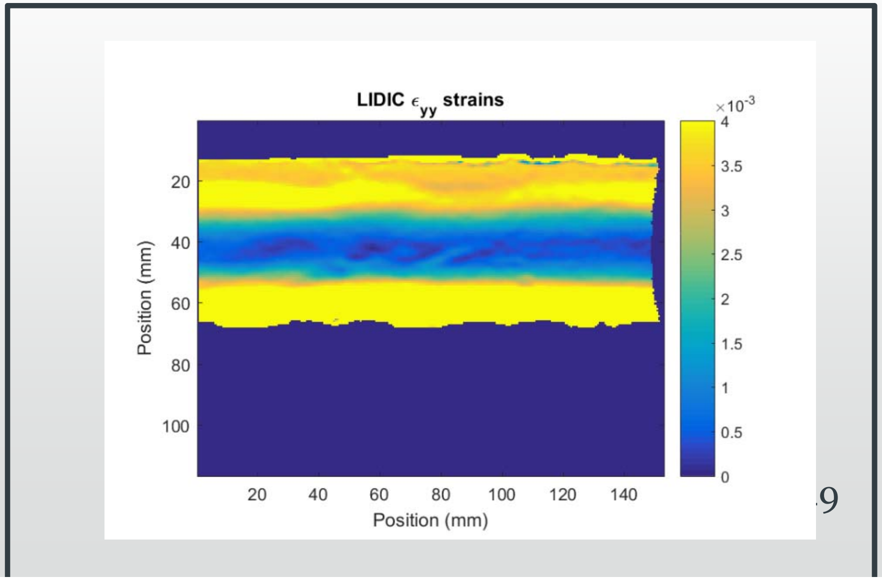
After 2nd load



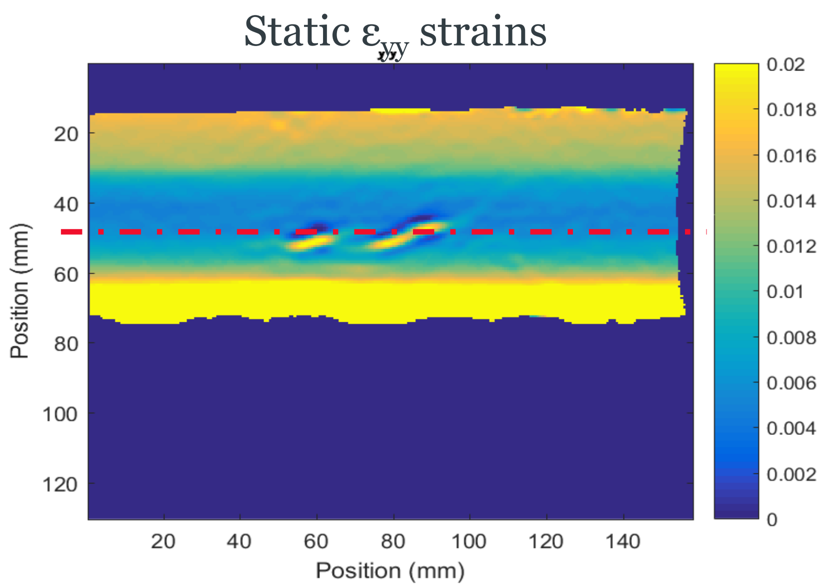
After 3rd load

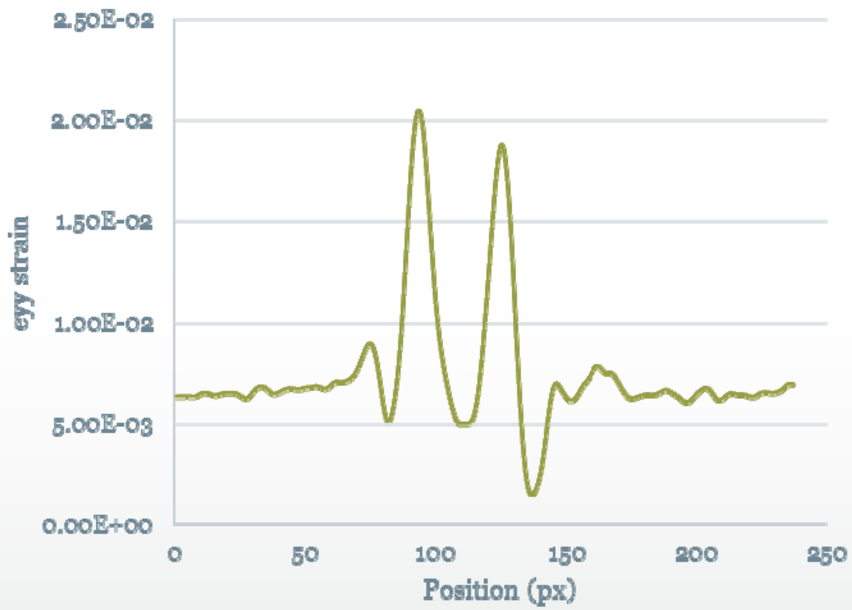


After 4th load



ε_{yy} immediately prior to load drop 44.1 kN





