Thermoelastic stress analysis of composite materials and structures: progress and prospects

6th November 2024

BSSM 60th Anniversary Showcase

Airbus Filton

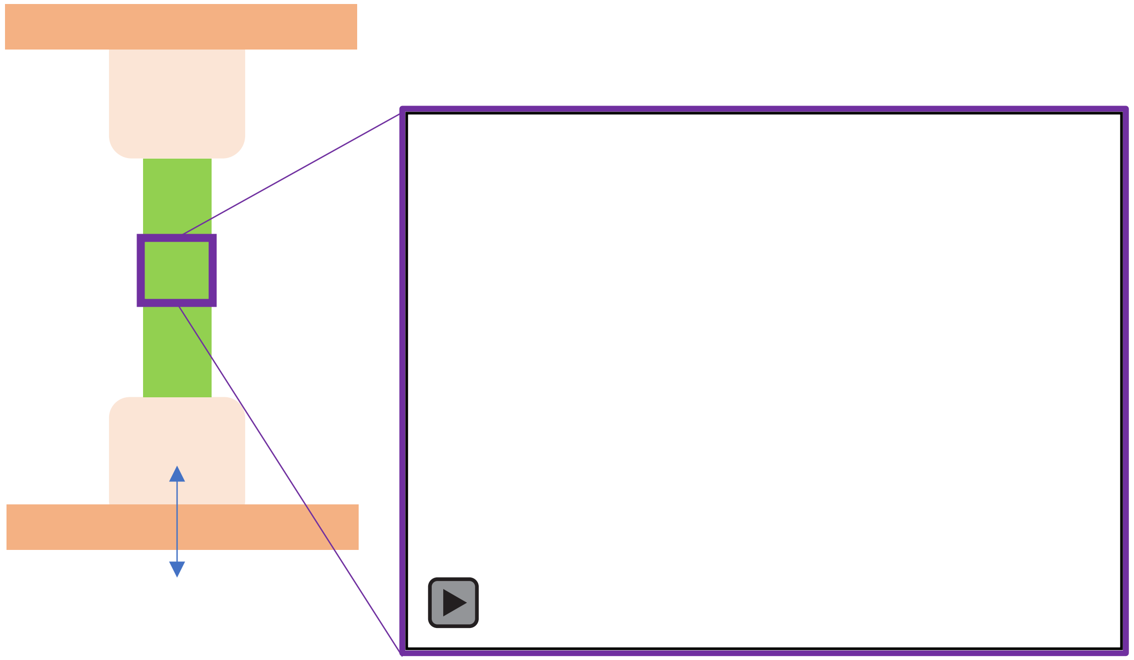
Rafa Ruiz-Iglesias, Irene Jimenez Fortunato, Tobias Laux, Riccardo Cappello, Ole Thomsen

Janice Dulieu- Barton

Outline

- Introduce thermoelastic stress analysis (TSA) - briefly
- Combining TSA with DIC
- Application to FRP materials
- Outcome of previous work
- TSA with realistic MD CFRP materials
- Application to structural scale
- Low cost cameras

Thermoelastic stress analysis (TSA)



