CompTest 2023

Full Field Data Fusion (FFDF) to characterise subsurface defects in composite structures

Janice Dulieu-Barton

Irene Jimenez Fortunato, Rafael Ruiz Iglesias, Emily Leung, Geir Olafsson, Ole Thybo Thomsen

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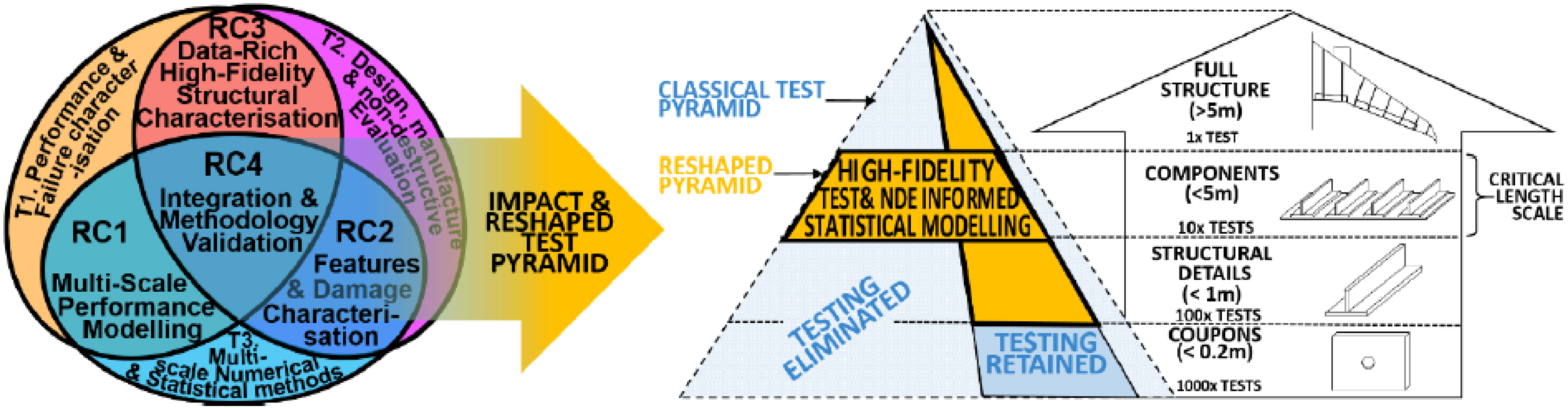
CERTEST Programme Grant



Overall aim is to be able to evaluate damage in composite substructure to provide an in-situ measure of subsurface damage in large scale tests

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Overview

- Introduce thermoelastic stress analysis (briefly)
- Combining TSA with DIC and application to CFRP
- Identifying non-adiabatic behaviour
- Revealing sub-surface defects
- Quantifying damage
- Progressing up the scale: application to sandwich structures… aerostructure….multiaxial tests

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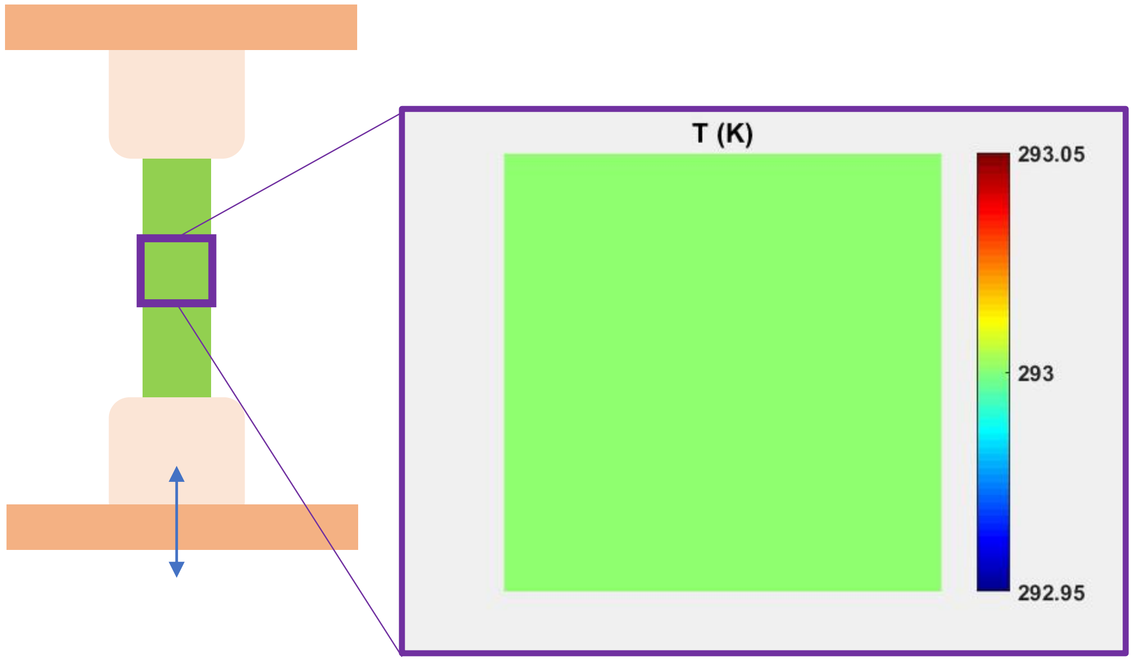
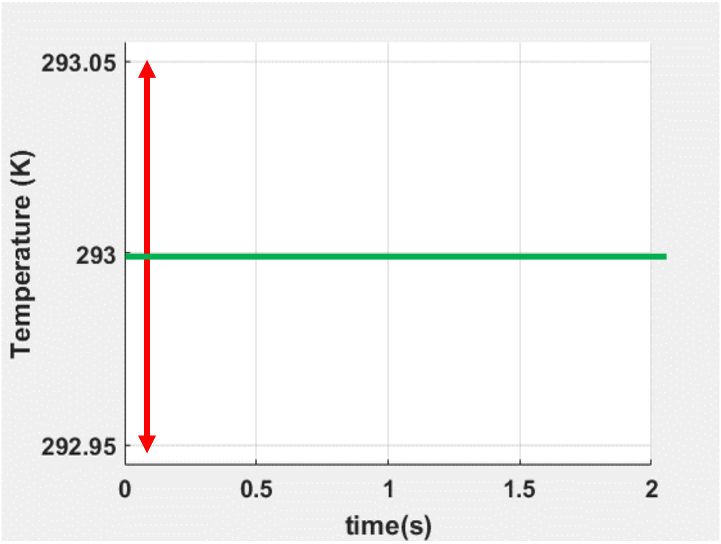
Thermoelastic stress analysis (TSA)





Assumes no heat transfer

Temperature change occurs adiabatically

Cyclic loading reduces diffusion

Lock-in notch filter

$$\Delta T = -\frac{1}{\rho C_p} T_0 (\alpha_1 \Delta\sigma_1 + \alpha_2 \Delta\sigma_2)$$

$$T(x,y,t) = \boxed{T_0} + 0.5\boxed{\Delta T}(x,y)\cos(2\pi f_0 t + \boxed{\phi})$$

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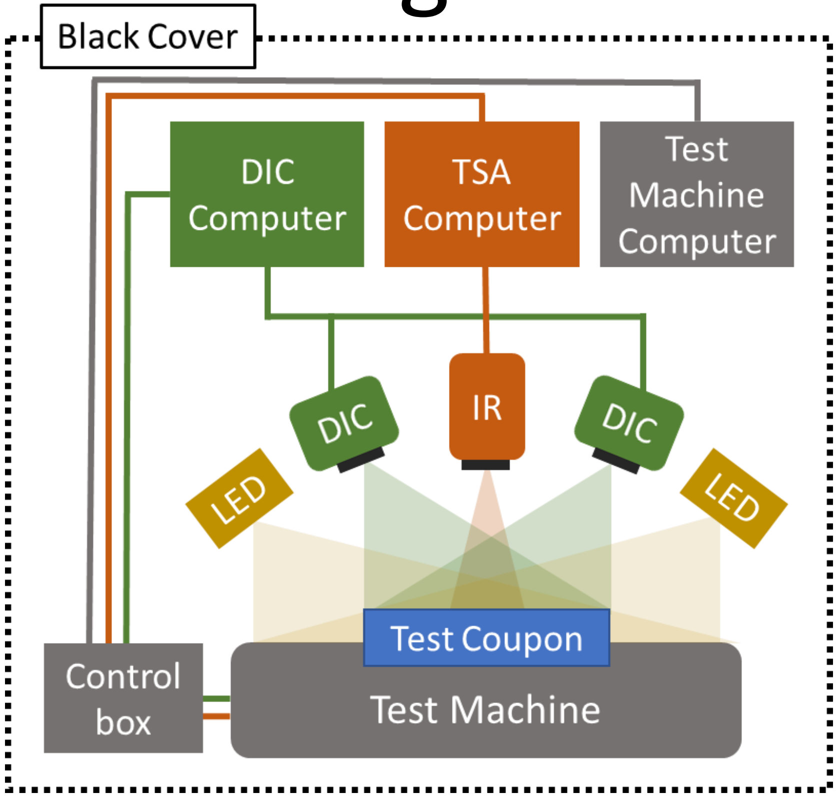
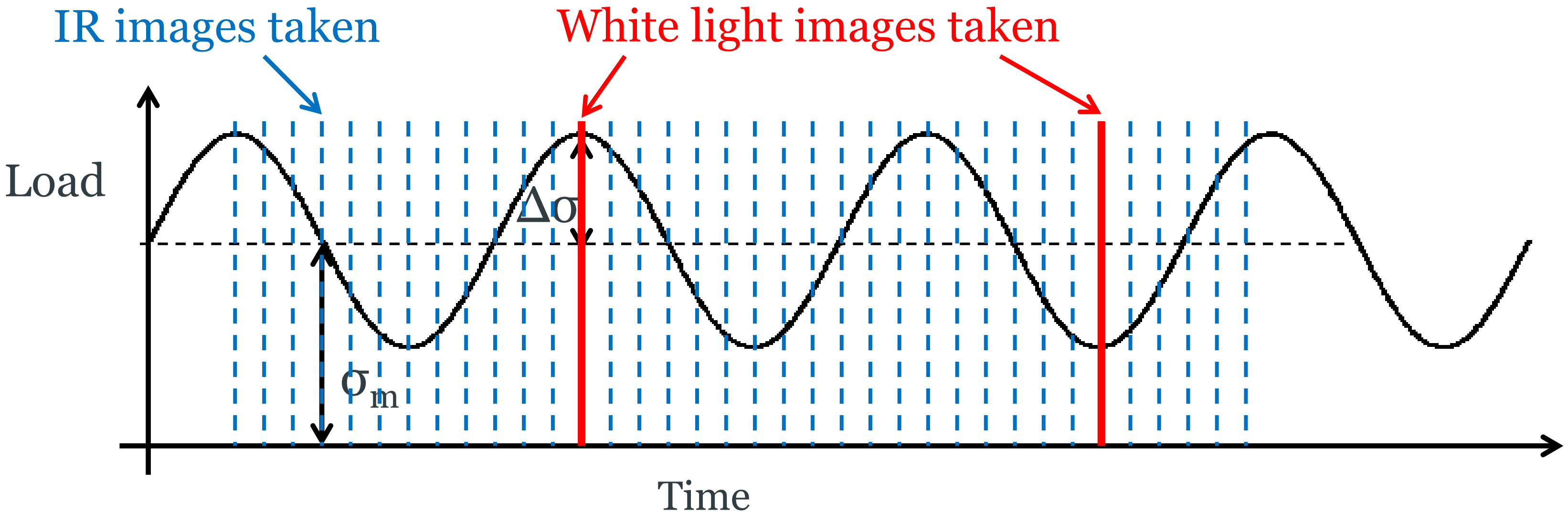
Combining TSA and DIC during cyclic loading





$$\varepsilon(x,y,t) = \varepsilon_0 + 0.5\Delta\varepsilon\,(x,y)cos(2\pi f_0 t + \phi)$$

- Triggering image capture avoids interrupting the cyclic loading
- BUT Precise camera triggering is required.
- Use the TSA lock-in processing to remove the need for triggering – notch filters DIC strains same as TSA

Optics and Lasers in Engineering 68 (2015) 149–159

Contents lists available at ScienceDirect

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ELSEVIER

The use of a lock-in amplifier to apply digital image correlation to cyclically loaded components

CrossMark

R.K. Fruehmann [a], J.M. Dulieu-Barton [a,*], S. Quinn [a], J.P. Tyler [b]

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[b] Enabling Process Technologies Ltd., Bristol BS20 8ET, United Kingdom