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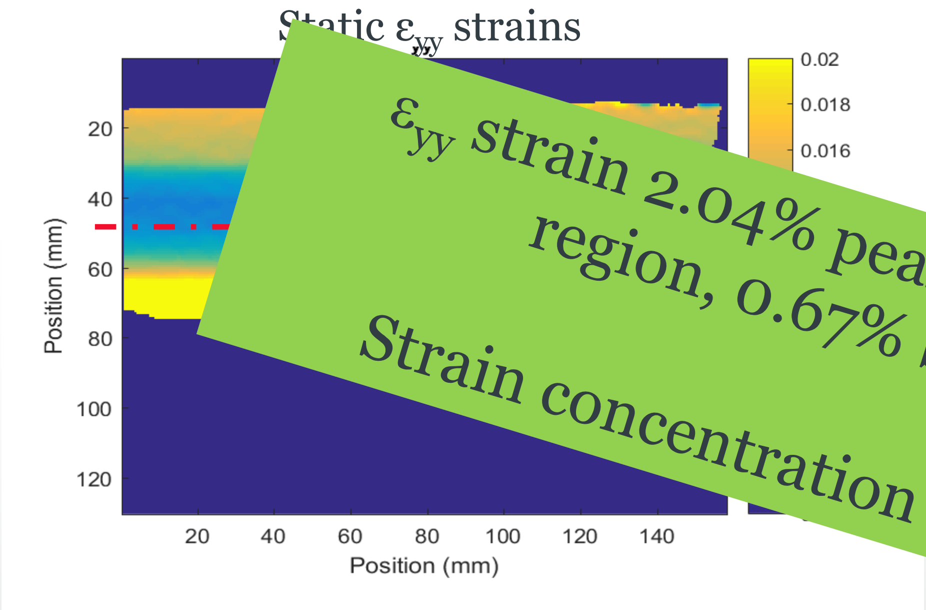
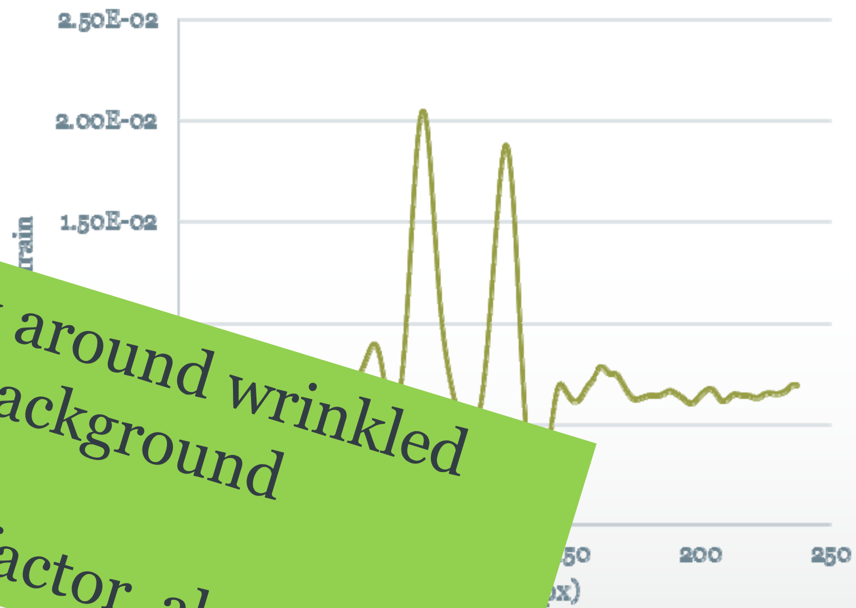




ε_{yy} strain 2.04% peak around wrinkled region, 0.67% background

Strain concentration factor about 3

How far did we get – feasibility demonstrated?

