Validation of a Numerical Model for Predictions of the Thermoelastic Effect in Laminated Composite Structures

<u>Riccardo Cappello</u>[a], Rafael Ruiz-Iglesias[a], Geir Olafsson[a], Giuseppe Pitarresi[b] , Giuseppe Catalanotti[c] and Janice Dulieu-Barton[a]

[a] **Bristol Composites Institute (BCI), University of Bristol, UK**

[b] University of Palermo, Italy

[c] Kore University of Enna, Italy

Outline

- Thermoelastic Stress Analysis and non adiabaticity in composite laminates
- Numerical Model
- Experimental setup and material properties
- Comparison between numerical and experimental results
- Analysis of the effects of surface resin layer and loading frequency on the thermoelastic response
- Coupon with non-uniform temperature distribution
- Conclusions

Engineering and Physical Sciences Research Council

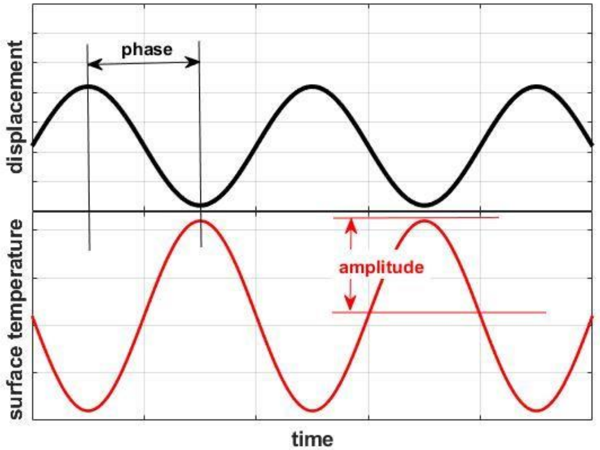
Thermoelastic Stress Analysis (TSA)

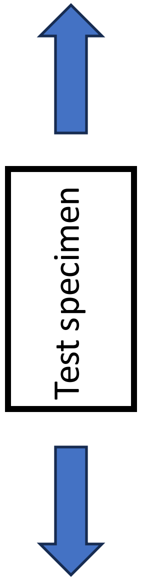
$$\rho c_{\varepsilon} \dot{T} = T \frac{\partial \sigma_{ij}}{\partial T} \dot{\varepsilon}_{ij} + \cancel{\dot{Q}}$$

Thermoelastic effect (reversible)