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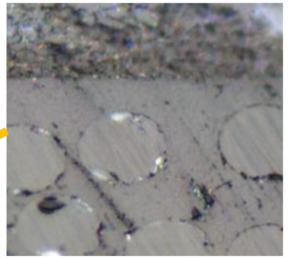
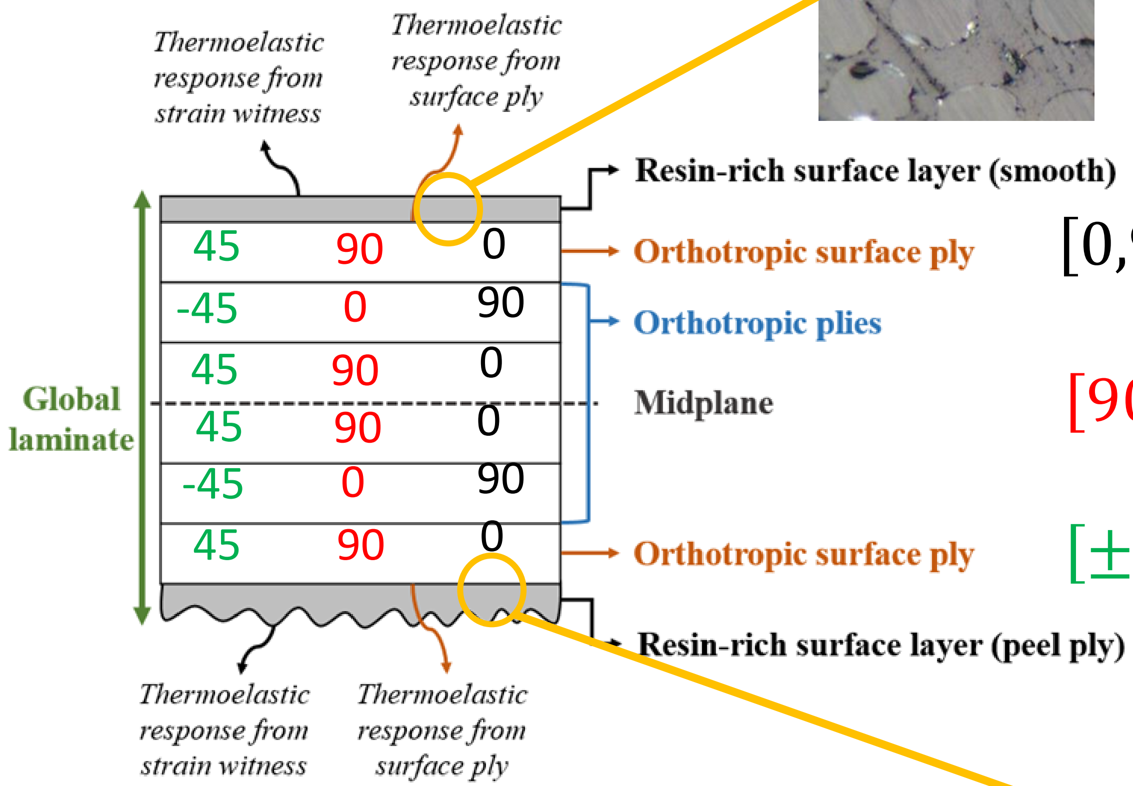
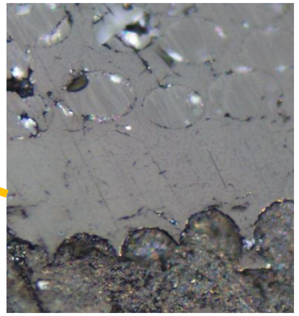
Typical composite laminate







$[0,90]_{3s}$

$[90,0]_{3s}$ Same mechanical behaviour

$[\pm 45]_{3s}$ Shear dominated

Simultaneous use of full-field imaging techniques

Thermoelastic Stress Analysis (TSA) – measured $\frac{\Delta T}{T_0}$

Digital Image Correlation (DIC) – independent calculation of $\frac{\Delta T}{T_0}$ from measured strains –using measured material properties

Specimens made from GFRP and CFRP

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Heat transfer in each laminate type

ΔT calculated from material properties for a constant strain

ΔT (K)	0	90	45/-45	resin	laminate
GFRP	0.1028	0.1014	0.0758	0.1180	0.1029
CFRP	0.0155	0.1186	0.0178	0.1438	0.0676

$$\dot{T} = \frac{T_0}{\rho C_\varepsilon} \frac{\partial \sigma_{ij}}{\partial T} \dot{\varepsilon}_{ij} - \cancel{\frac{\dot{Q}}{\rho C_\varepsilon}}$$

$$\dot{Q} = k \nabla^2 T$$

Thermal conductivity, *k*, is low

Little change in ΔT between plies

Adiabatic conditions

ΔT is the same in +45 and -45 ply – adiabatic conditions

Thick surface resin – strain witness

Thermal conductivity, *k*, high

Step changes in ΔT at ply interfaces

Non adiabatic behaviour at low frequencies

Laminate is homogenised/smeared value

Is ΔT occurring adiabatically – conduct tests at different loading frequencies

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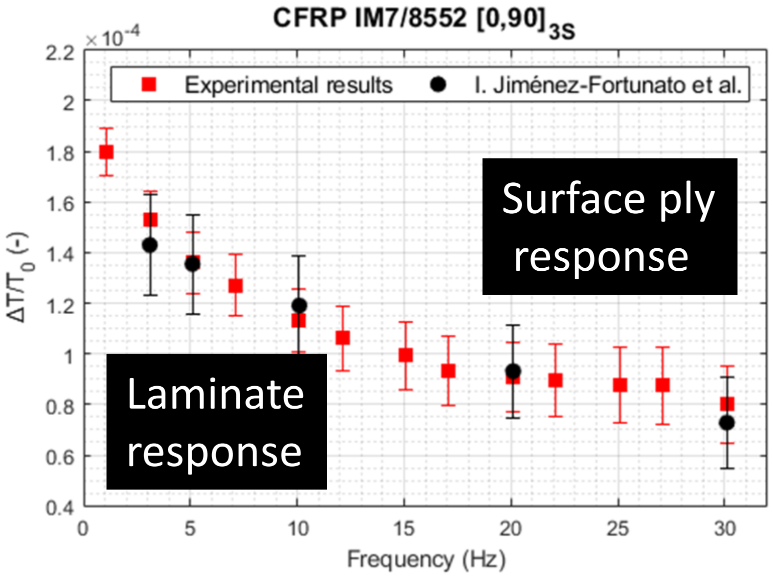
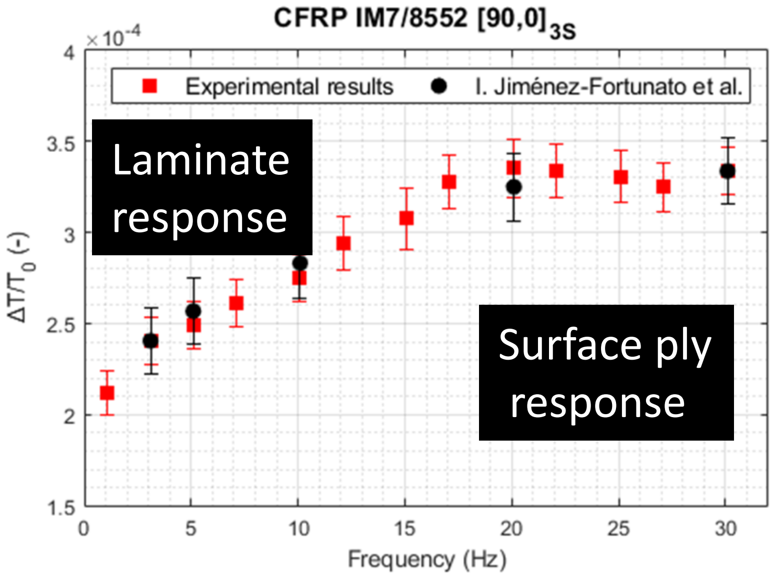
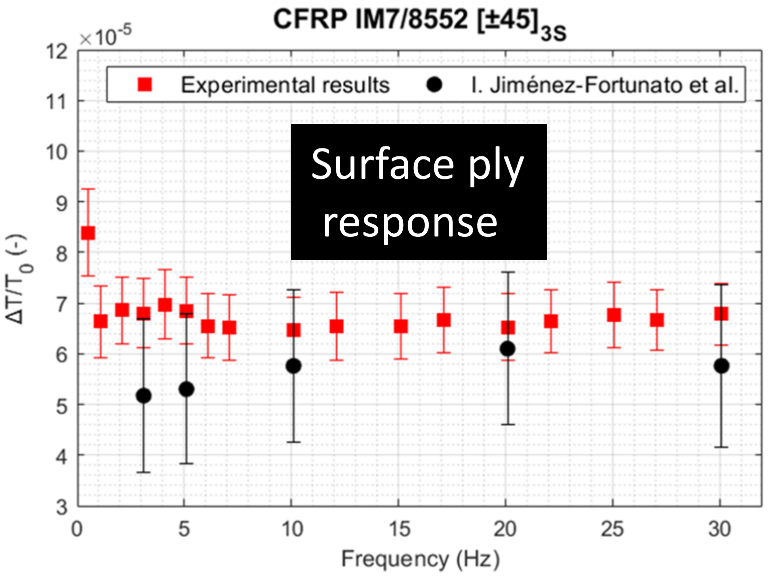
Heat transfer in undamaged CFRP laminates







Composites: Part A 149 (2021) 106515

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Composites Part A

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ELSEVIER

On the source of the thermoelastic response from orthotropic fibre reinforced composite laminates

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[a] School of Engineering, University of Southampton, UK
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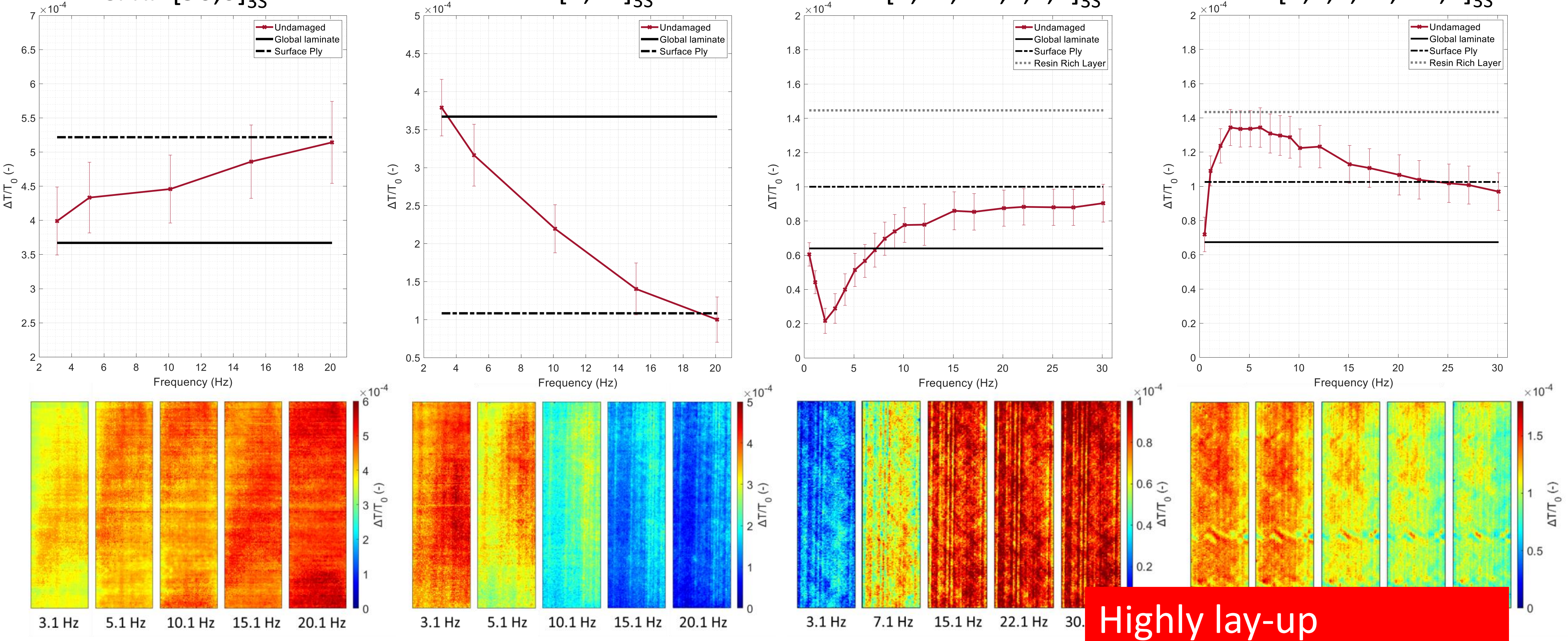
Heat transfer in CFRP undamaged laminates

CFRP $[90,0]_{3S}$ | CFRP $[0,90]_{3S}$ | CFRP $[0,45,-45,0,0,0]_{3S}$ | CFRP $[0,0,0,45,-45,0]_{3S}$



Highly lay-up dependent in CFRP

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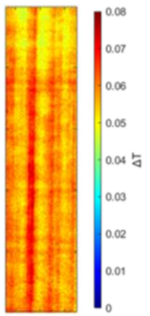
Full-field data fusion

Opportunity to identify subsurface damage by subtracting surface ply image (DIC) from TSA image at low frequencies