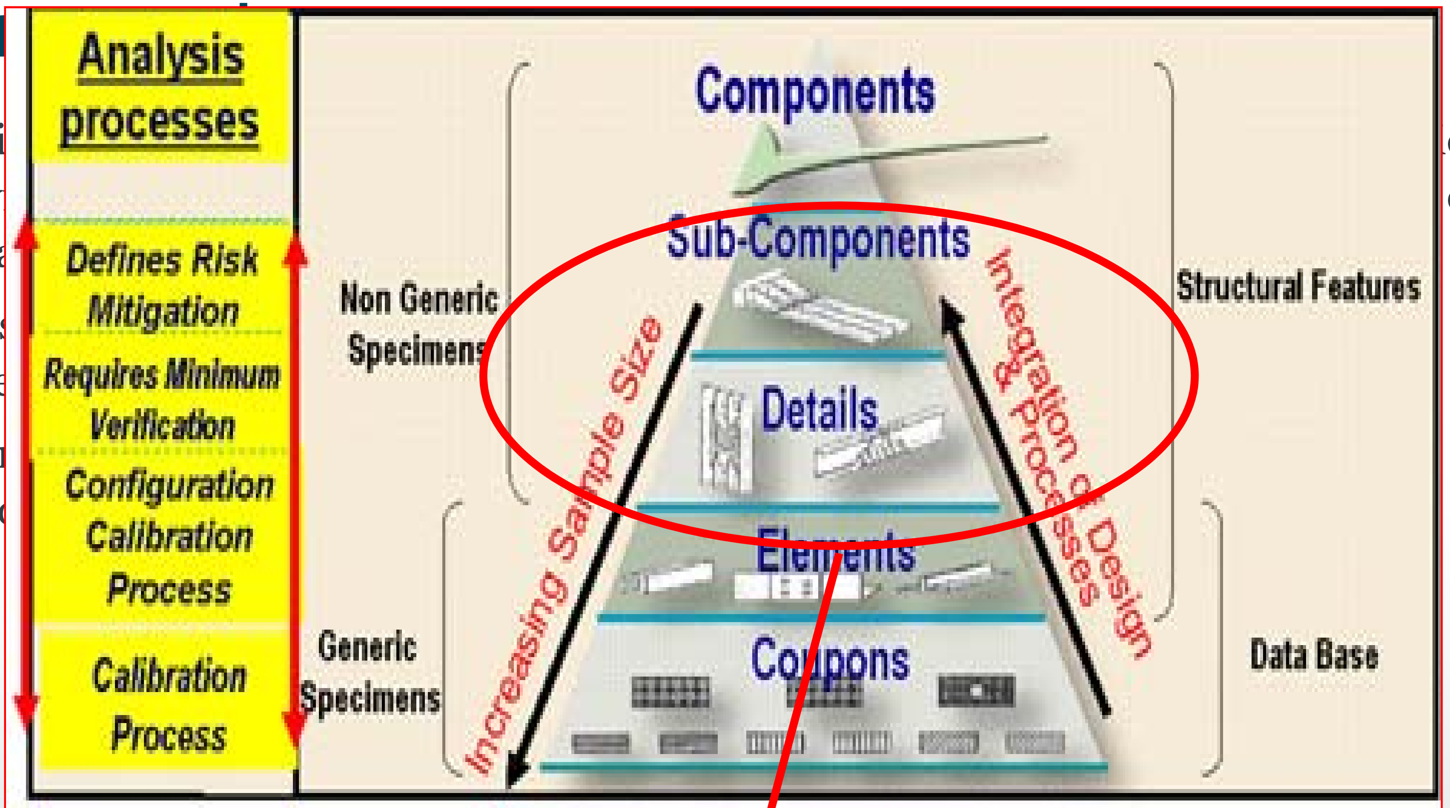
- Composite substructure modelling and testing conducted successfully
- X-ray CT scan identified sub-surface wrinkle in spar corner
- TSA and LIDIC capture sub-surface wrinkle defects - local stress and strain fields & load redistribution during initiation and progression of delamination
- High-fidelity FE model accurately predicts onset of delamination failure – good correspondance between predicted (43 kN) and observed (44.1 kN) failure loads