Assumes no heat transfer

Temperature change occurs adiabatically

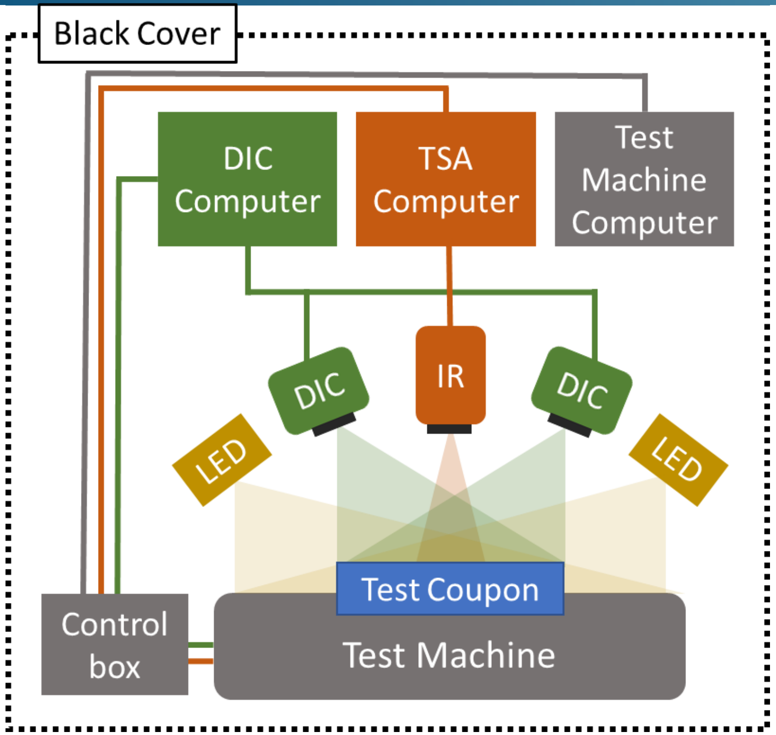
Cyclic loading reduces diffusion

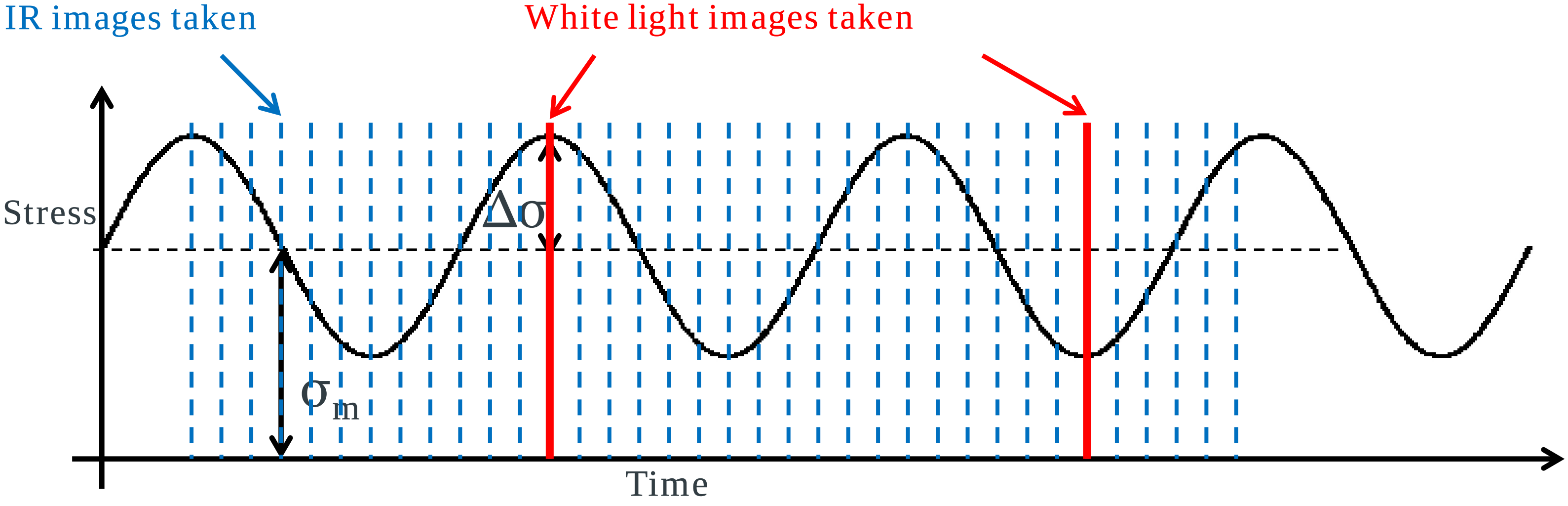
Lock-in notch filter

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

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

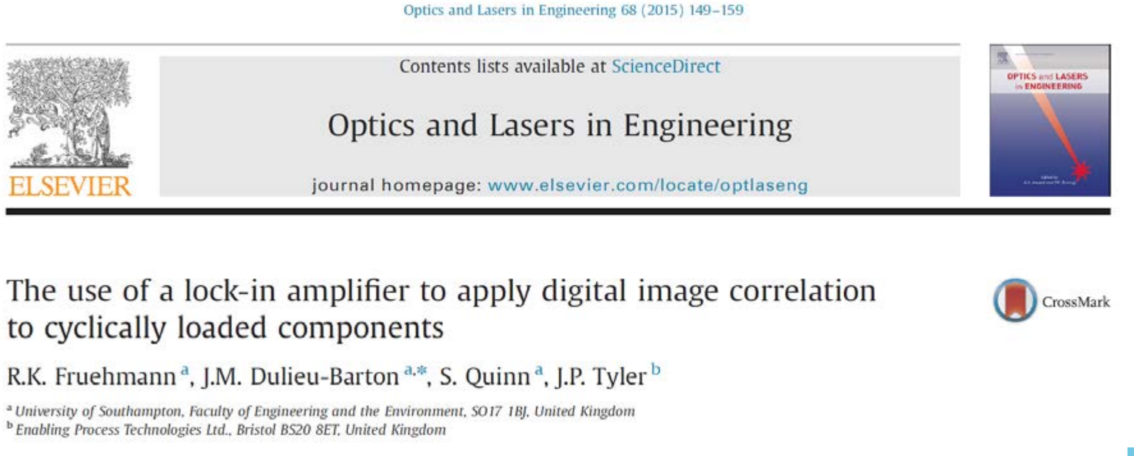
Combining TSA and DIC during cyclic loading





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

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



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Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

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

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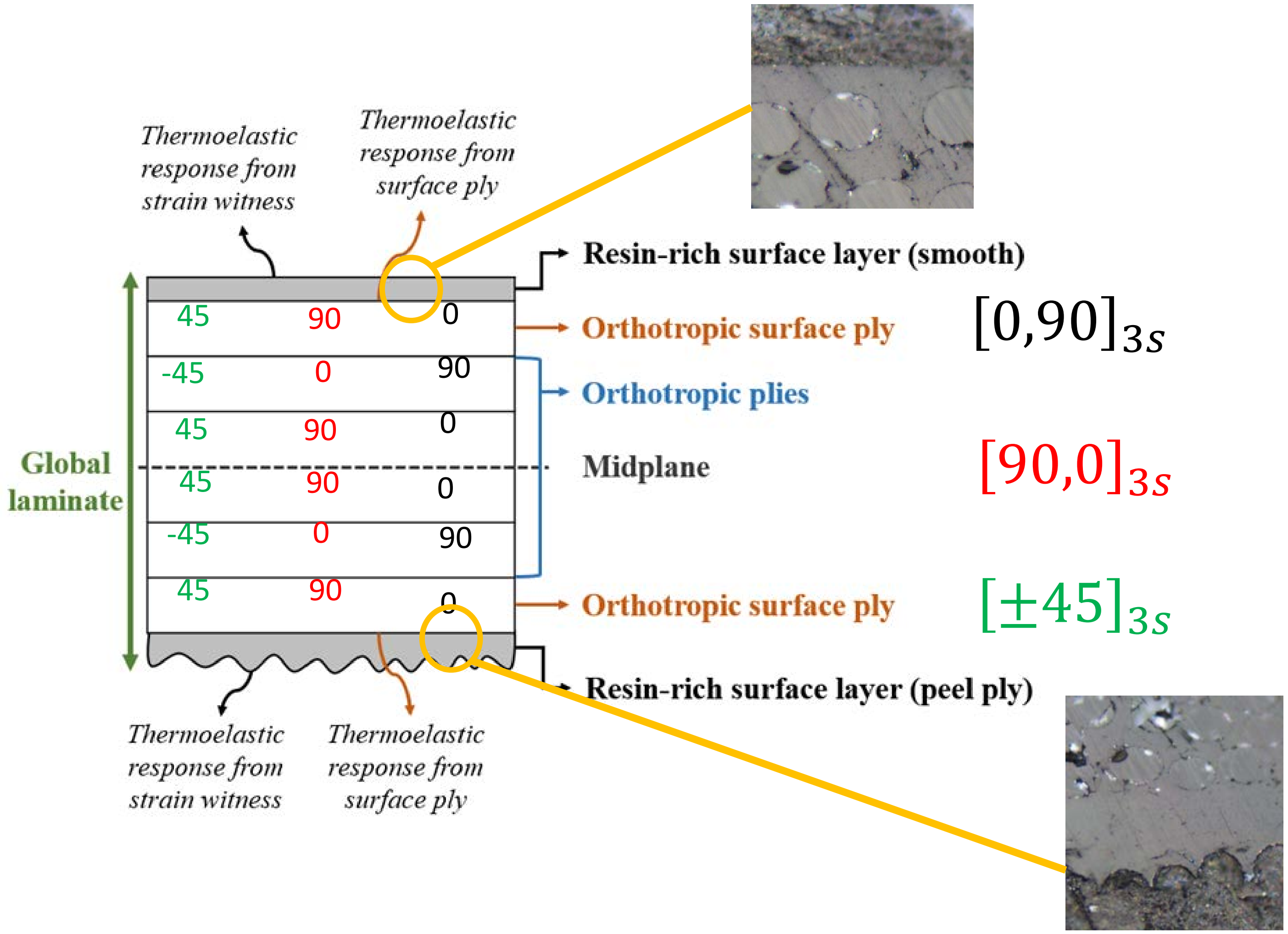
Typical composite laminate



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 specimen type

Structures 2025

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

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

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

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

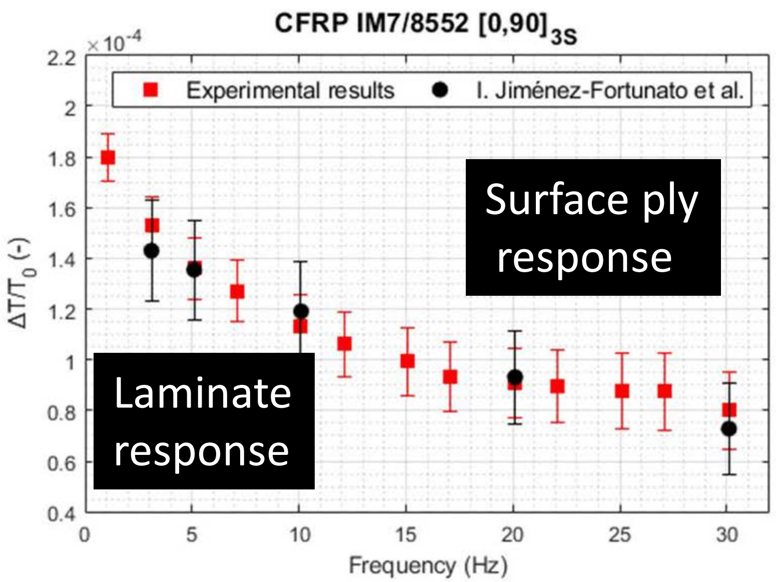
Step changes in Δ*T* at ply interfaces

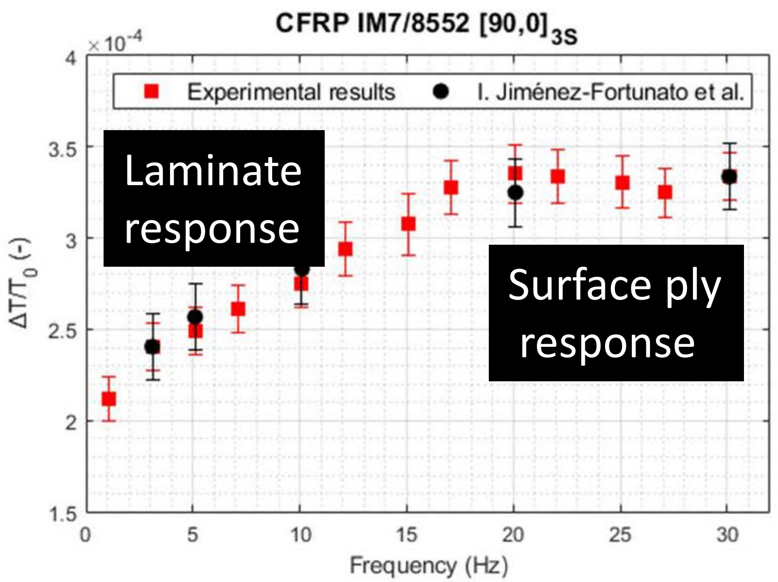
Non adiabatic behaviour at low frequencies