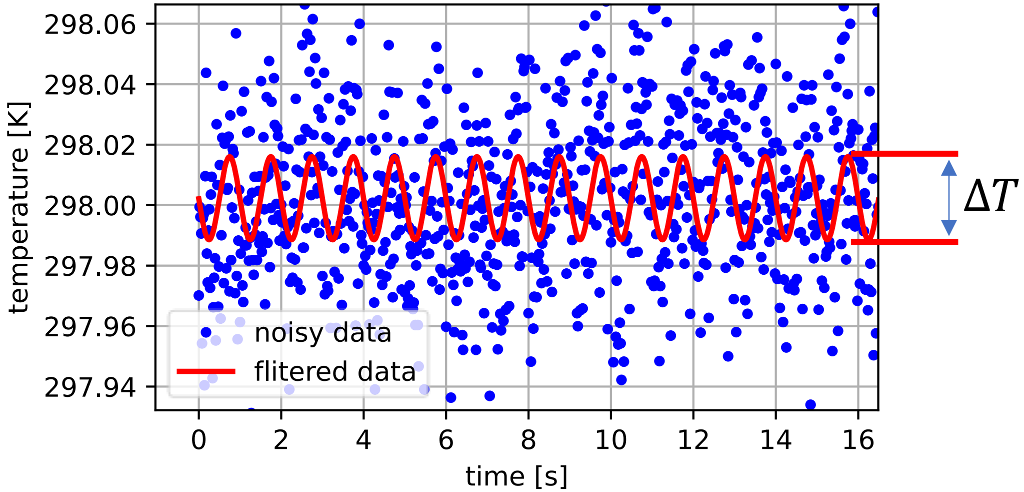
Temperature variations

Deformations in elastic field





$\sin(\omega t)$

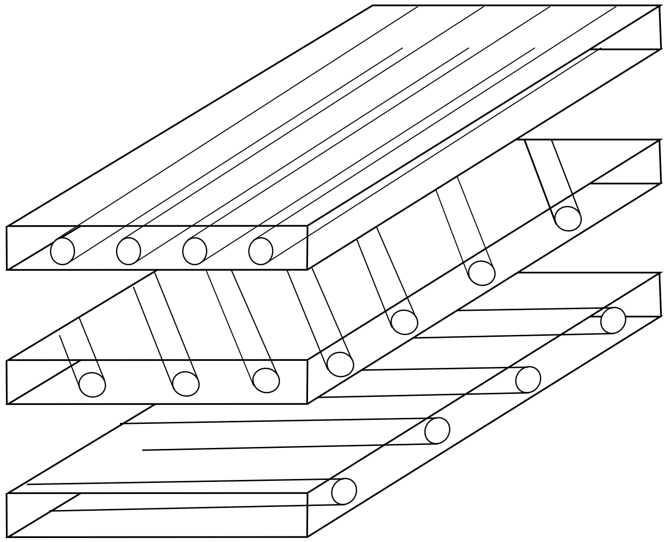


$$\boxed{\Delta T = -T_o \frac{1}{\rho \cdot c_p} (\alpha_1 \Delta\sigma_1 + \alpha_2 \Delta\sigma_2)}$$

Thermoelastic temperature variation for orthotropic material

University of Bristol · University of Bath · University of Southampton · University of Exeter

TSA in composite laminates



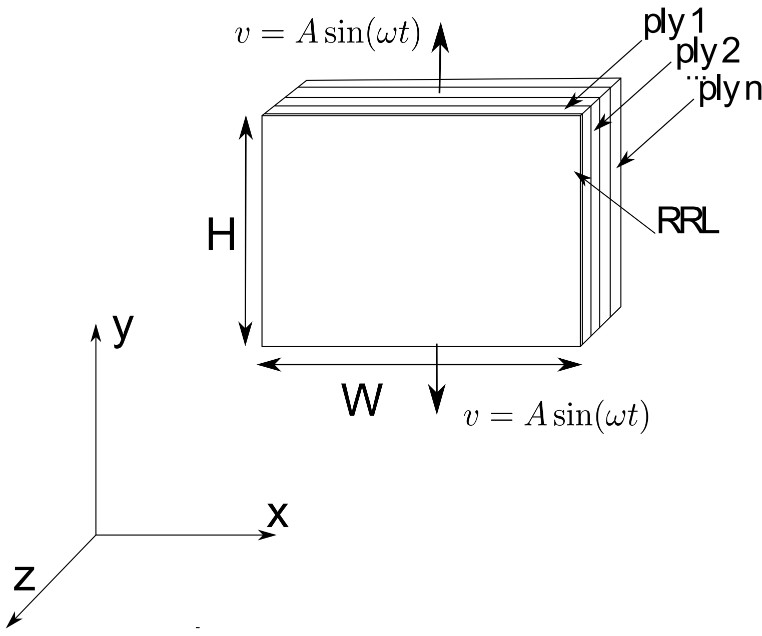
$$\Delta T = -\frac{T_o}{c_p \cdot \rho} \cdot \begin{bmatrix} (C_{1111} \cdot \alpha_{11} + C_{1122} \cdot \alpha_{22} + C_{1133} \cdot \alpha_{33}) \cdot \Delta\varepsilon_{11} + \\ +(C_{2211} \cdot \alpha_{11} + C_{2222} \cdot \alpha_{22} + C_{2233} \cdot \alpha_{33}) \cdot \Delta\varepsilon_{22} + \\ +(C_{3311} \cdot \alpha_{11} + C_{3322} \cdot \alpha_{22} + C_{3333} \cdot \alpha_{33}) \cdot \Delta\varepsilon_{33} \end{bmatrix}$$

Each ply represents a different heat source depending on its orientation, generating through-thickness temperature gradients → non adiabatic behaviour.