Infra-red images

output: Images

Notch filter



Final output: ΔT, T_0, phase

Apply surface ply model to give surface ply TSA response

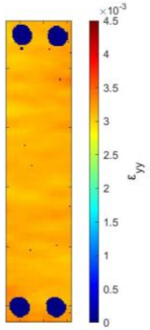
White light images

output: Images

DIC

output: Strains

Notch filter



Final output: Δε, phase

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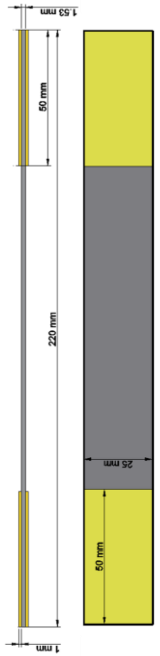
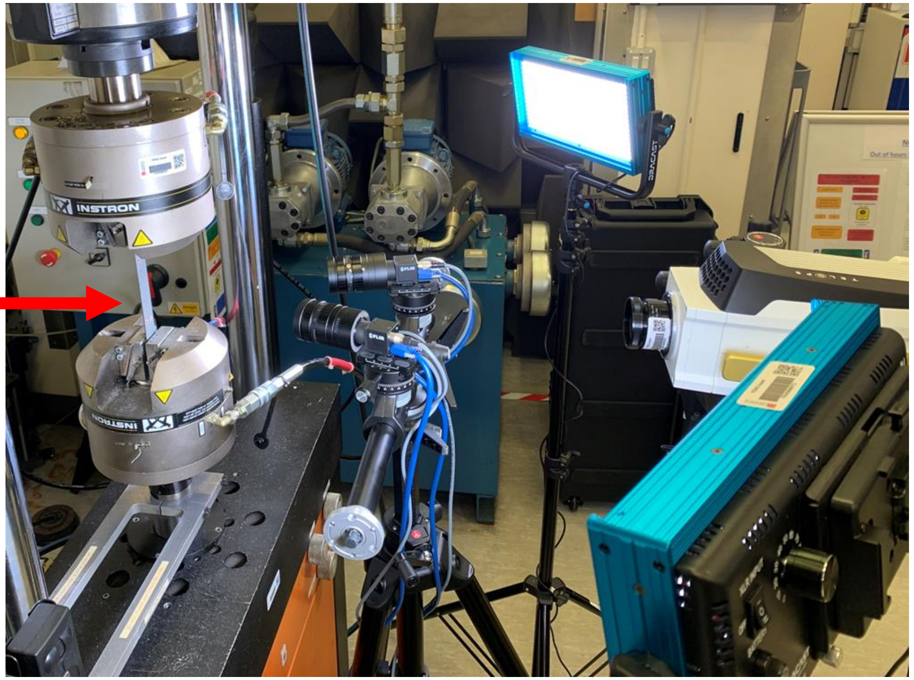
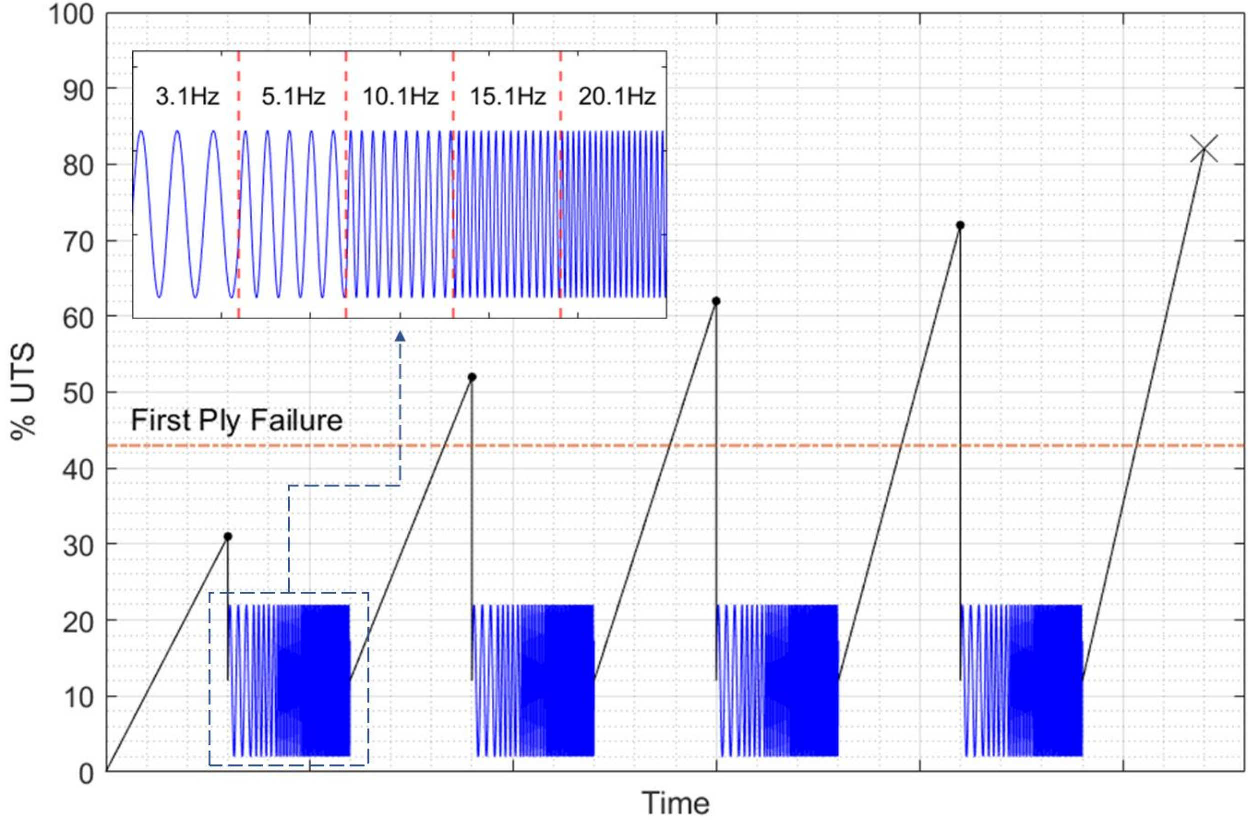
Test specimens and loading





Layup	Loading scenario	FPF
$[0,90]_{3S}$	Tension Loading	541 MPa

**Tension mode → uniform strain state through the laminate thickness*



Load Ramp → **Induce damage progressively** (in tension)

Cyclic Loading → TSA and LIDIC **(Inspection)**

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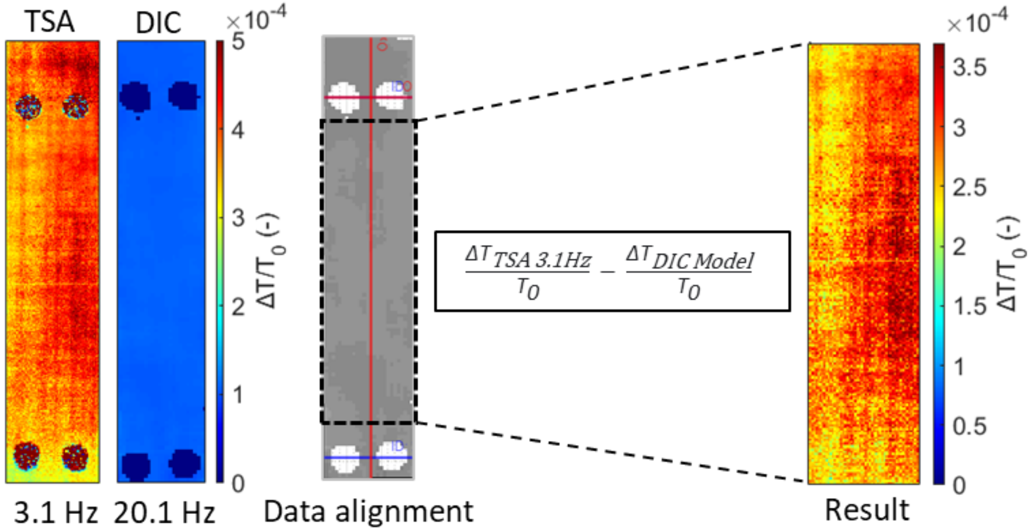
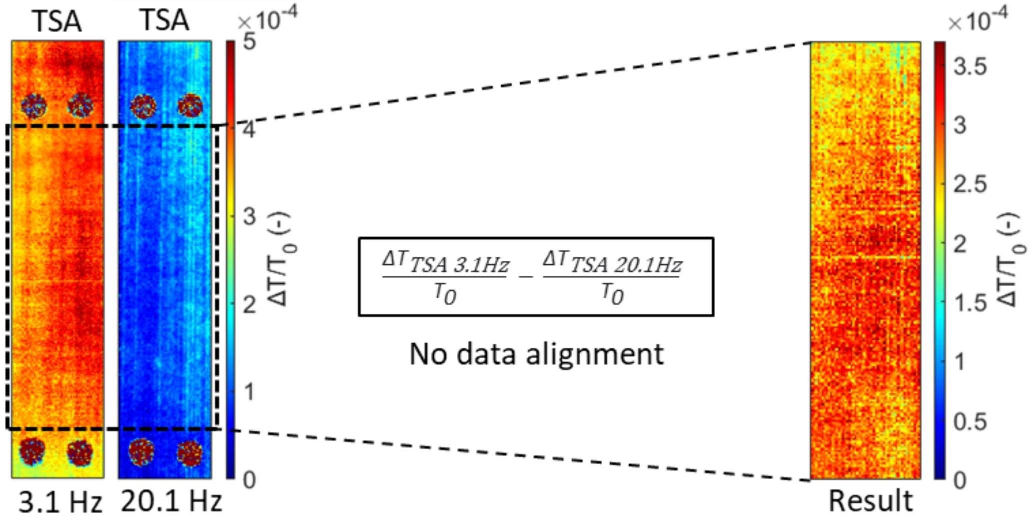
Sub-surface inspection methodology

Methodology 1



- **Interpolation** between full-field maps is **required**
- **Fully adiabatic** response from DIC model

Methodology 2



- **Interpolation bias is avoided**
- **Assumes** that adiabatic conditions are achieved

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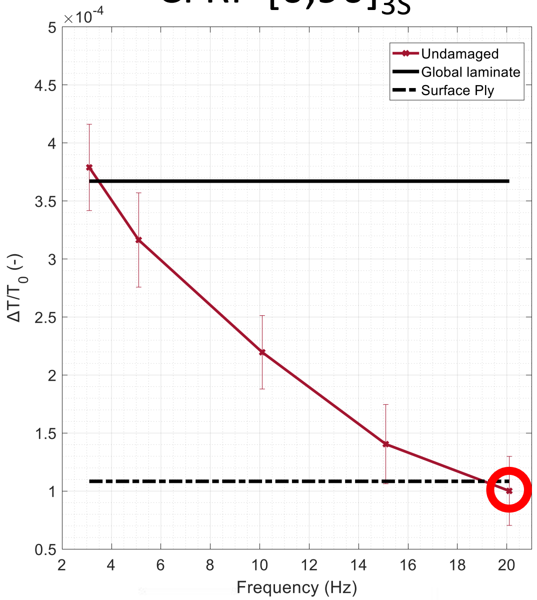
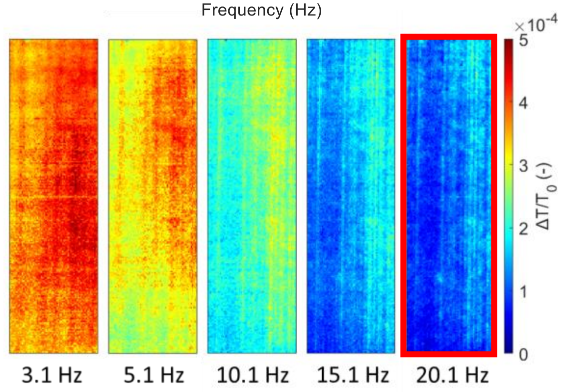
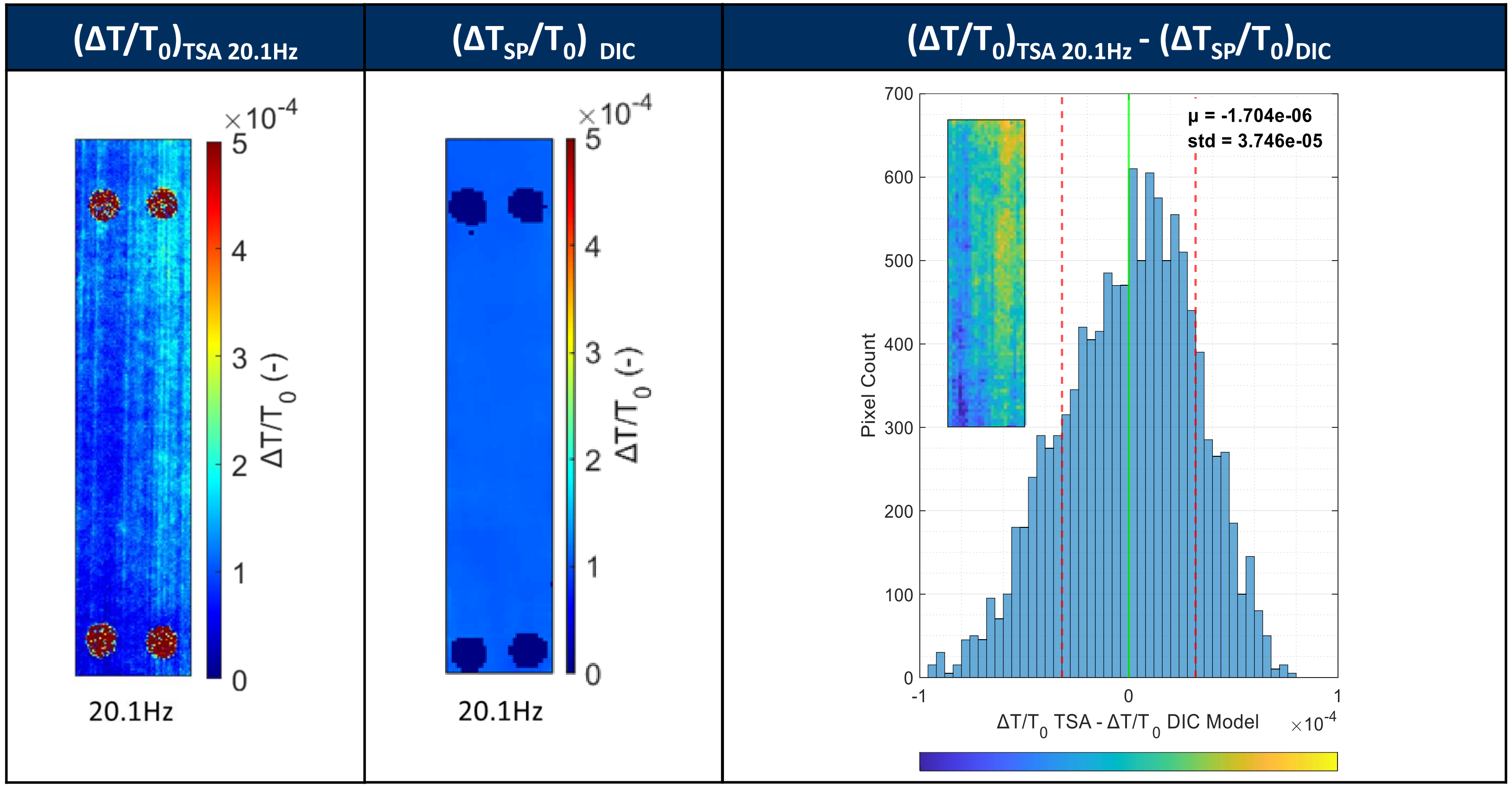
Identification of adiabatic behaviour