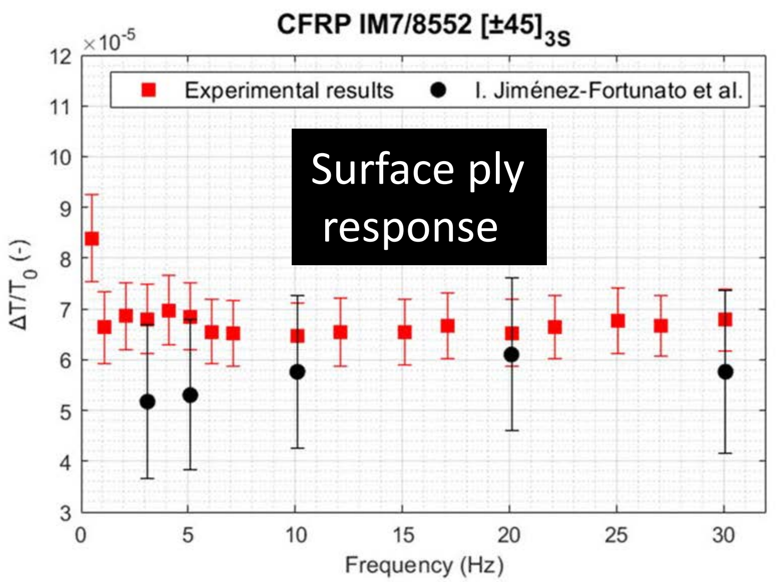
Laminate is homogenised value

Is *ΔT* occurring adiabatically – conduct tests at different loading frequencies

Non-adiabatic behaviour in CFRP at low frequency







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Composites Part A

journal homepage: www.elsevier.com/locate/compositesa

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Check for updates

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

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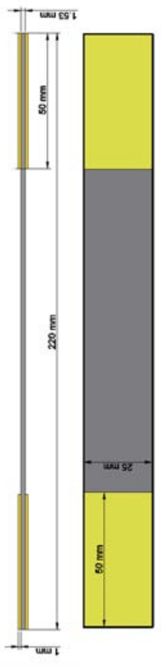
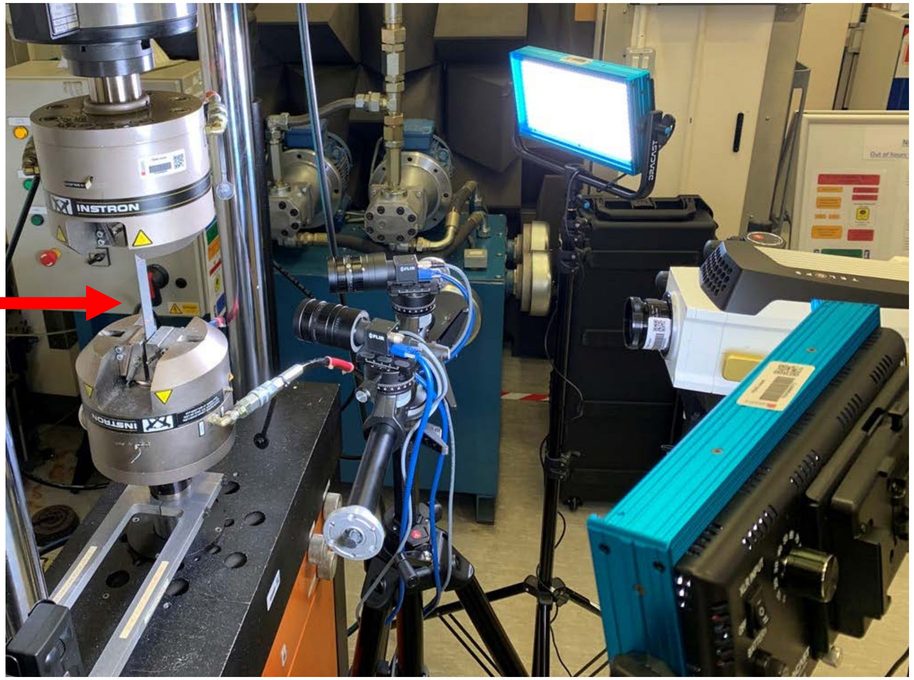
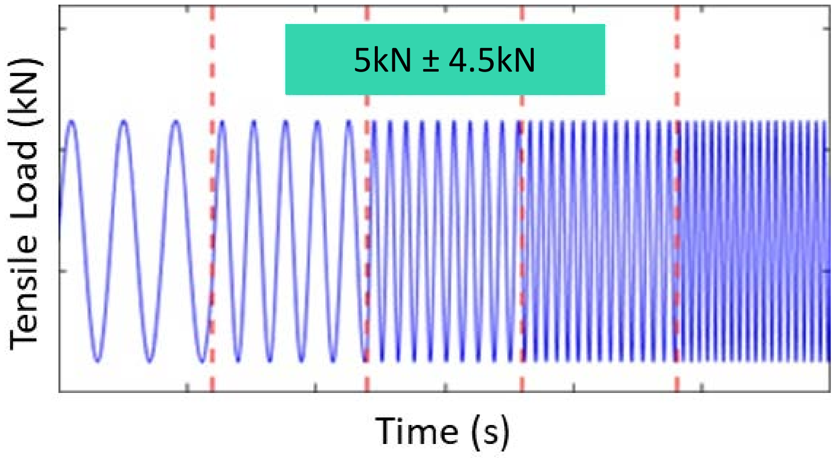
Findings from previous work

- Thermoelastic response from FRP materials is dependent on manufacturing approach V_f and resin rich surface layer
- Stress induced temperature change similar ply-by-ply for GFRP – little heat transfer – response from resin rich layer – strain witness
- For CFRP at low loading frequencies (< 15 Hz) heat transfer taking place in 'cross ply laminates'
- Recommendation carry out calibration programme to help interpret results from structural specimens
- Opportunity CFRP tune loading frequency to observe subsurface behaviour
- Further investigation required CFRP laminates with off axis (45^o) plies