Numerical Model

Via a Python script, a parametric model has been developed in Abaqus:

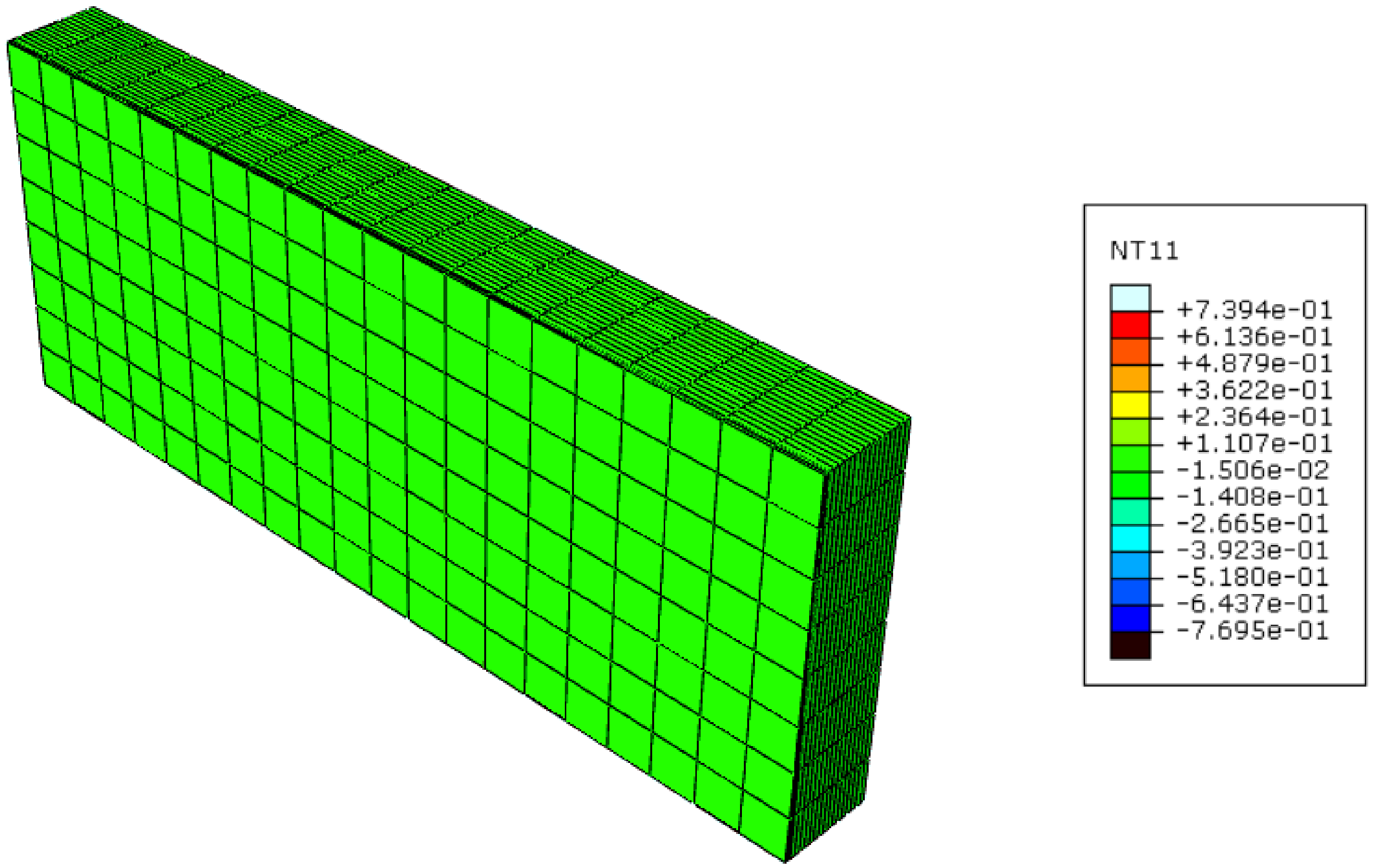
- Geometry (H, W) of the specimen, number (N) and thickness (T) of plies, lay-up, material system are fully customisable.
- Inclusion of a surface resin-rich layer (RRL).
- Symmetric displacement with a sinusoidal waveform applied to upper and lower faces of the specimen.
- Conduction between plies.
- Coupled temperature-displacement analysis (C3D8T brick elements).