CFRP $[0,90]_{3S}$



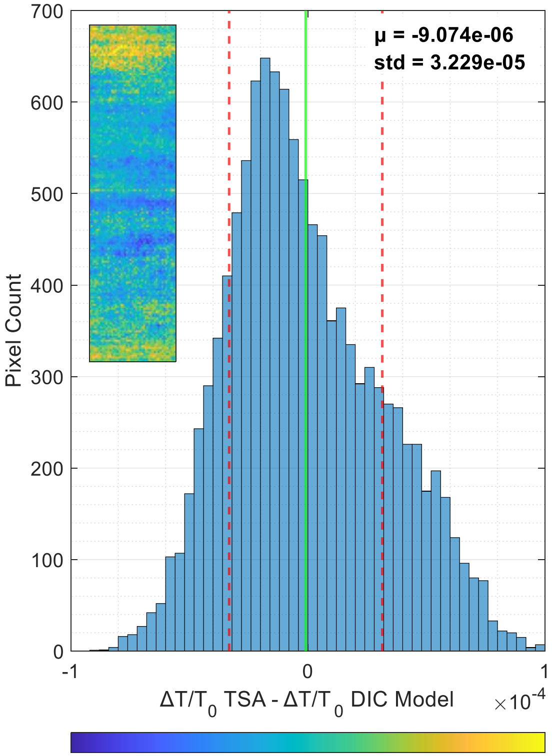




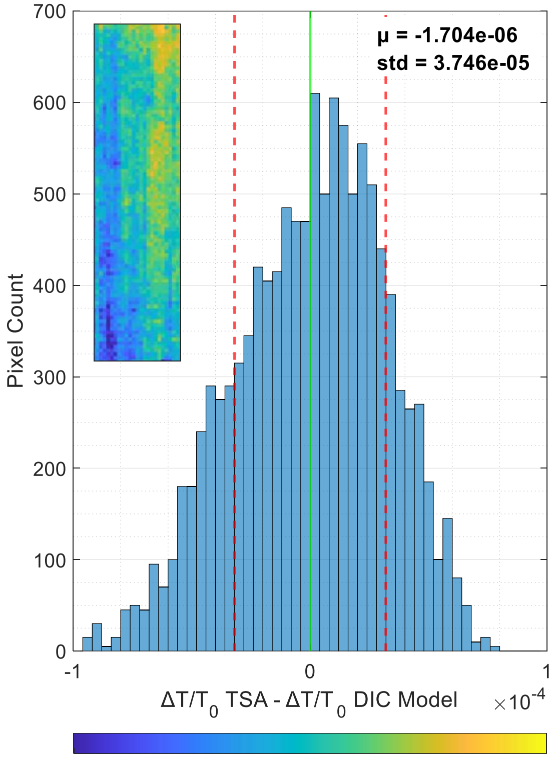
<u>The frequency for adiabatic behaviour is identified</u> by fusing the TSA data with the surface ply thermoelastic response model from DIC

Identification of adiabatic behaviour

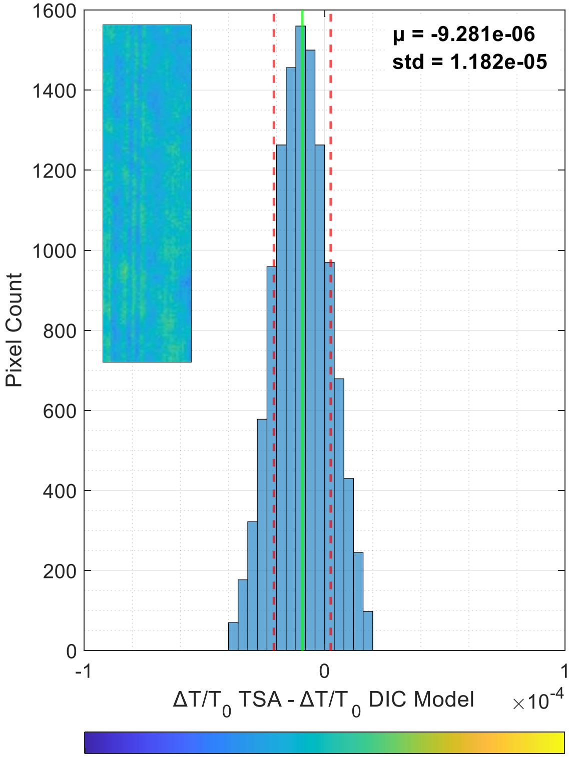
CFRP $[90,0]_{3S}$



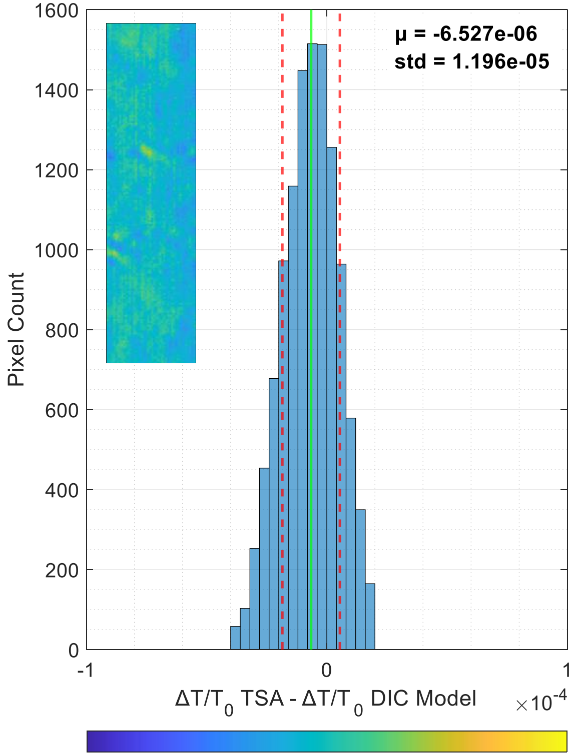
CFRP $[0,90]_{3S}$



CFRP $[0,45,-45,0,0,0]_{3S}$



CFRP $[0,0,0,45,-45,0]_{3S}$



Adiabatic behaviour at 20.1 Hz

Smeared laminate response at 3.1 Hz

Adiabatic behaviour at 30.1 Hz

Smeared laminate response at 0.5 Hz

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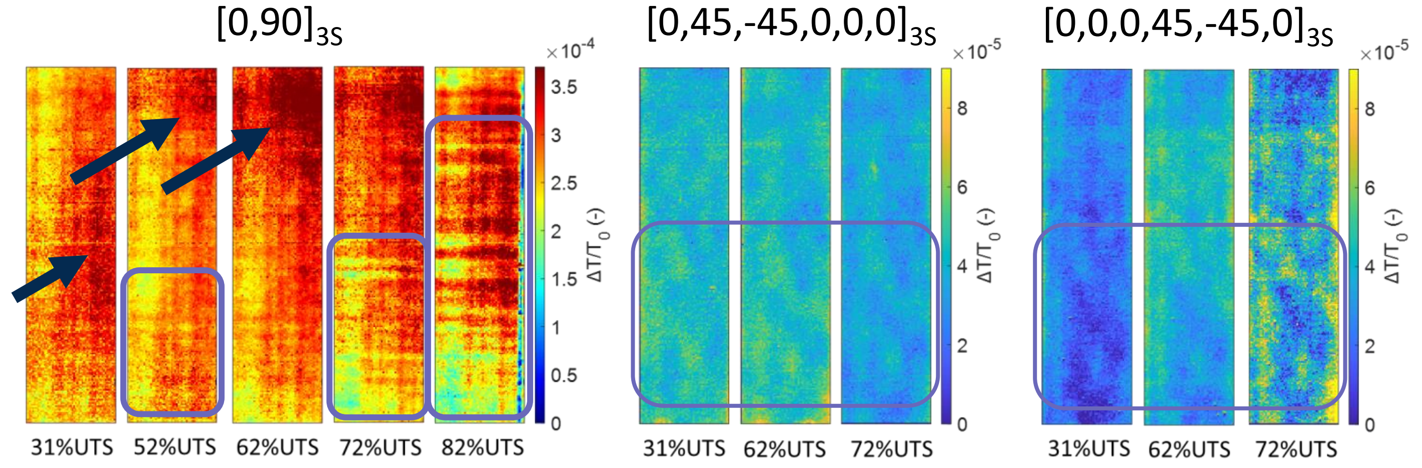
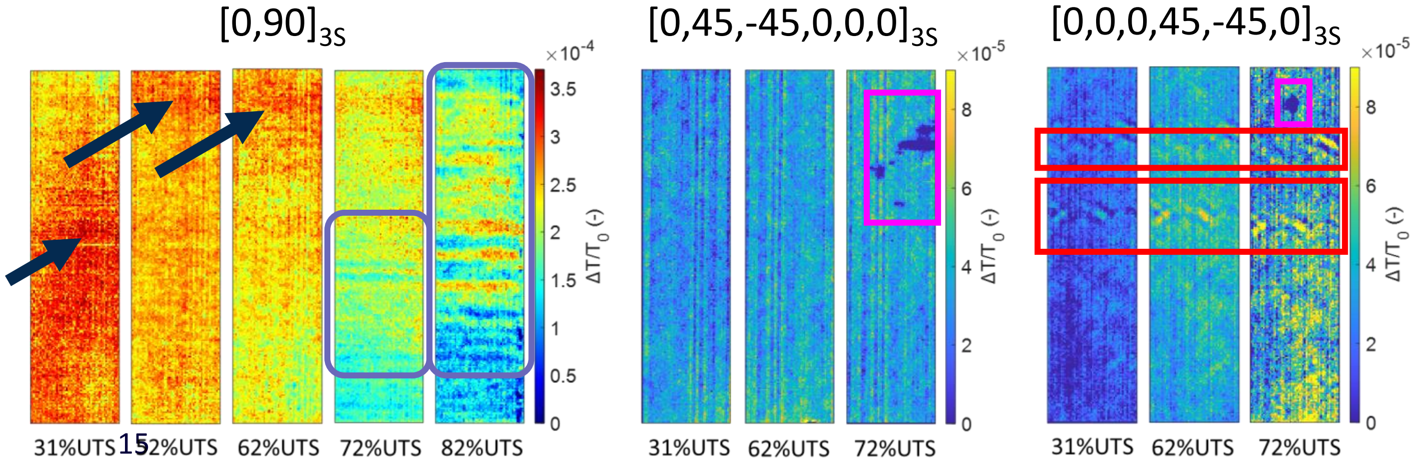
Subsurface Damage Analysis in CFRP Laminates

Methodology 1: $(\Delta T/T_0)_{TSA\ Low\ frequency} - (\Delta T_{SP}/T_0)_{DIC}$



Methodology 2: $(\Delta T/T_0)_{TSA\ Low\ frequency} - (\Delta T/T_0)_{TSA\ High\ frequency}$



$[0,90]_{3S}$

- **After FPF → Regions of ↑$\Delta T/T_0$ change**
- **Subsurface defects start to be visible after FPF**
- **More subsurface features** are observed with **M1**
- **M2 shows a decrease of the subsurface response**

$[0,45,-45,0,0,0]_S$

- **Subsurface response (±45) is observed in M1**
- **M2 shows a similar** subsurface $\Delta T/T_0$ to M1
- **Possible delamination detected using M2!**

$[0,0,0,45,-45,0]_S$

- **Subsurface response (±45) is observed in M1**
- **Wrinkles are observed**
- **Possible delamination detected using M2!**

Damage Quantification

A **thermoelastic theory** was defined in [3] for anisotropic materials and a **damage parameter** was defined using TSA

$$\Delta T = -\frac{T_0}{\rho C_p} \cdot (\alpha_x \sigma_x + \alpha_y \sigma_y) \xrightarrow[\text{i.e. the laminate stress}]{\text{In pure tension: } (\alpha_x\sigma_x + \cancel{\alpha_y\sigma_y})} \frac{\Delta T}{T_0} = K_{Undamaged} \cdot \frac{\Delta\sigma_x}{(1 - D)^2}$$

$K_{Undamaged}$ → $-(\alpha_x)/\rho C_p$

D → Damage parameter

* *Undamaged: D=0*
* *Damaged: D ≠ 0*

$$\boxed{D_{TSA} = 1 - \sqrt{K_{Undamaged} \cdot \Delta\sigma \cdot \left(\frac{\Delta T}{T_0}\right)^{-1}}}$$

$$\boxed{D_{YM} = \frac{E_{Undamaged} - E_{Damaged}}{E_{Undamaged}}}$$

- Damage parametrisation carried out at low frequencies
- Full-field damage parametrisation → **Subsurface**
- **Does the D_{TSA} gives better a better quantification of actual damage?** → **Localised ROIs**