Off axis plies







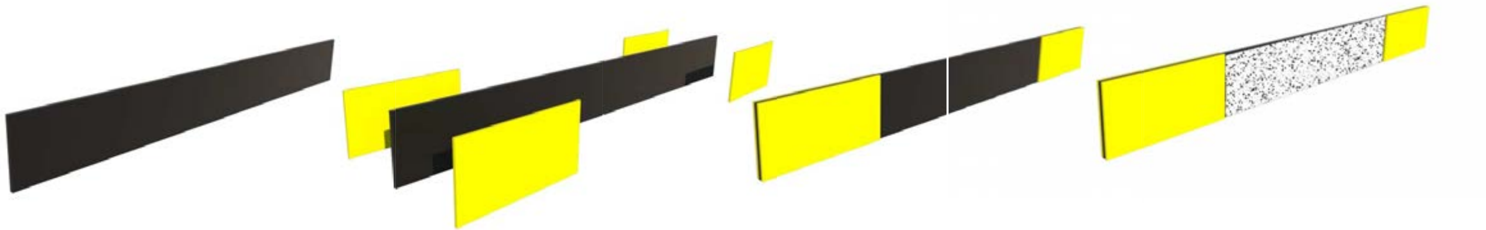
Cyclic load **below FPF**

Loading frequency (Hz): 0.5, 1.1, 2.1, 3.1, 4.1, 5.1, 7.1, 10.1… 30.1

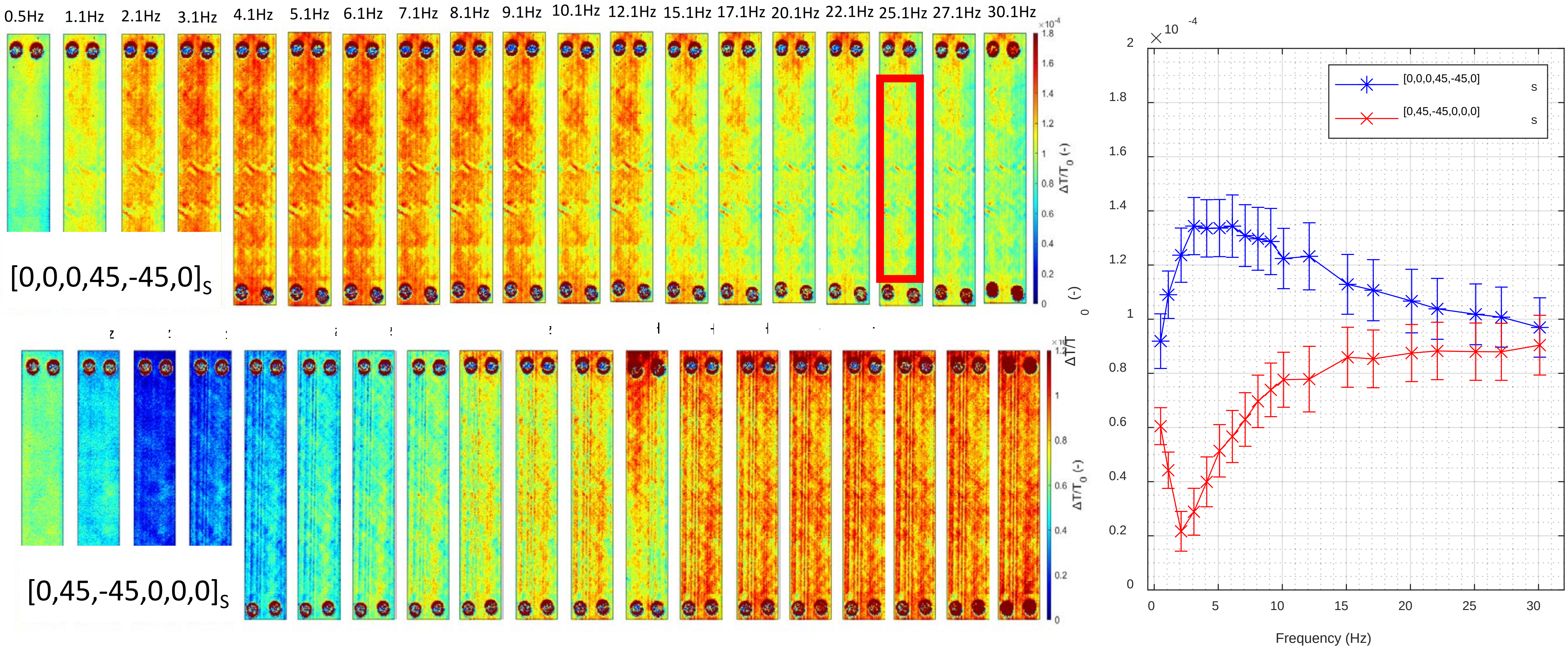
Two laminate lay-ups

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

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



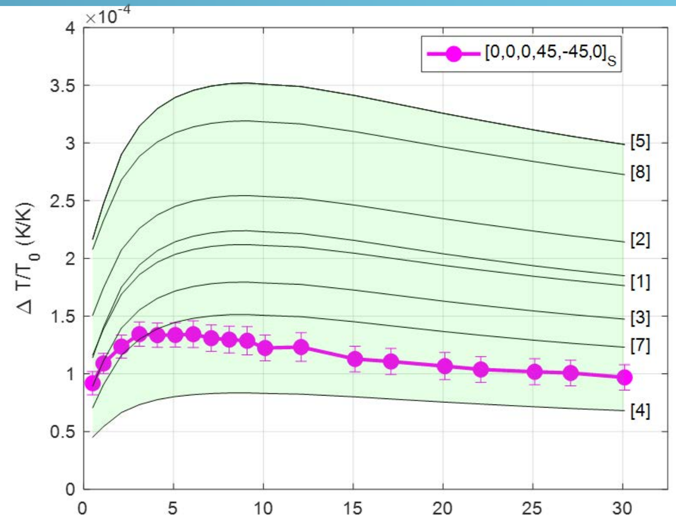
Effect of 45° plies

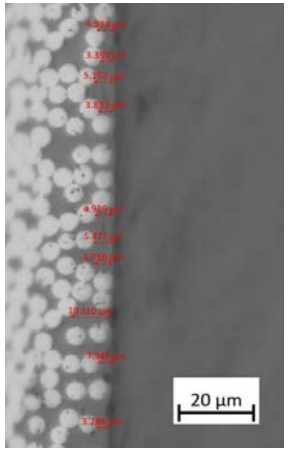


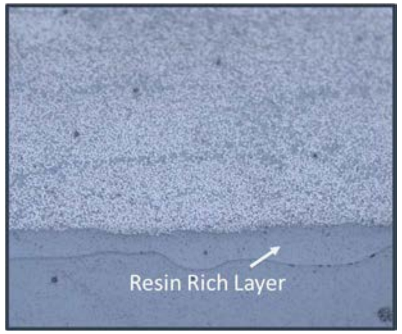
Making a model of heat transfer

Wong A. A non-adiabatic thermoelastic theory for composite laminates. Journal of Physics and Chemistry of Solids. 31 December 1991; 52: 483–494.

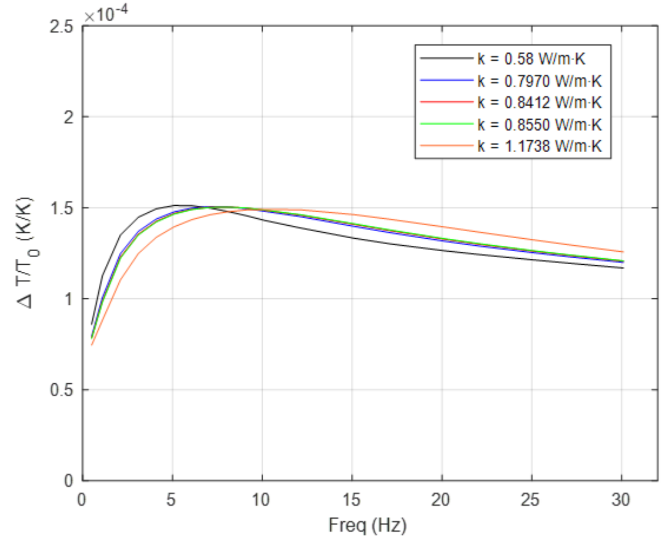
Reference	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	% Variation
Young's modulus E_1 (GPa)	148.8	171.4	161.0	164.0	161.0	158.5	161.0	165.0	22.26
Young's modulus E_2 (GPa)	9.19	9.08	11.38	12.00	11.38	8.96	11.38	9.00	15.29
Poisson's ratio ν_{12}	0.34	0.32	0.32	0.30	0.32	0.32	0.32	0.34	0.04
Bending stiffness G_{12} (GPa)	5.06	5.30	5.17	5.00	5.20	4.69	5.17	5.60	1.14
Thermal expansion coeff. α_1 (10^{-6} K^{-1})	-0.3	-5.5	-0.1	-0.1	-0.9	-0.17	0	-1.0	298.12
Thermal expansion coeff. α_2 (10^{-6} K^{-1})	28.4	25.5	31	12.4	28.8	36.5	30	18	196.20