*For more details on the model: Cappello, Riccardo, Giuseppe Pitarresi, and Giuseppe Catalanotti. "Thermoelastic Stress Analysis for composite laminates: A numerical investigation." *Composites Science and Technology* (2023): 110103.

Numerical Model: an example

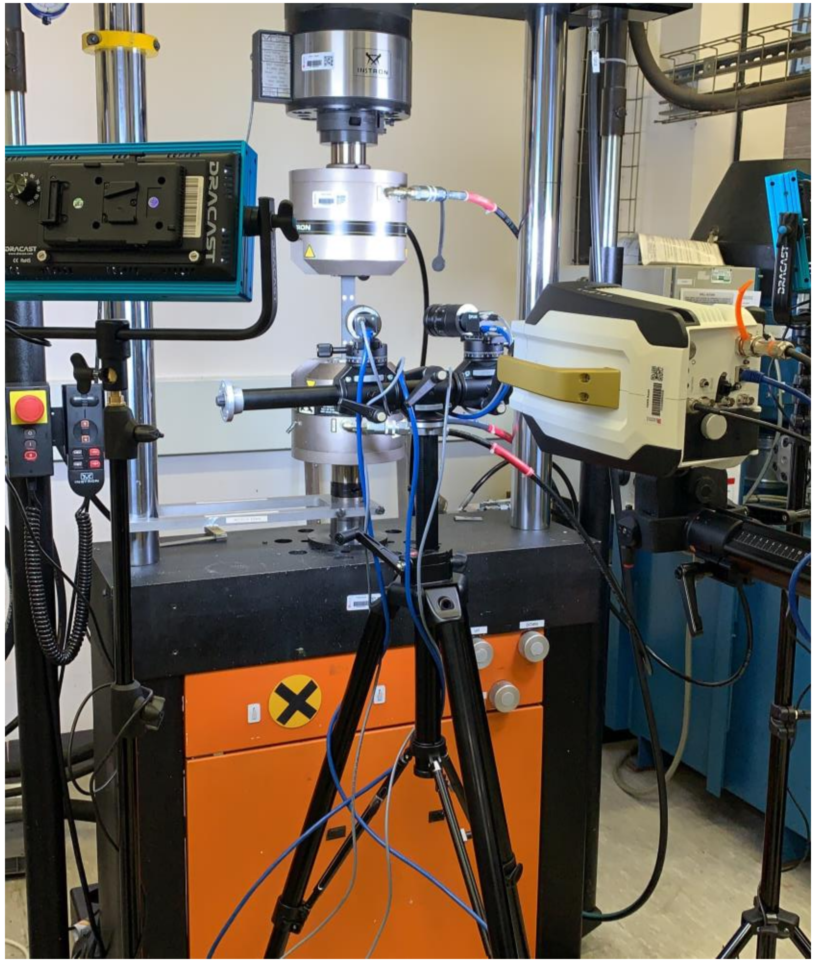
- **Carbon fibre**
- **Loading Frequency: 20 Hz**
- **Layup [0/45/-45/90]s**