Future directions & final comments

- Siemens Gamesa Renewable Energy – 2 newly started PhD projects on 'high-fidelity wind blade substructure/component testing' (AIMS: improved understanding of damage and failure envelopes, reduced safety factors, certification process)
- Establish a industry-university-regulatory body network - focus on composite aerostructures
- Prepare and submit a large grant proposal to EPSRC (UK) on 'Integrated high fidelity composite substructure testing and multi-scale analysis'
  - Demonstrators:
    - More complex and larger substructures/components
    - Realistic 'in-situ' & multiaxial loading states
    - Manufacturing defects & artefacts
  - Integration of 'virtual testing' (model based) and physical testing (data protocols, approaches/measures for 'validation' of predictions)
  - Probabilistic methodology – 'statistical base' for design and certification
  - Certification requirements – 'design for certification'

Future directions & final co...

- Si... ...delity w... ...of da...
- Es... ae...
- Pr... fi...



'High fidelity testing integrated with multi-scale modelling'
Centre of testing pyramid populated!

- Certification requirements – 'design for certification'

N|I|L = National Infrastructure Laboratory & 'Structures 2025'

- **Boldrewood Innovation Campus**
- Co-location with Lloyd's Register's Global Technology Centre
- N|I|L total cost £47M - £26 M from EPSRC/UKCRIC
- Completion ultimo 2018 – launch first quarter 2019
- Part of the UK Collaboratorium for Research in Infrastructure and Cities - UKCRIC