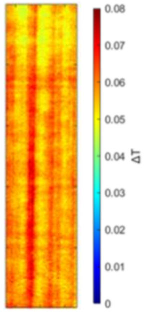
[3] Zhang D, Sandor B (1990) A thermoelasticity theory for damage in anisotropic materials. Fatigue Fract Eng Mater Struct 13:497–509

DATA PROCESSING STEPS (TSA & DIC)

IR images

output: Images

Lock-In Algorithm



$\Delta T/T_0$

White light images

output: Images

DIC

Strains – Laminate apparent stiffness

Damage Parameter

$$D_{TSA} = 1 - \sqrt{K_{Undamaged} \cdot \Delta\sigma \cdot \left(\frac{\Delta T}{T_0}\right)^{-1}}$$

$$D_{YM} = \frac{E_{Undamaged} - E_{Damaged}}{E_{Undamaged}}$$

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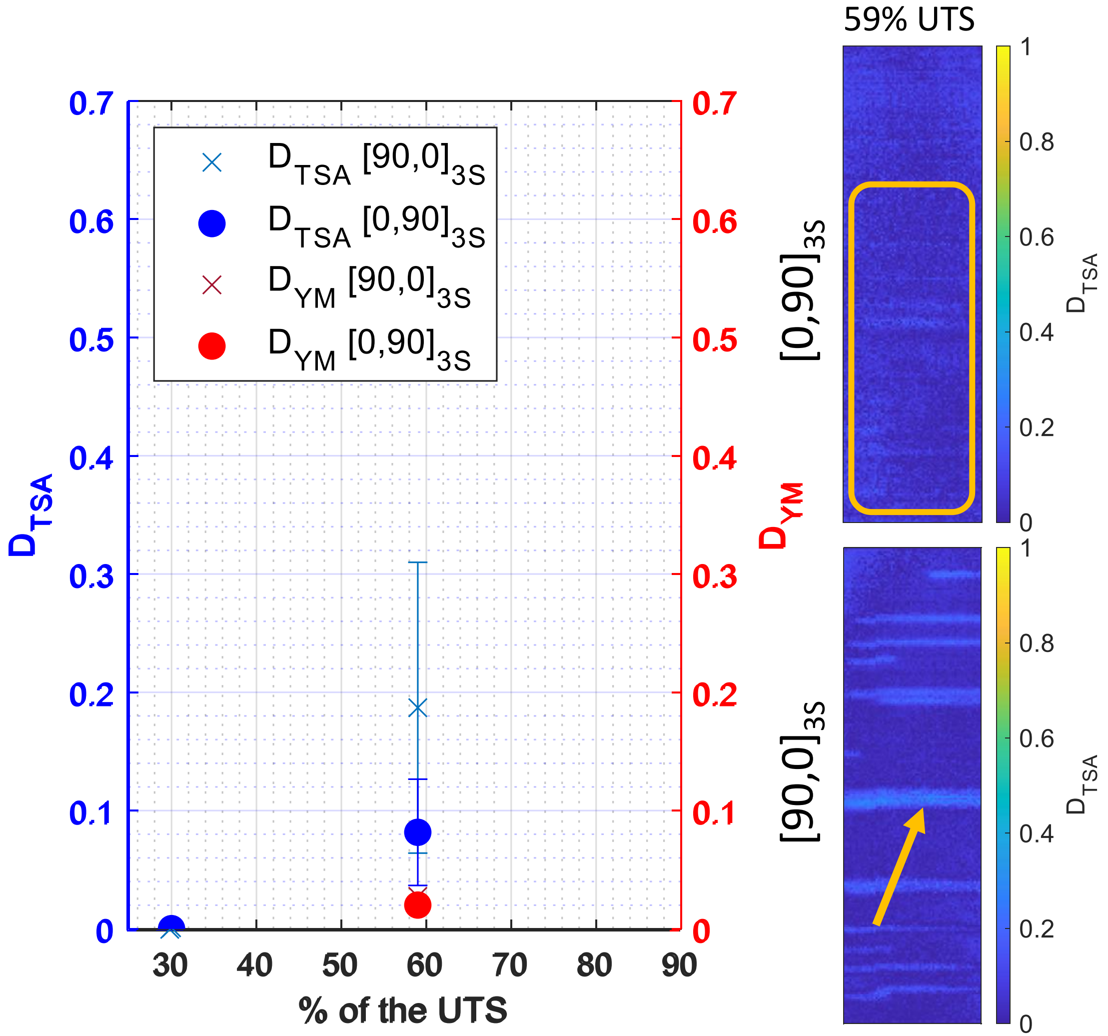
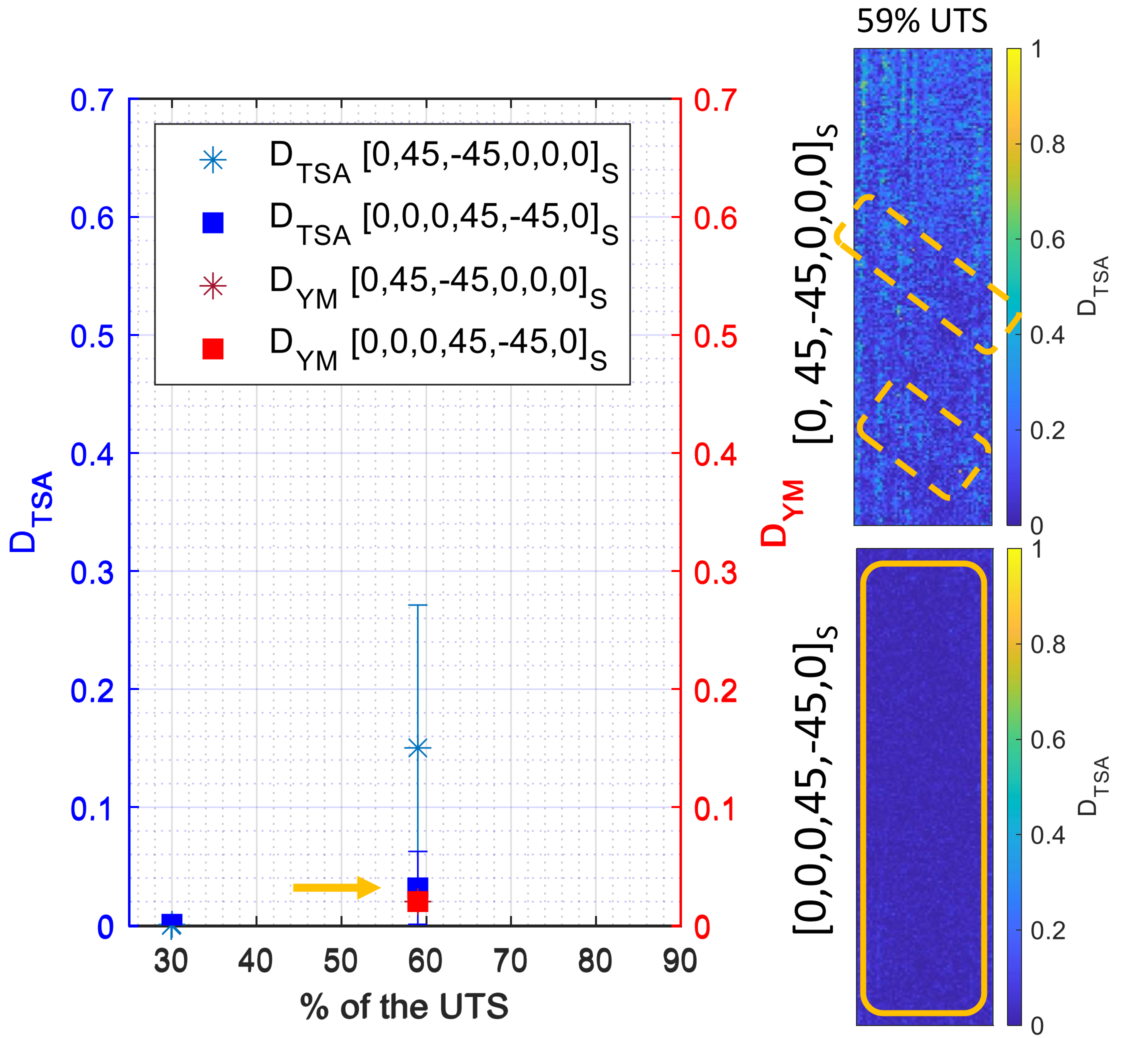
Damage Quantification: Multidirectional laminates





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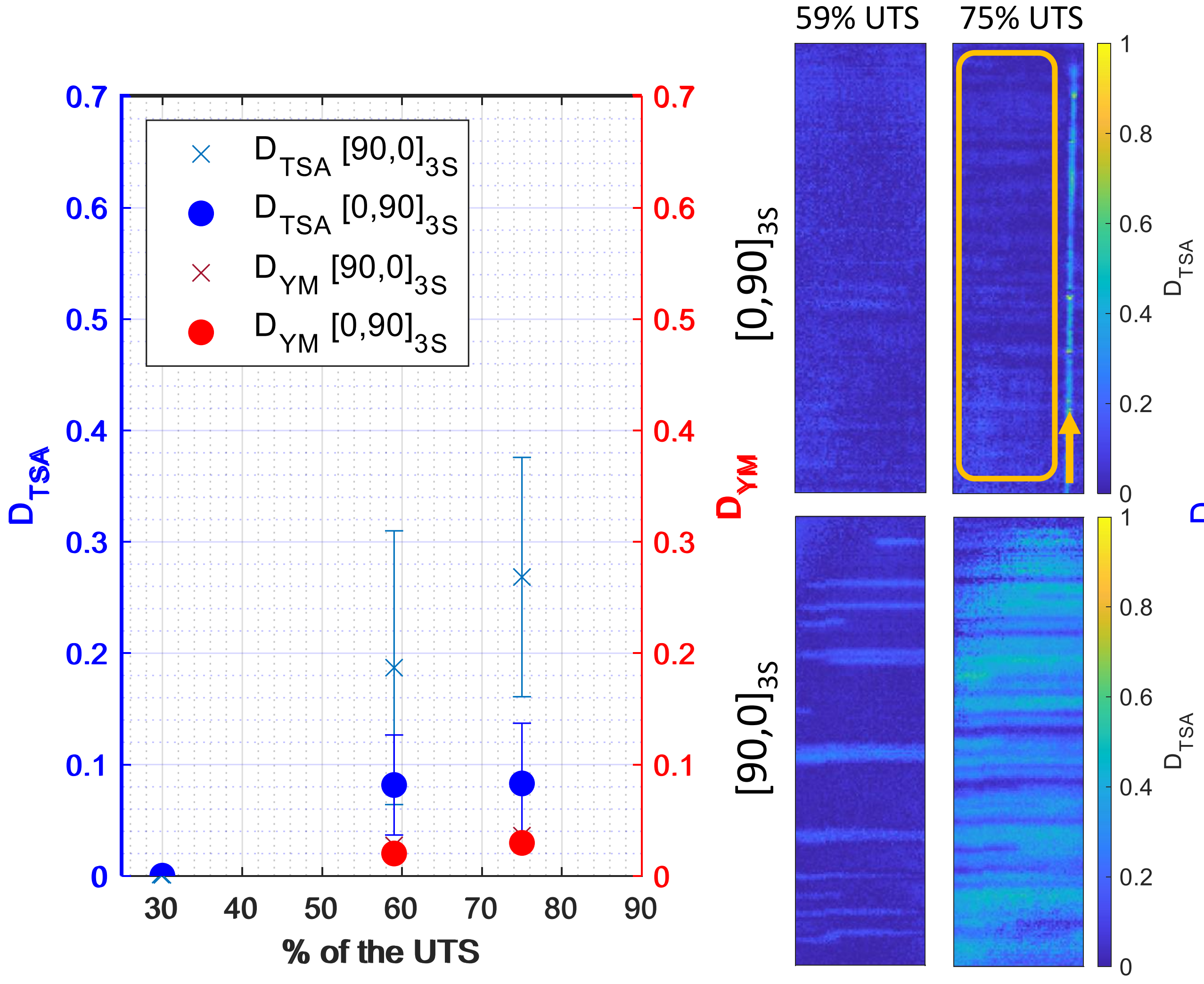
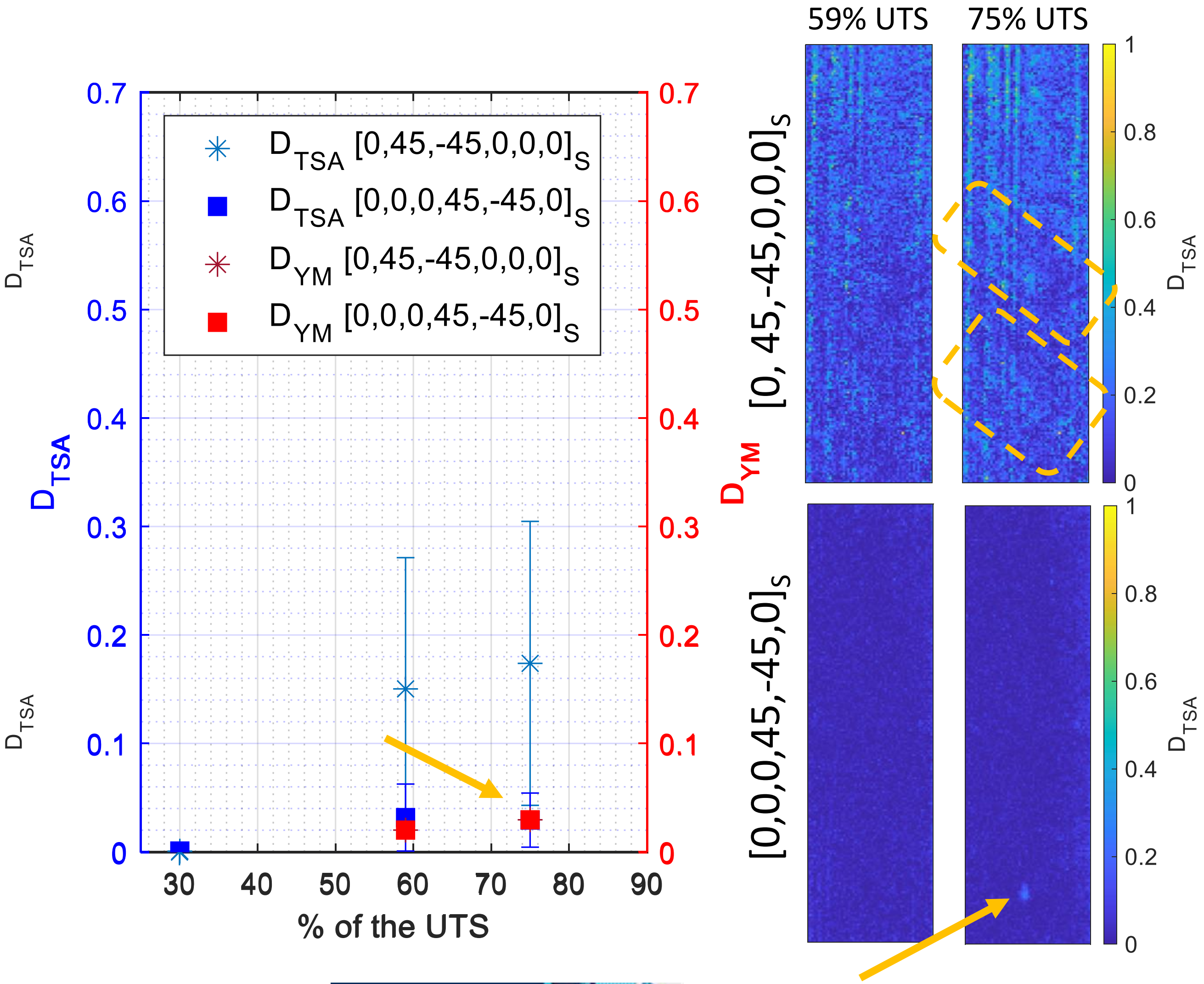
Damage Quantification: Multidirectional laminates