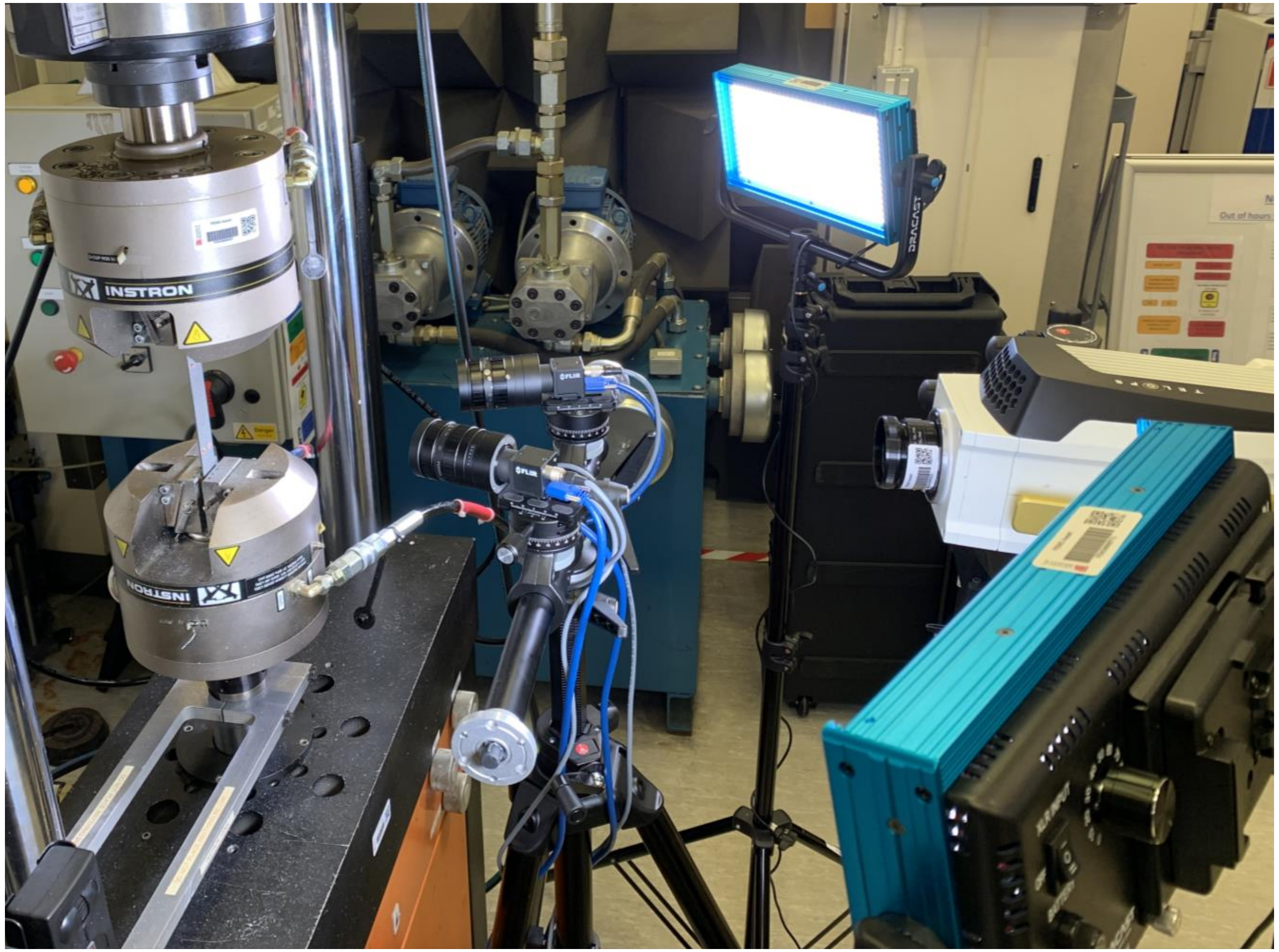


Engineering and Physical Sciences Research Council

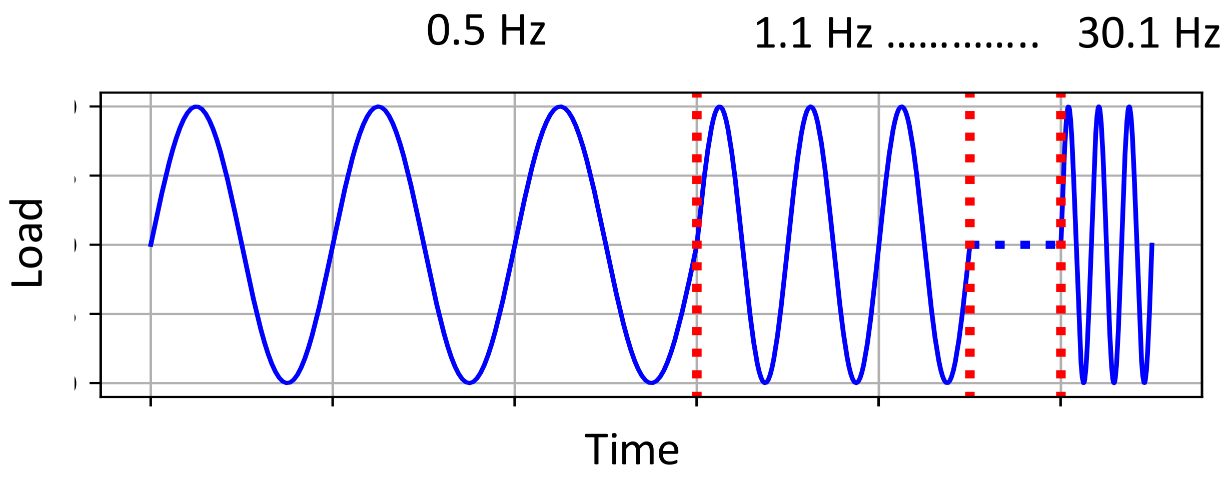
University of Bristol · University of Bath · University of Southampton · University of Exeter