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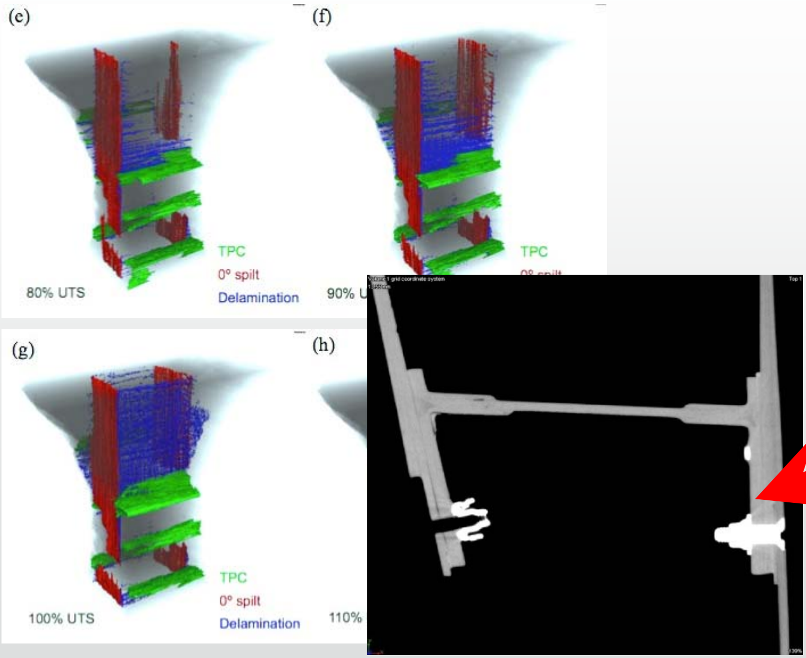
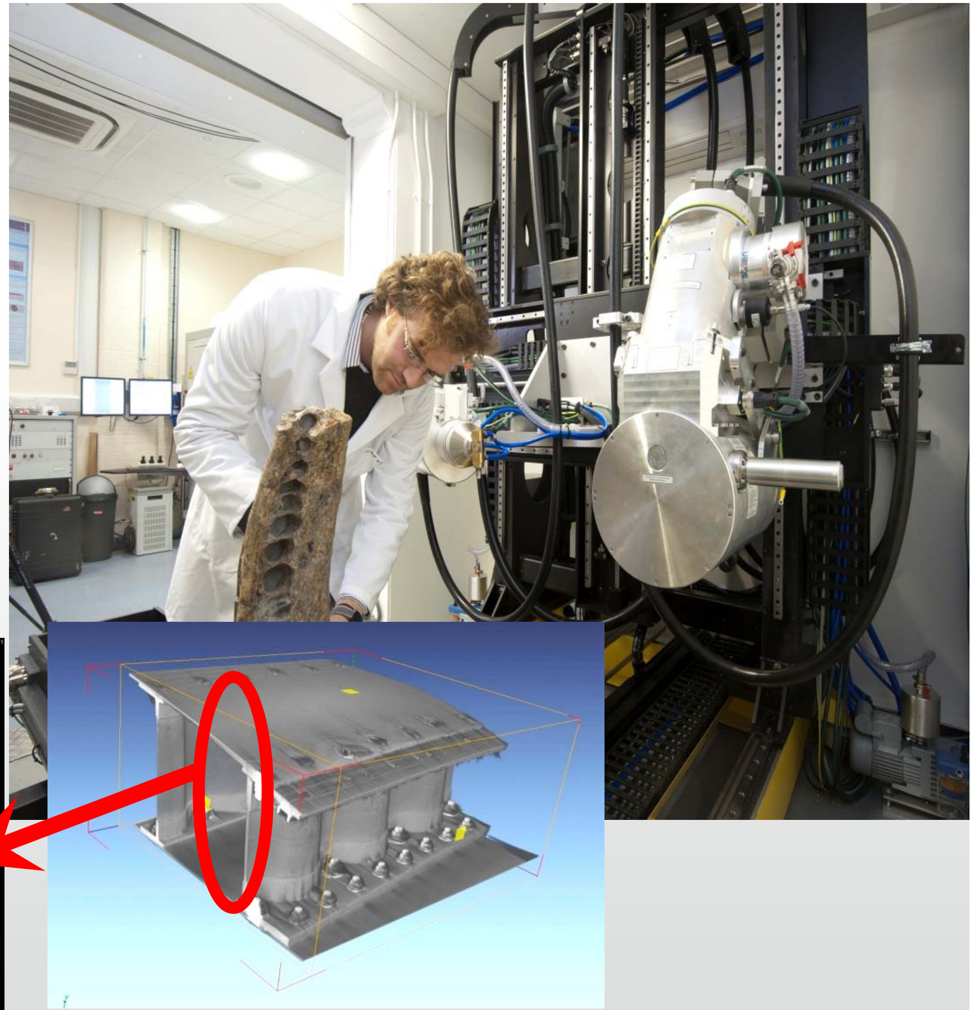
Material and component testing

- USP: imaging systems including white light and Infrared techniques, such as Digital Image Correlation and Thermoelastic Stress Analysis
- Facilities: Testing machines/frames 1 to 630 kN, high speed/strain rate testing, drop hammer test rig, high/low temperature capability

Micro-computed tomography

- Seven complementary μ-CT systems
- Resolutions down to 200nm
- Largest, highest energy, high resolution CT in UK University sector
- 5 X-ray CT units/hutches





Multi-scale materials and structures testing centre

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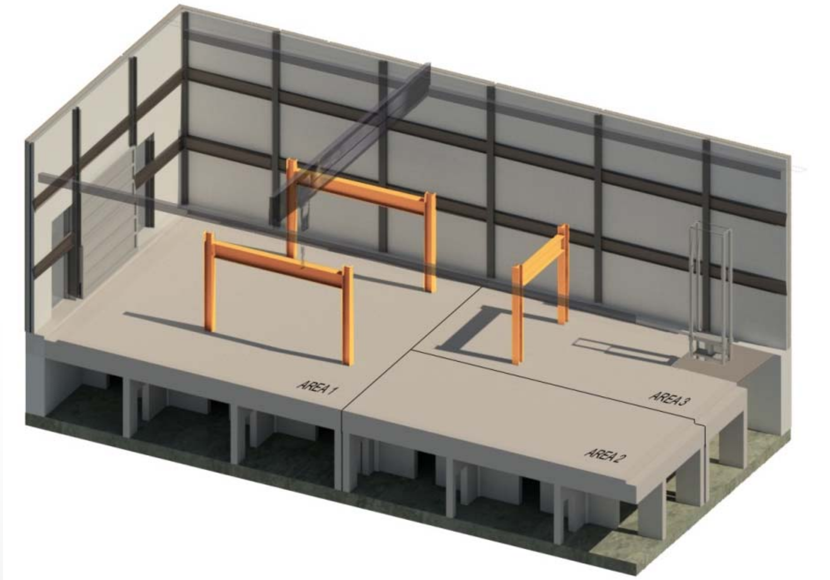