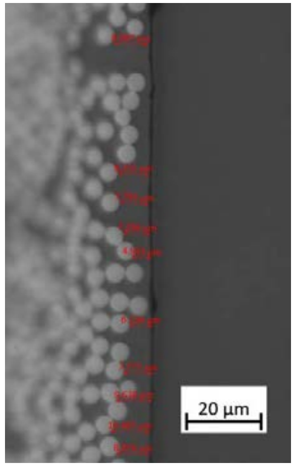






8552 Resin Reference	[1]	[4]	[7]	[8]	[18]	[19]	CV (%)
Young's modulus E_{1r} (GPa)	3.8	5	4.67	4.08	X	X	12.45
Poisson's ratio ν_r	0.35	0.40	0.33	0.38	X	X	8.52
Bending stiffness G_r (GPa)	1.41	X	X	1.48	X	X	3.43
Density ρ_r (kg m^{-3})	1153	X	X	X	1301	1300	6.81
Specific heat capacity Cp_r (J kg^{-1} K^{-1})	1100	X	X	X	1350	1025	14.69
Thermal expansion coeff. α_r (10^{-6} K^{-1})	53.5	60	65	46.7	48.0	X	14.31



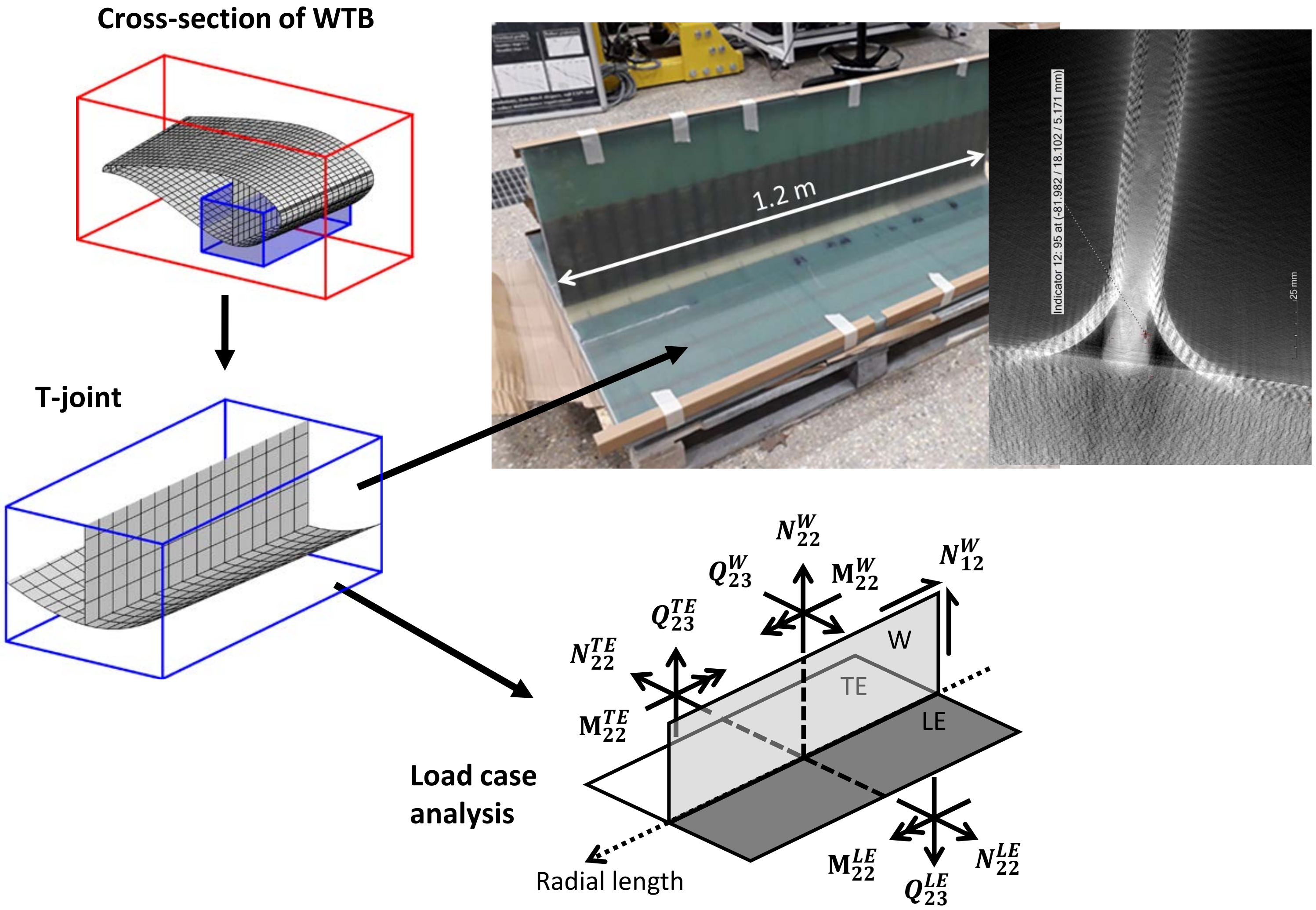


Can TSA be used to assess CFRP components?

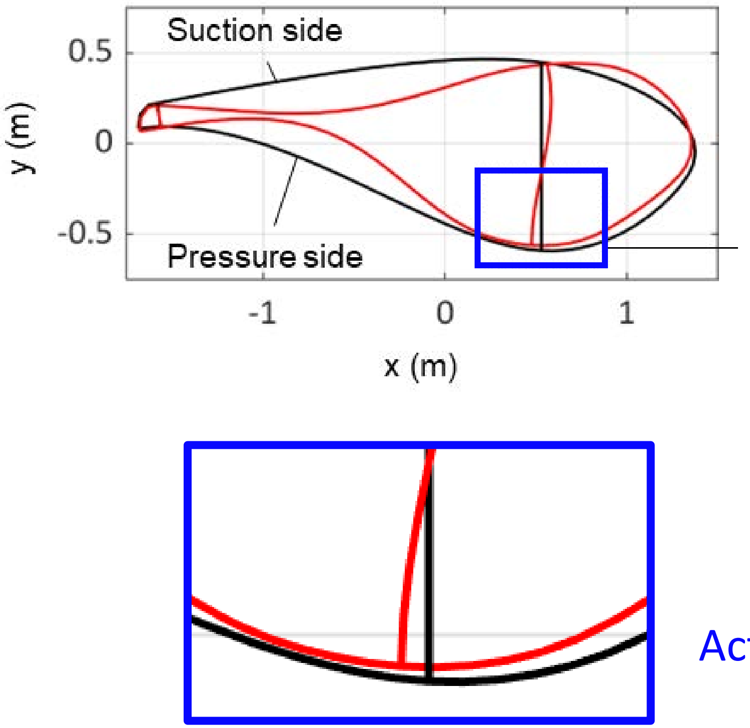
- Demonstrated the thermoelastic response is highly dependent on lay-up
- Need to assess factors such as resin-rich layer
- Paint coating also has an effect (need to speckle to use DIC)
- Only considered 1D thermal conduction through thickness
- In-plane conduction e.g. around damage - modification of stress field changes heat transfer characteristics locally
- Need for a model that considers 3D heat diffusion
- Fusing data with DIC can be used to:
    - Identify sub surface damage in situ in CFRP composites
    - Identify difficult to measure quantities such as the CTEs of CFRP composites