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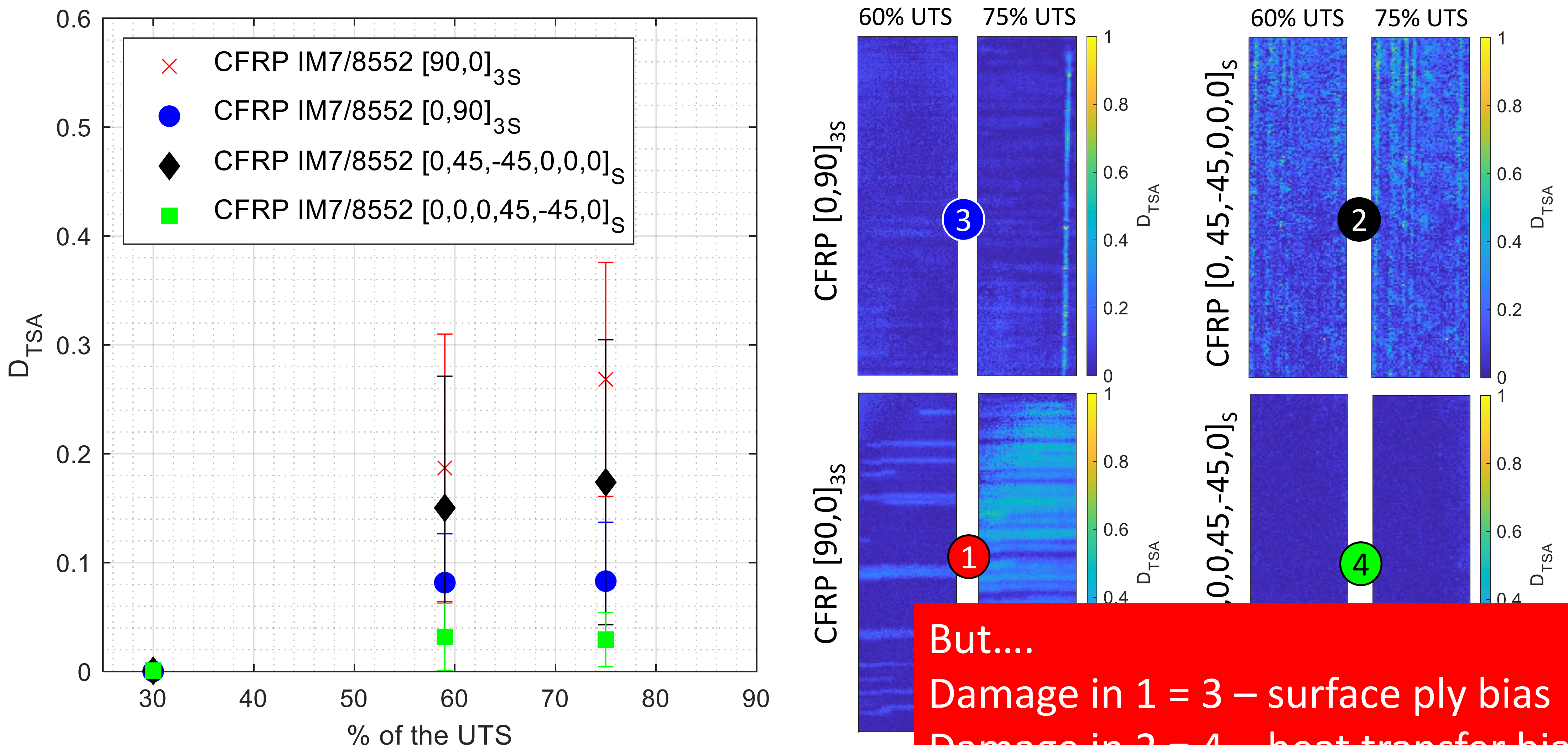
TSA damage quantification: overview



But….

Damage in 1 = 3 – surface ply bias

Damage in 2 = 4 – heat transfer bias

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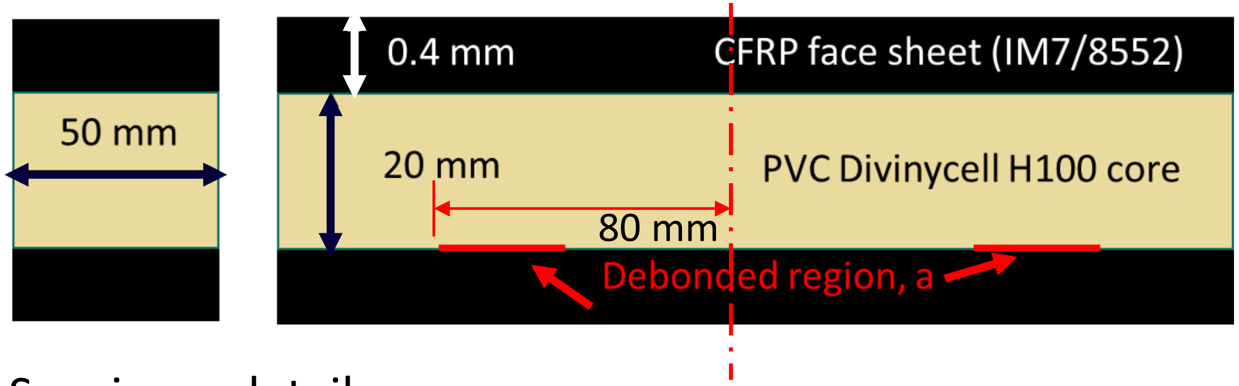
Moving up the scale …defects in sandwich structures

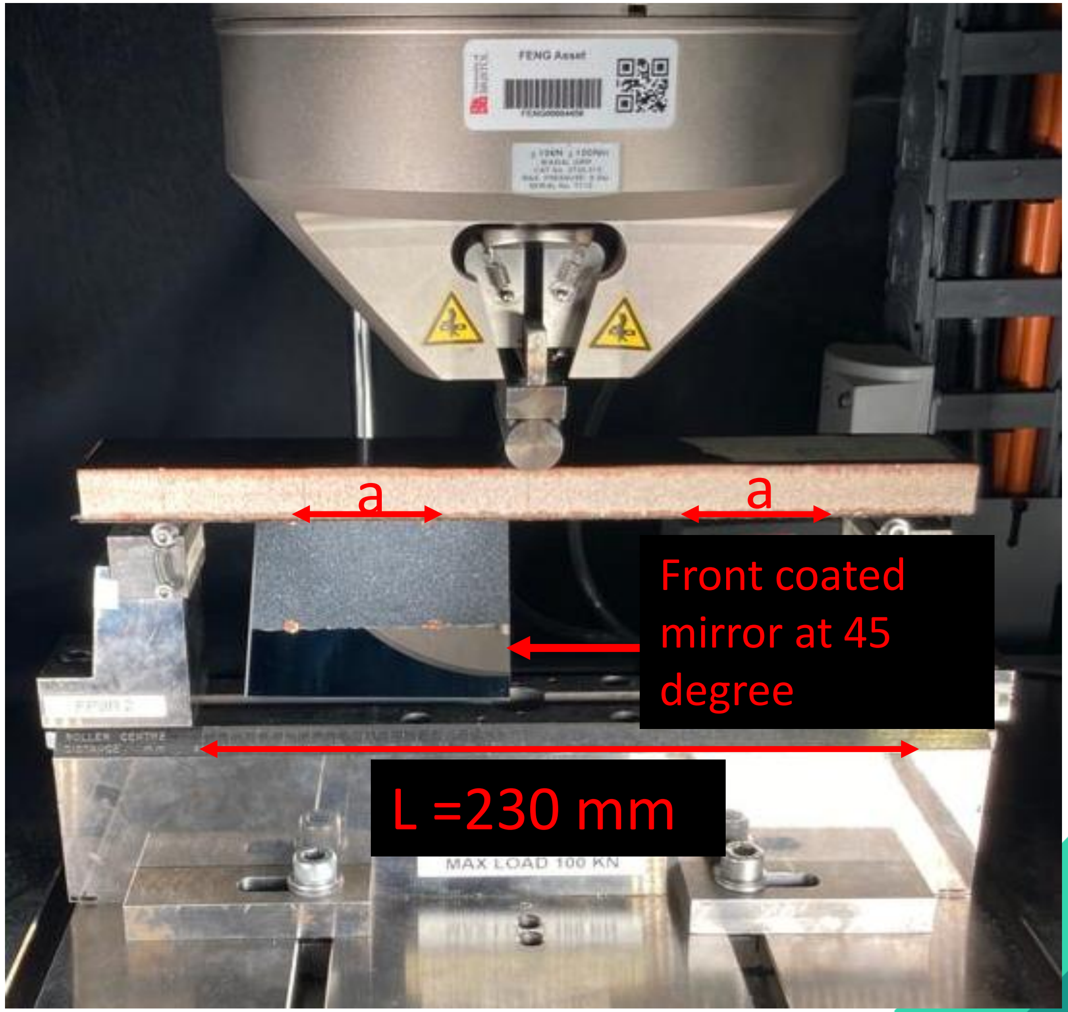


Specimen details

- Face sheet lay-up: $[0]_3$
- Core density : 100 $\mathrm{kg/m^3}$
- Debonded region, a: 10 mm, 20 mm, 30 mm

Specimen is loaded in 3-point bending

- Debonded side at interface of bottom face sheet and core
- Front coated mirror is at 45 °
- Support span, L = 230 mm