30 m by 15 m strong floor for multi-axial testing of large structures

STRUCTURES 2025: A HIGH FIDELITY, DATA RICH, PARADIGM FOR STRUCTURAL TESTING (£1.2M – UK Engineering and Physical Sciences Research Council /£1.0 M from Industry – Strategic Equipment Grant)

Structures 2025 Vision

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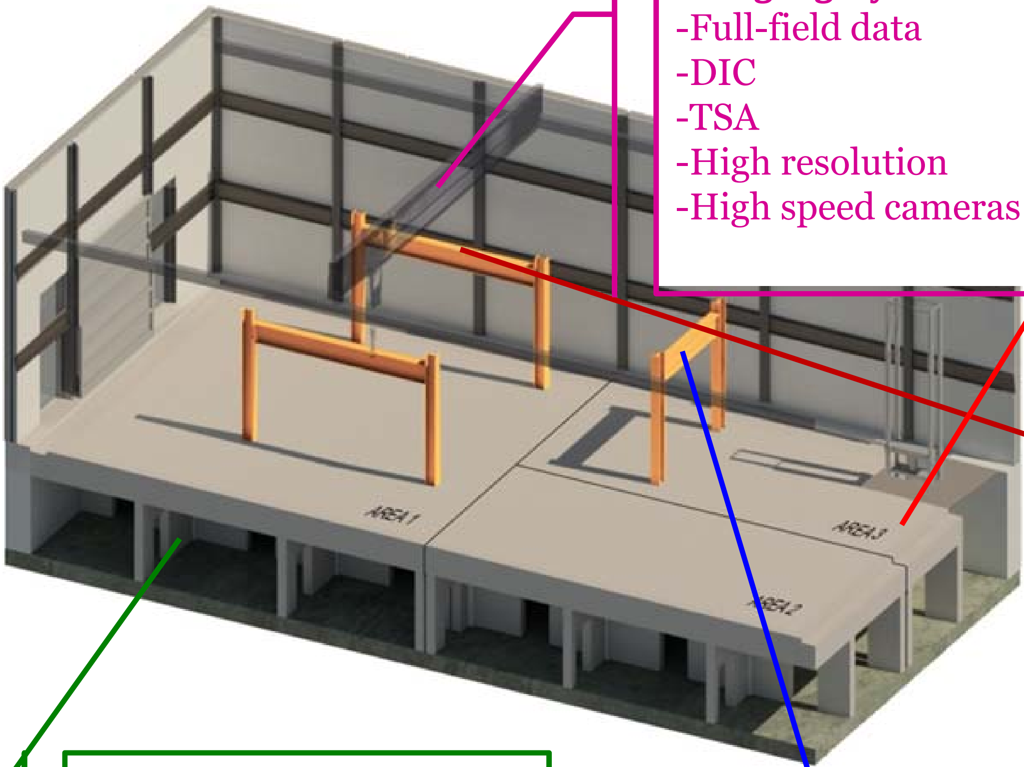
Imaging Systems
-Full-field data
-DIC
-TSA
-High resolution
-High speed cameras

Strong floor
- 1m thick reinforced concrete
- 1m spaced strong points
- Large load capacity



Actuators:
-Large load range
-Synchronous control
-Flexibility

Hydraulics
- 1000 l/min ring main
- Large deflections
- High loads
- ‘Plug and play’
- Complex loading

Load frames:
-Multi axial loading
-Flexible set up
-Large structures
-Modular design