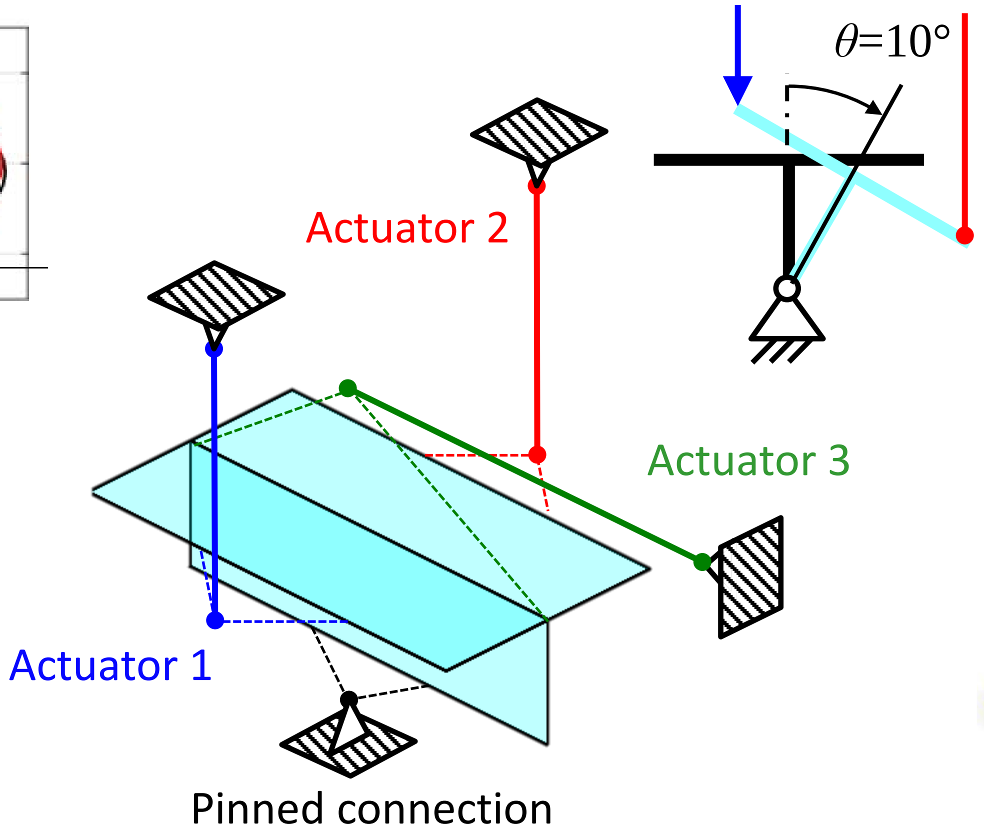
Opportunity for large scale tests on GFRP

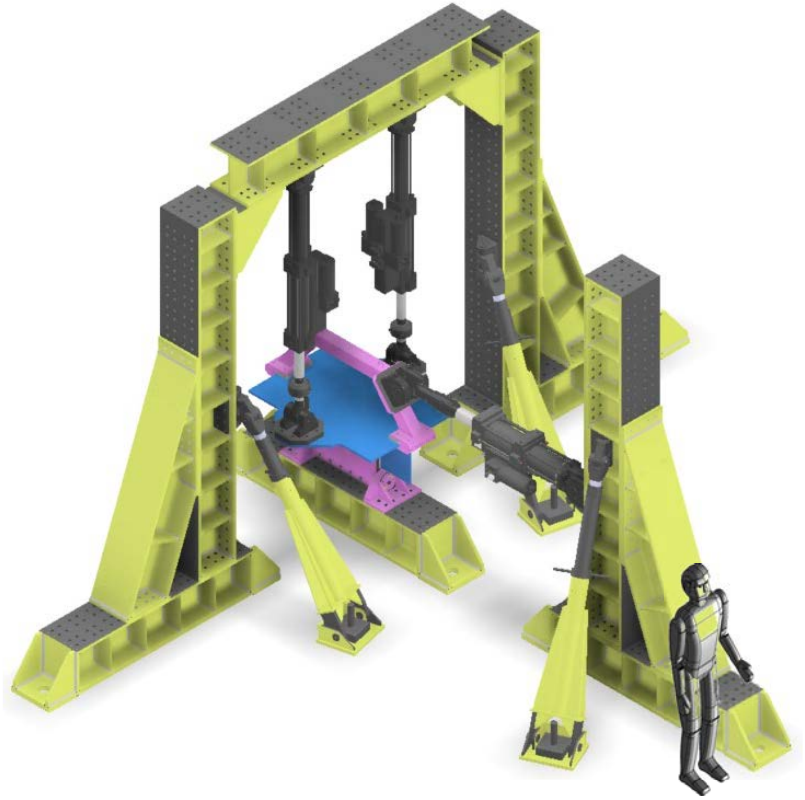
- GFRP – response from resin rich layer
- Adiabatic even at low frequencies
- Can TSA help determine failure mode in conjunction with DIC
- Can a large specimen be loaded realistically?



Wind turbine blade substructure loading



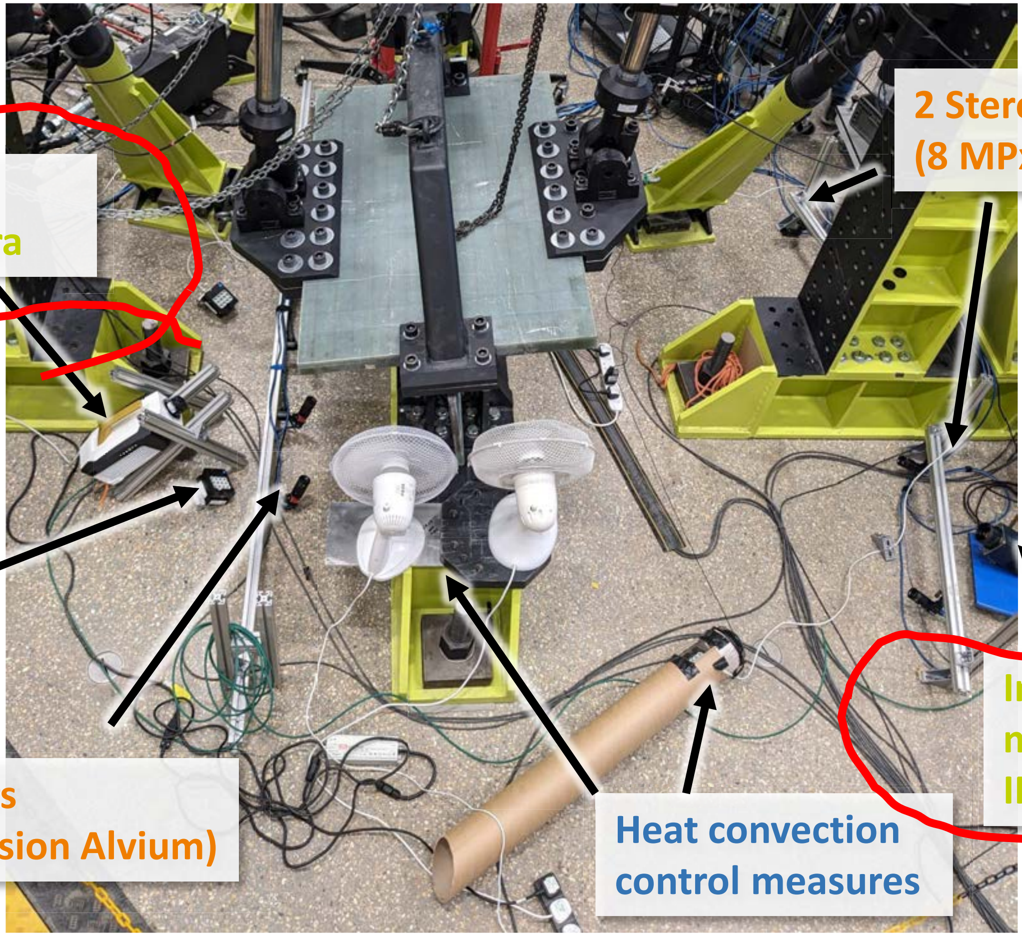


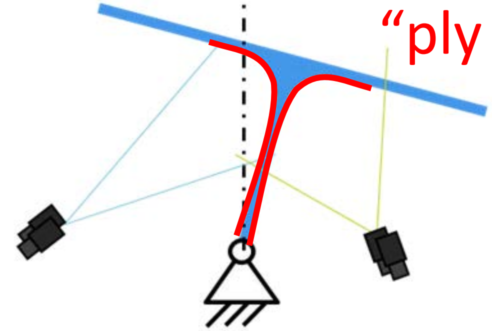


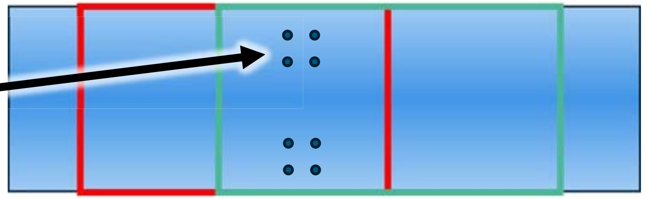
FE prediction → Test schematic → Detailed test design