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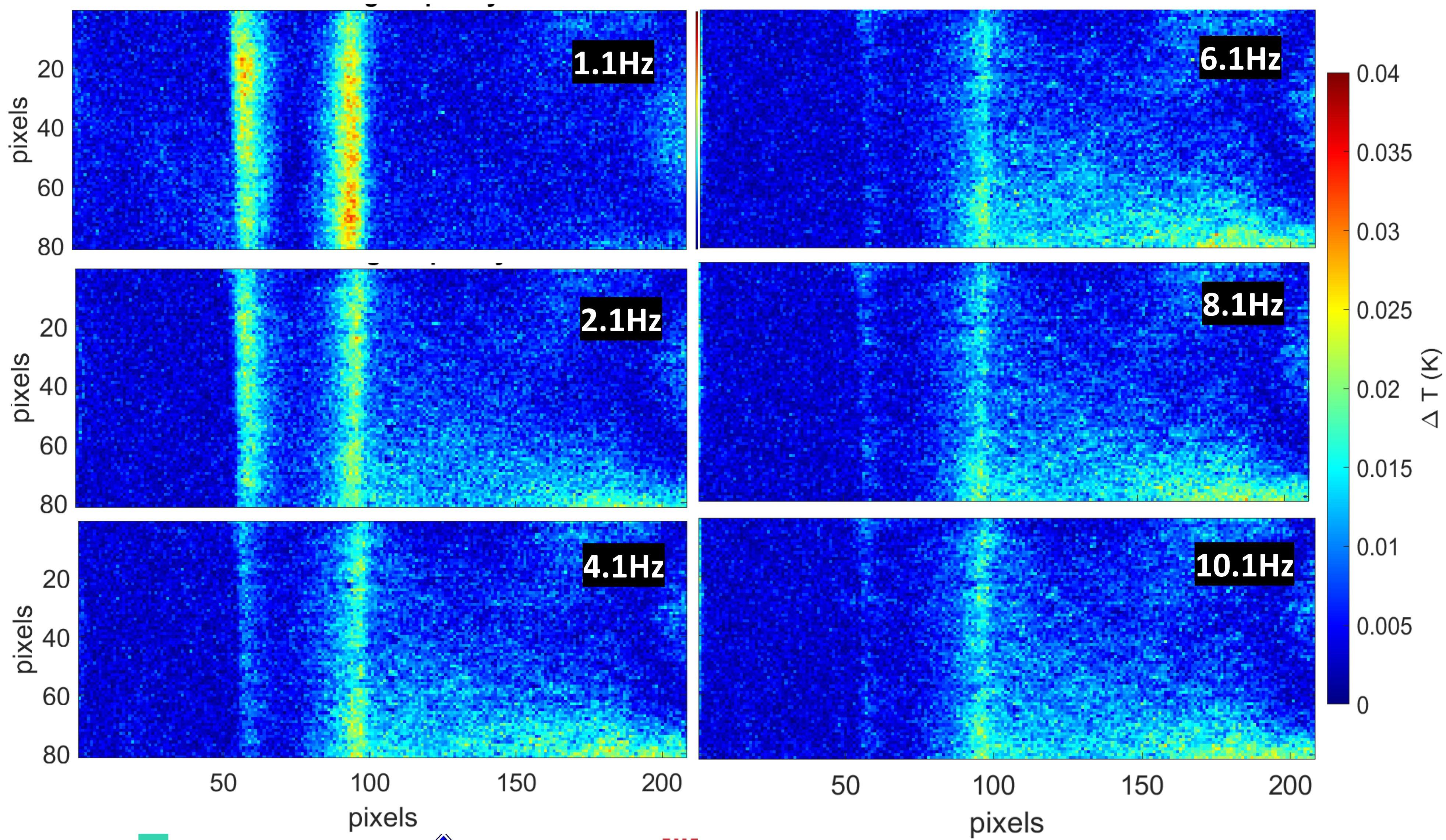
Diab

ΔT from lower face sheet using mirror a =20 mm



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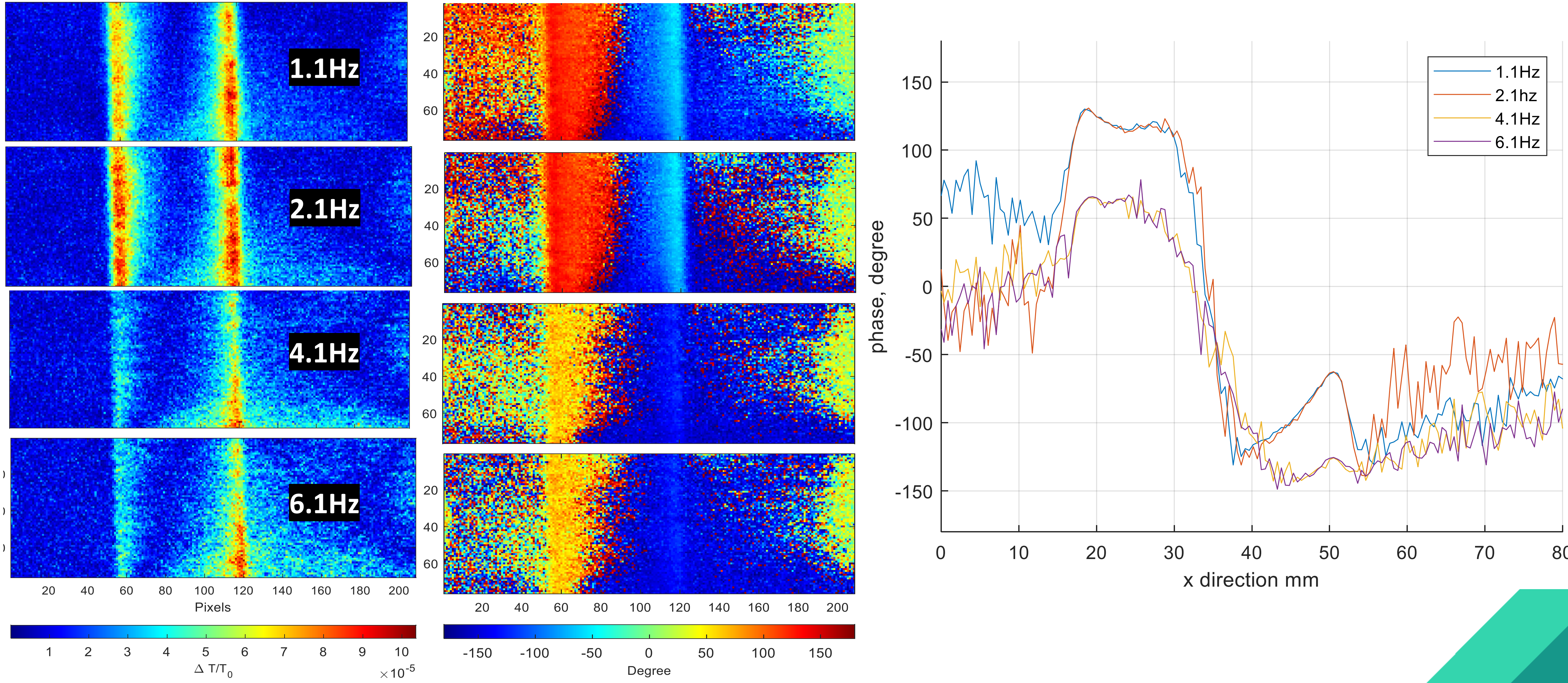
Diab

ΔT and phase from lower face sheet using mirror a =30 mm



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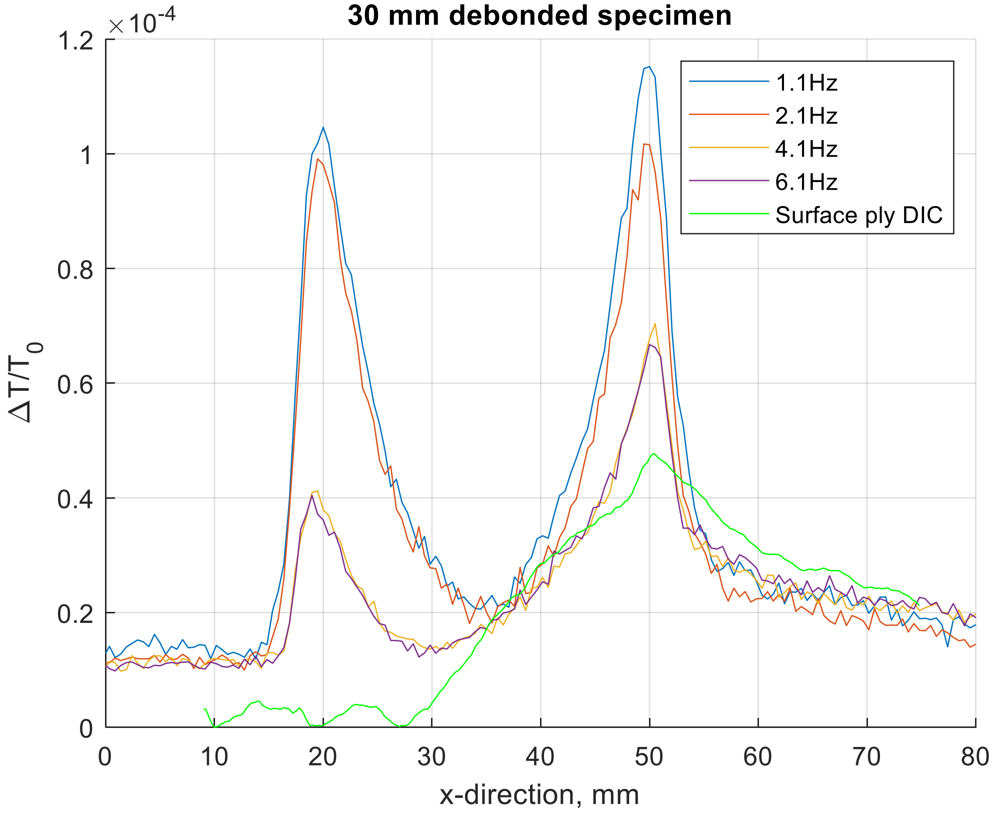
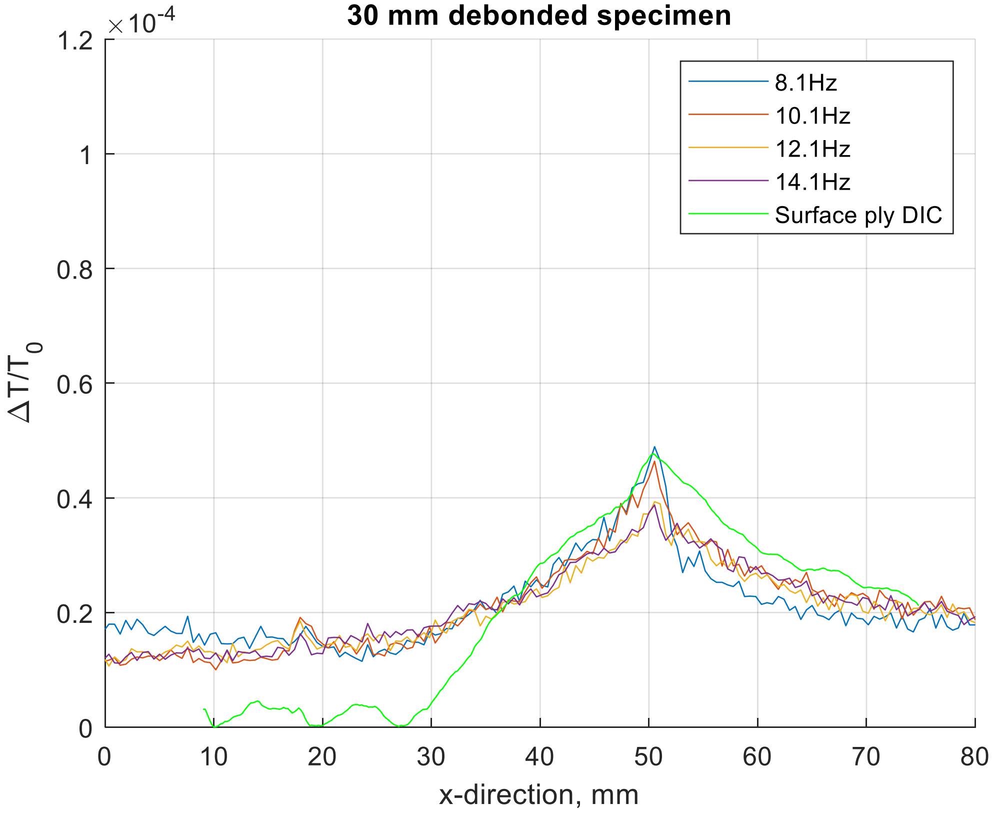
Comparison of TSA and DIC $\left(\frac{\Delta T}{T_0}\right)$ a = 30 mm





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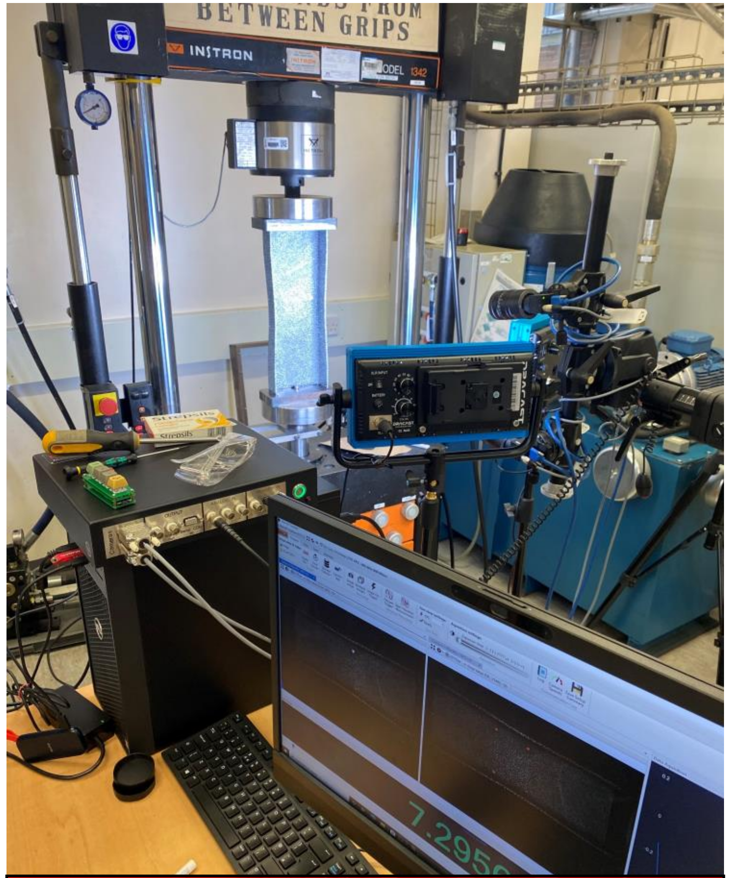
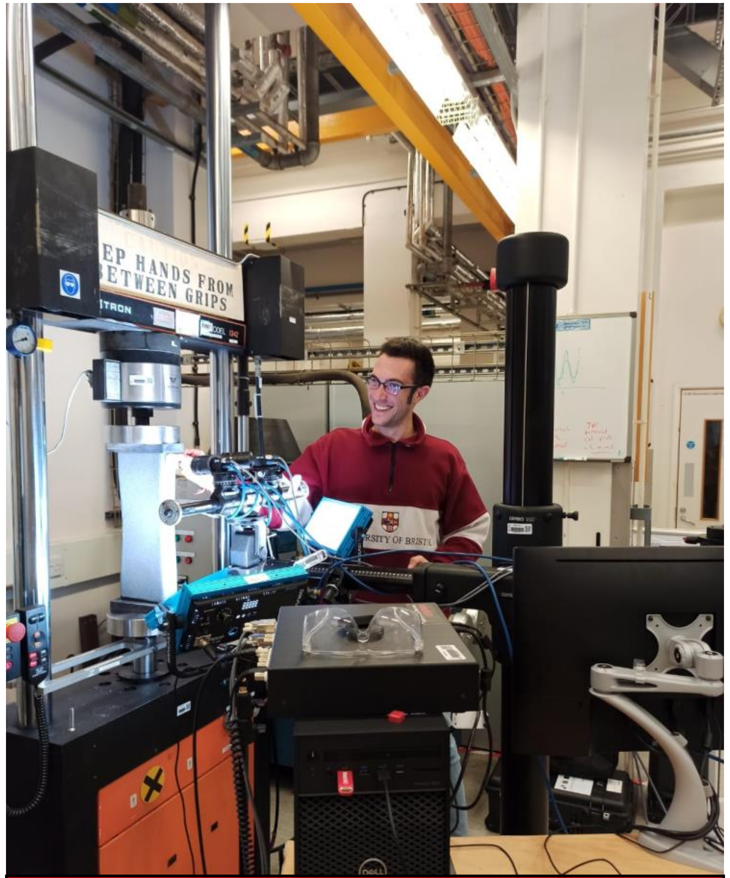
Diab