Structures 2025 Vision

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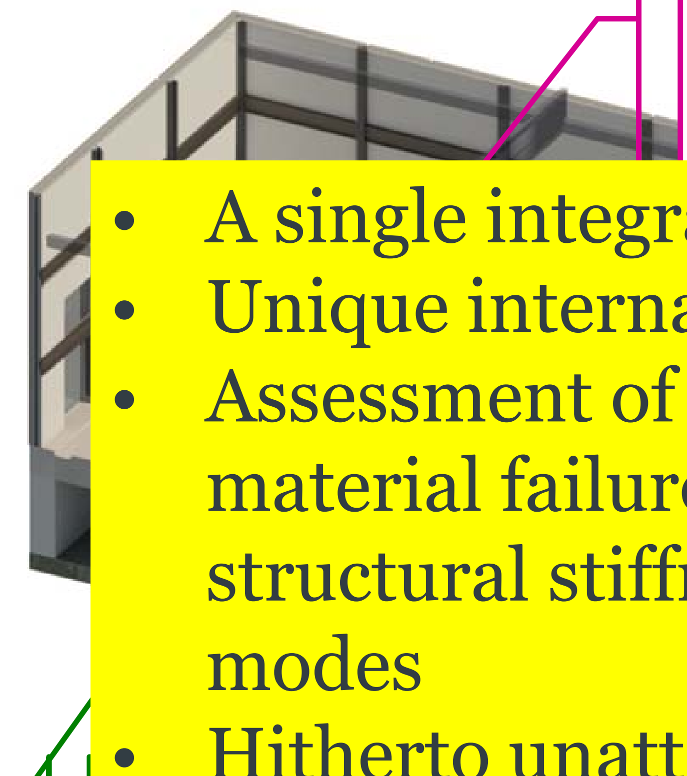

Imaging Systems
- Full-field data
- DIC
- TSA

Strong floor
- 1m thick reinforced concrete

points

ty

- A single integrated system
- Unique internationally
- Assessment of interactions between material failure mechanisms/modes and structural stiffness/strength driven failure modes
- Hitherto unattainable level of physical realism and fidelity

- High loads
- ‘Plug and play’
- Complex loading

- Flexible set up
- Large structures
- Modular design

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Why Imaging?

- An entire field can be observed as opposed to a single point (i.e. full-field),
- High resolution, both spatially and temporally making it data-rich,
- The field of view is controlled by the optics, which means it can cover multiple scales,
- Non-contact which means the measurement device does not modify the measurement.

Structures 2025: Goal

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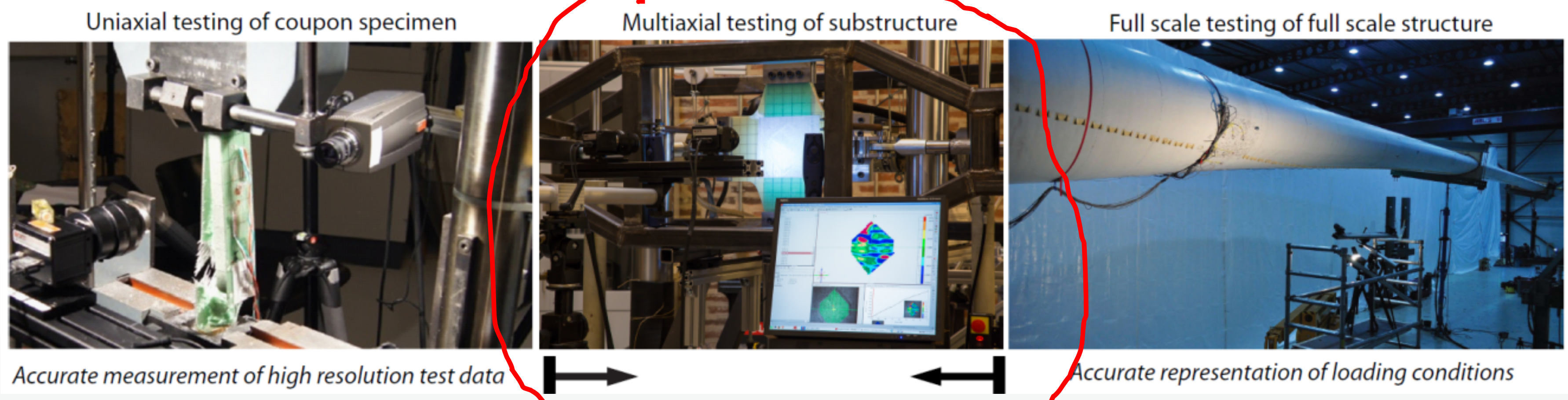

Revolutionise sub-structure, component and large scale testing!

Questions?