Imaging set-up composite T-joint

Far side **Near side**





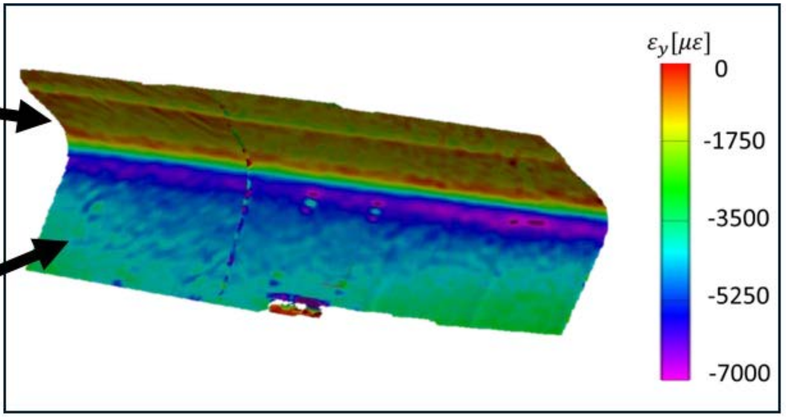


- Overlapping FoVs for multi-cam reconstruction/common fiducials
Cross correlation between different stereo pairs

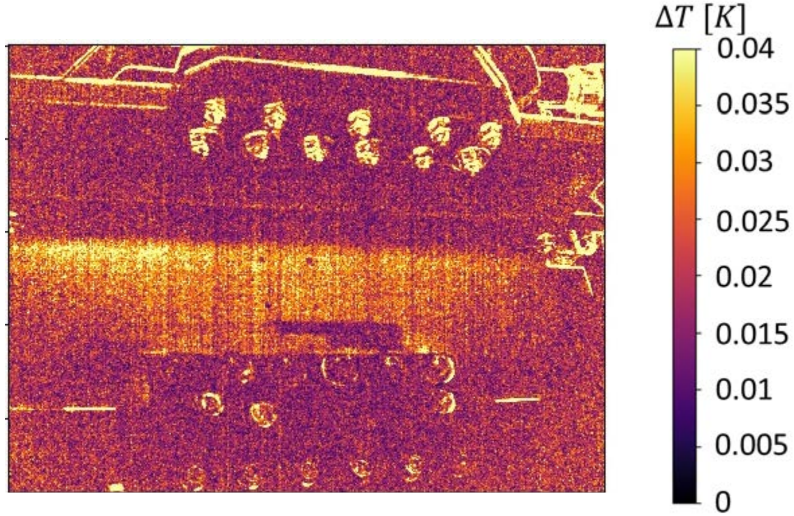
Composite specimen before initial failure