Experimental Setup





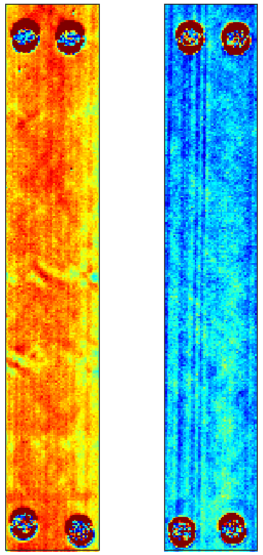
Experiments



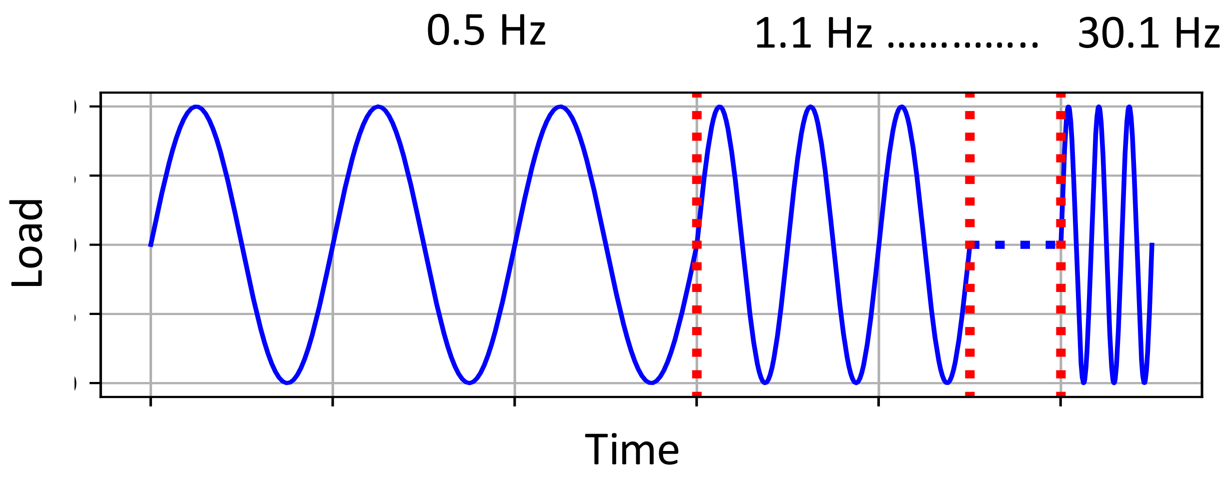
Layups	$[0, 0, 0, 45, -45, 0]_s$, $[0, 45, -45, 0, 0, 0]_s$
Loading frequencies (Hz)	0.5, 1.1, 2.1, 3.1, 4.1, 5.1, 6.1,7.1,8.1,9.1,10.1,
	12.1, 15.1, 17.1, 20.1, 22.1, 25.1, 27.1, 30.1
Ply thickness (mm)	0.125
Number of loading cycles	3
Resin layer thickness (μm)	(5, 12), (8, 25)
Experimental sampling frequency (Hz)	383.0
Numerical sampling	50 points per cycle