Scaling-up .. Aerostructure C-spar

C-Spar in the test machine



Speckled C-Spar



Rafa calibrating the DIC

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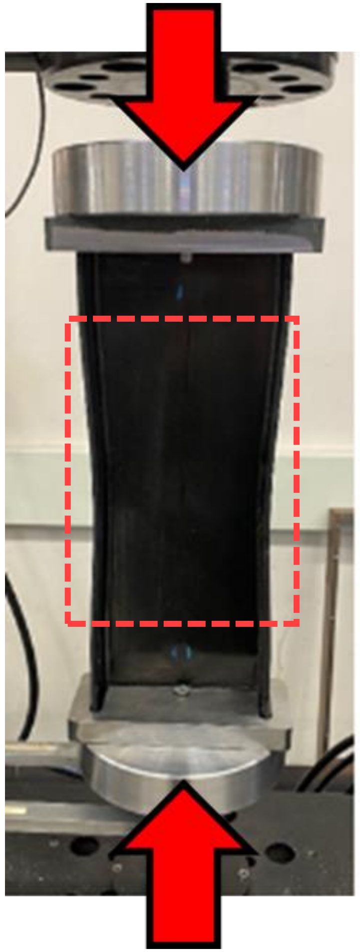
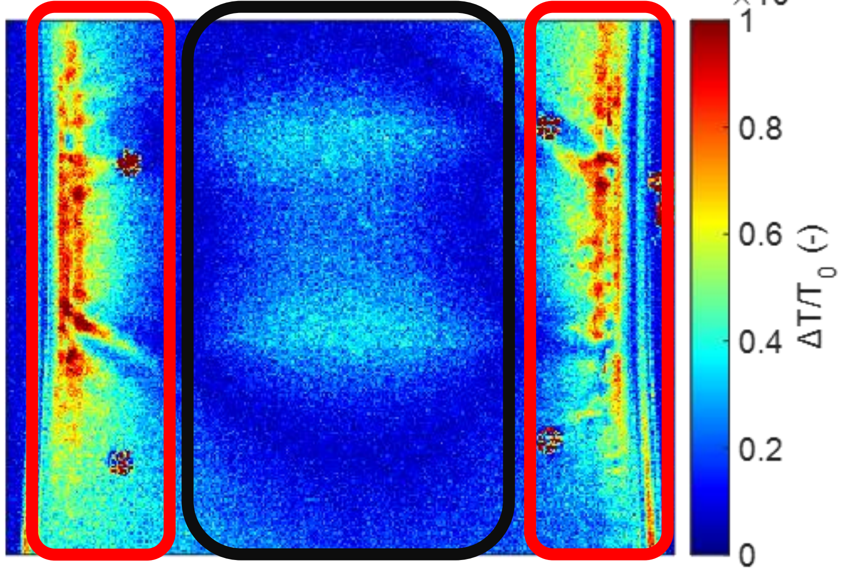
WIP: C-Spar



Undamaged

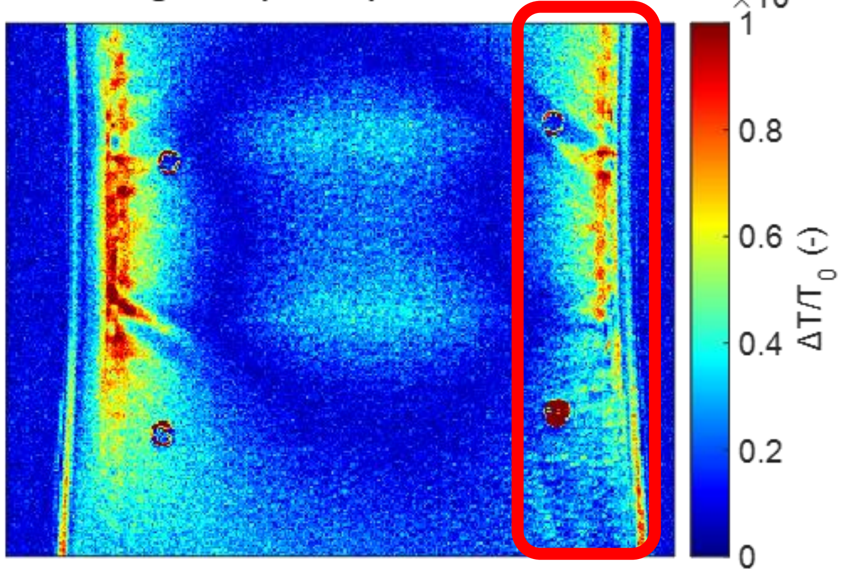
Loading Frequency = 3.1 Hz



Corners with wrinkles
High stress concentrations

Damaged

Loading Frequency = 3.1 Hz



Stress redistribution?

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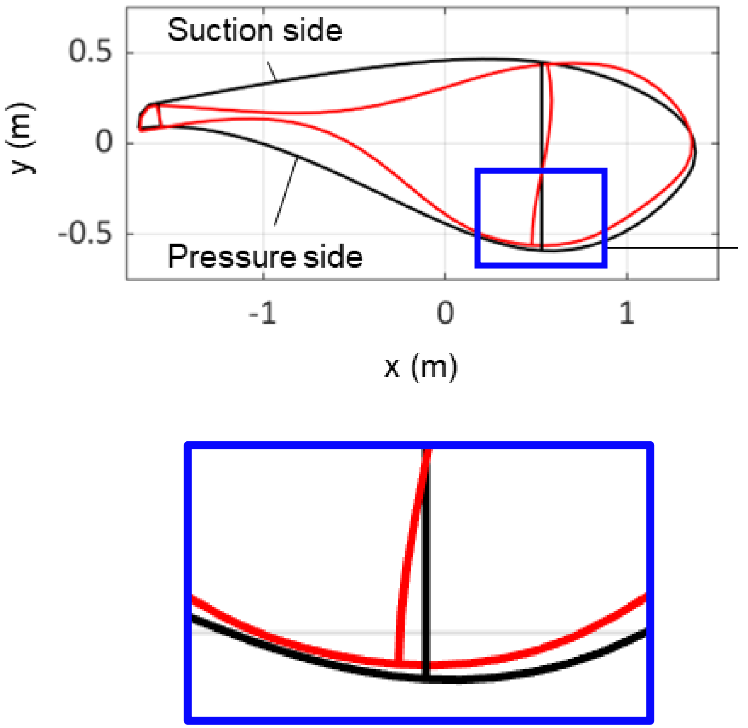
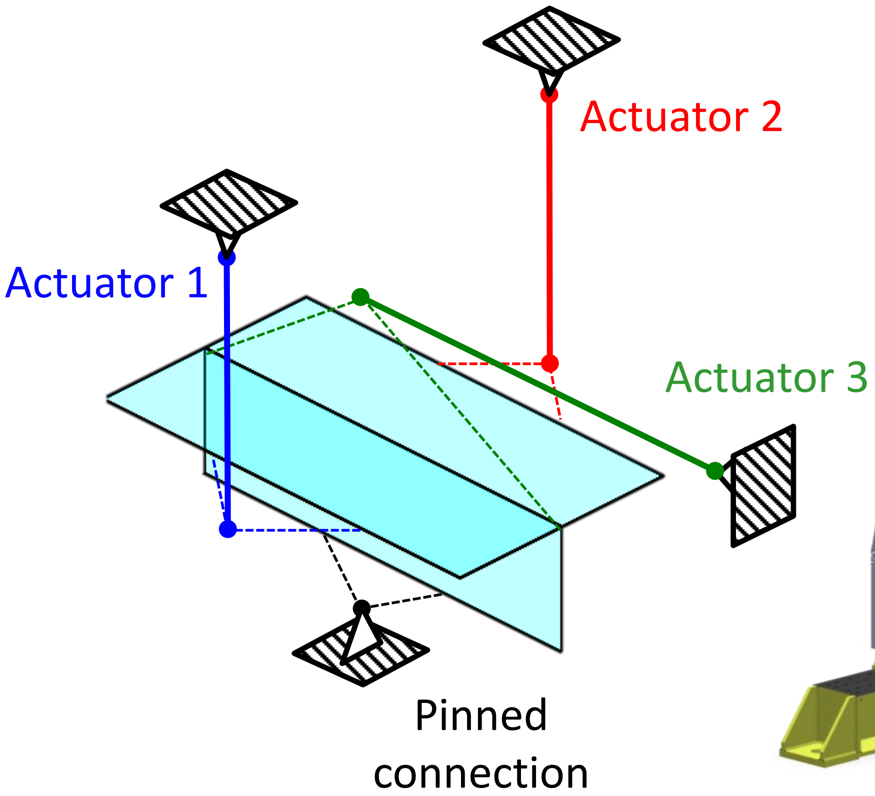
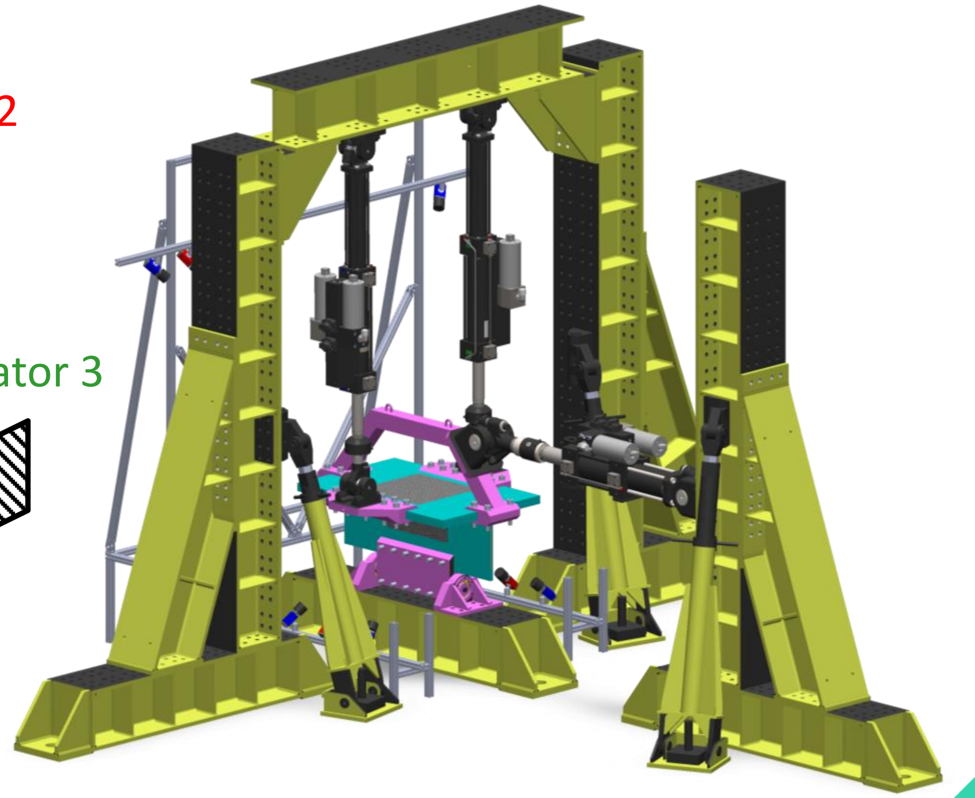
WIP: Multi-axial loading of WTB substructure







FE prediction → Test schematic → Detailed test design

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Conclusions

- A new approach that identifies sub-surface damage based on integrating TSA and DIC has been developed.
- Adiabatic conditions can be identified in CFRP components using the same data fusion approach
- A new means of damage quantification based on TSA was presented but further analysis is required
- Presented some initial results from sandwich structures and plans to upscale to a composite C-spar

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