Near side

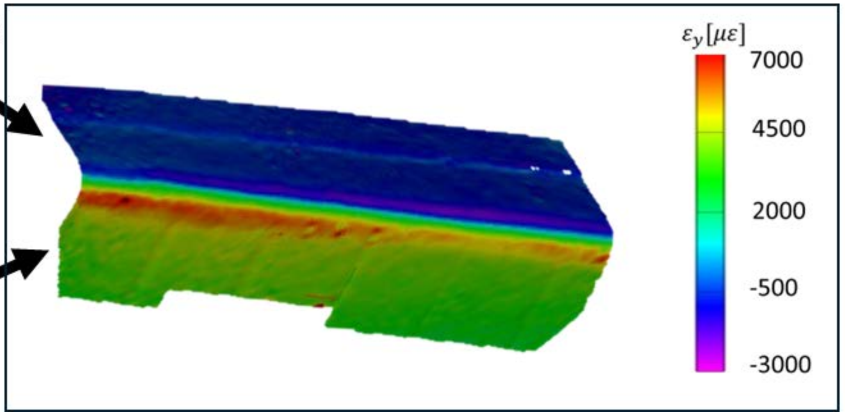
DIC

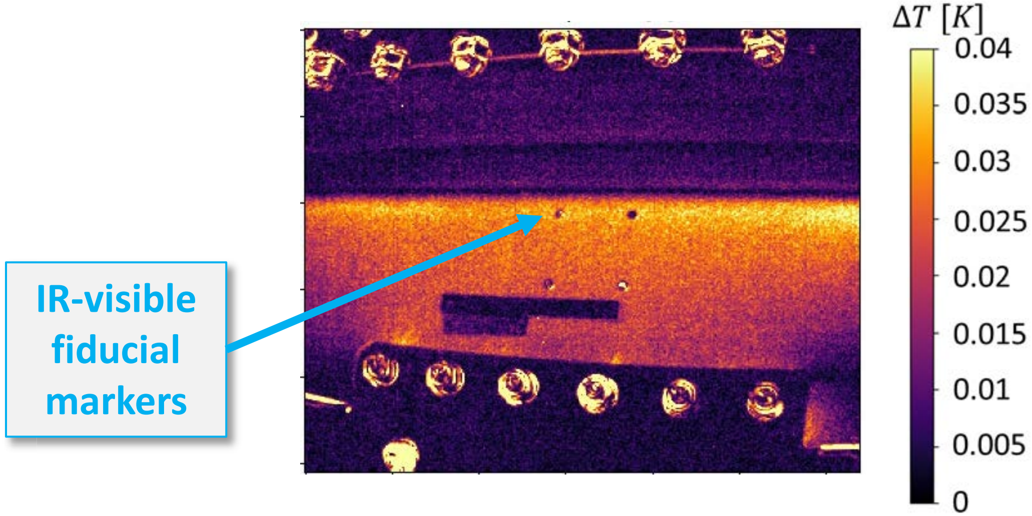


TSA

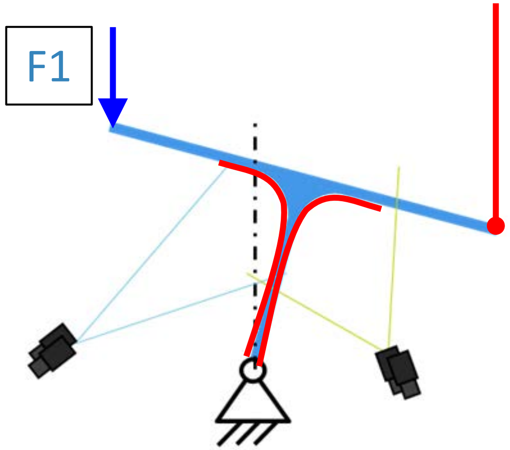


Far side



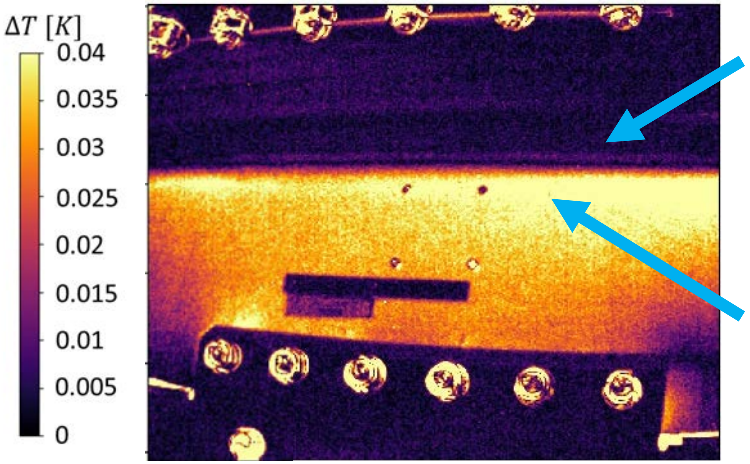


Forensic failure analysis - WIP



Undamaged specimen

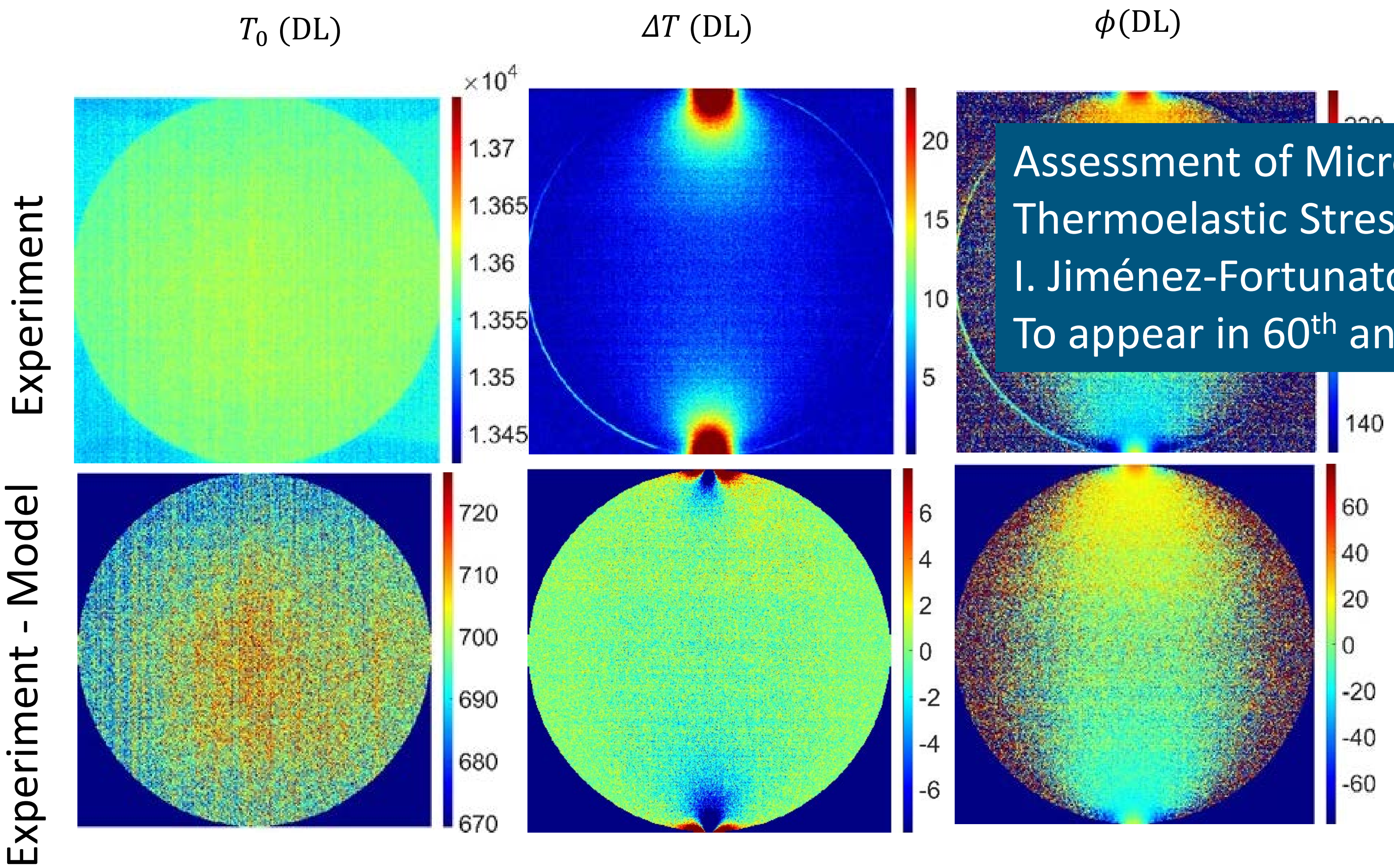
Damaged specimen

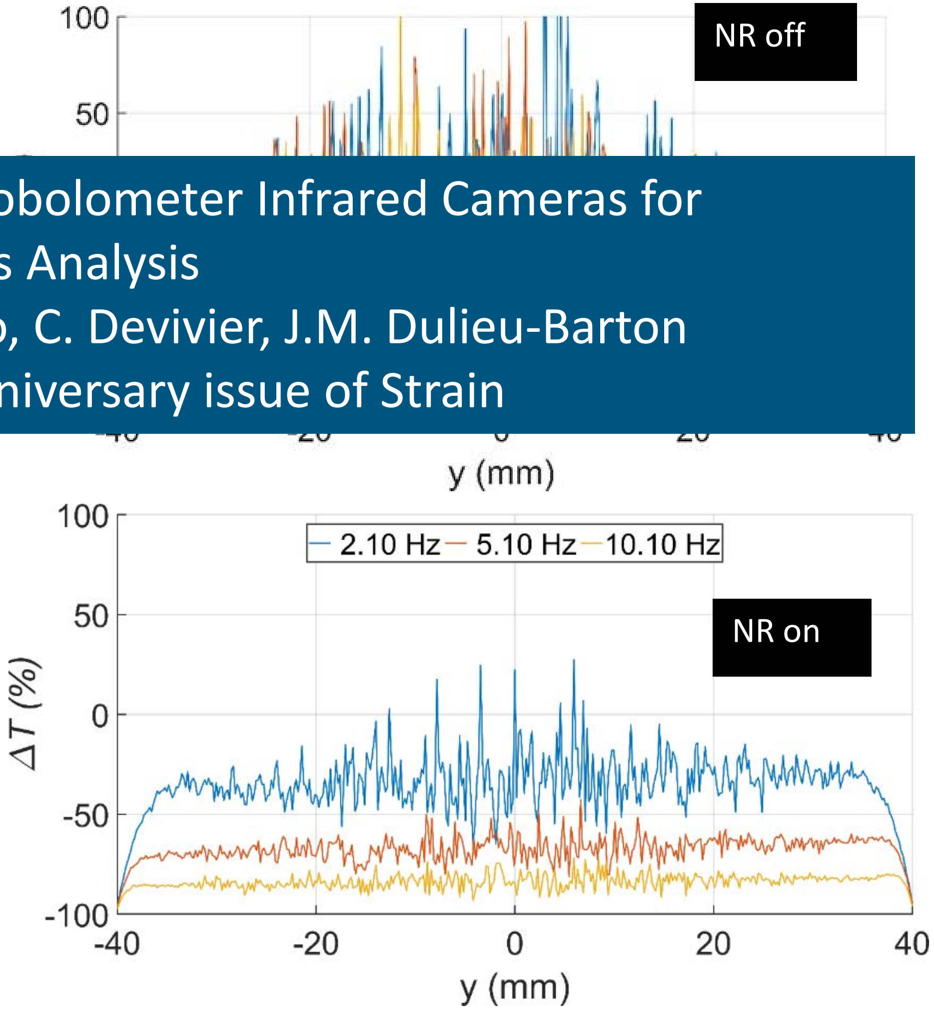


Reduction of thermoelastic signal on ply drop

Increase of thermoelastic signal in the web, indicating stress redistribution

Low-cost TSA and Brazilian Disc





Assessment of Microbolometer Infrared Cameras for Thermoelastic Stress Analysis

I. Jiménez-Fortunato, C. Devivier, J.M. Dulieu-Barton

To appear in 60th anniversary issue of Strain

It all started with SPATE

Engineering and Physical Sciences Research Council

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Thank you for listening

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