Property	IM7/8552
Young's modulus E_1 (GPa)	159.5*
Young's modulus E_2 (GPa)	10.1*
Poisson's ratio ν_{12}	0.325*
Shear modulus G_{12} (GPa)	5.14*
Fibre V_f (%)	58.0*
Thermal expansion coeff. α_1 (10^{-6} K^{-1})	-0.127*
Thermal expansion coeff. α_2 (10^{-6} K^{-1})	21.9*
Thermal conductivity k_1 (W m K^{-1})	5
Thermal conductivity k_2 (W m K^{-1})	0.6
Density ρ (Kg dm^{-3})	1.57*
Specific heat C_ε (J Kg^{-1} K^{-1})	857

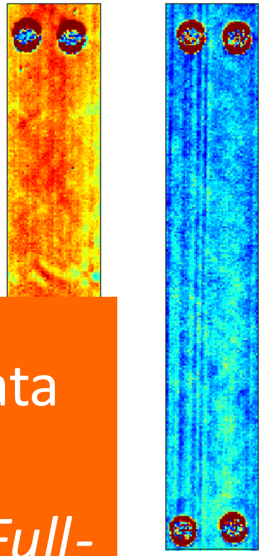
Property	Epoxy resin
Young's modulus E (GPa)	3.8
Poisson's ratio ν	0.35
Shear modulus G_{12} (GPa)	2.71
Thermal expansion coeff. αr (10^{-6} K^{-1})	53.5
Thermal conductivity k (W m K^{-1})	0.2
Density ρ (Kg dm^{-3})	1.153
Specific heat C_ε (J Kg^{-1} K^{-1})	1110



Experiments



Property	IM7/8552
Young's modulus E_1 (GPa)	159.5*
Young's modulus E_2 (GPa)	10.1*
Poisson's ratio ν_{12}	0.325*
Shear modulus G_{12} (GPa)	5.14*
Fibre V_f (%)	58.0*
Thermal expansion coeff. α_1 (10^{-6} K^{-1})	-0.127*
Thermal expansion coeff. α_2 (10^{-6} K^{-1})	21.9*
Thermal conductivity k_1 (W m K^{-1})	5
Thermal conductivity k_2 (W m K^{-1})	0.6
Density ρ (Kg dm^{-3})	1.57*
Specific heat C_ε (J Kg^{-1} K^{-1})	857



25. Thermography-based Nondestructive Evaluation (NDE), Process Monitoring, Data Fusion(Hemlock/Oak)– **Monday 3rd (05:10 PM)**

A Tool to Obtain the Coefficients of Thermal Expansion for CFRP Composites using Full-Field Data Fusion #17536 R. Ruiz-Iglesias

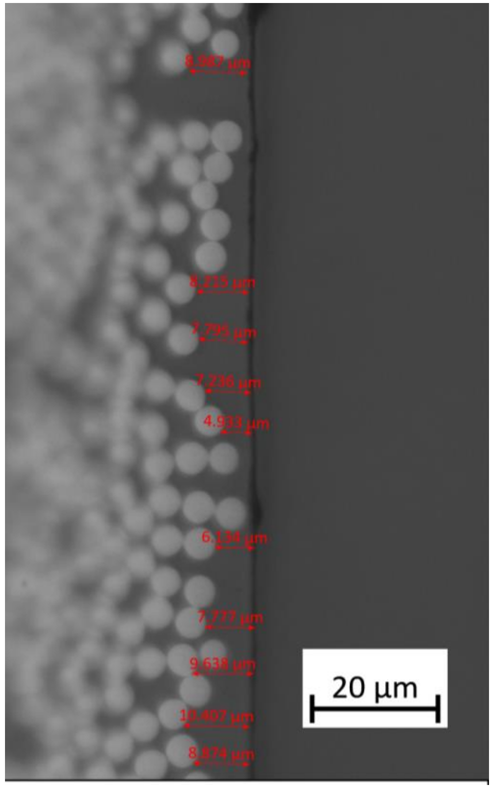
Engineering and Physical Sciences Research Council
University of Bristol
University of Bath
University of Southampton
University of Exeter

Engineering and Physical Sciences Research Council

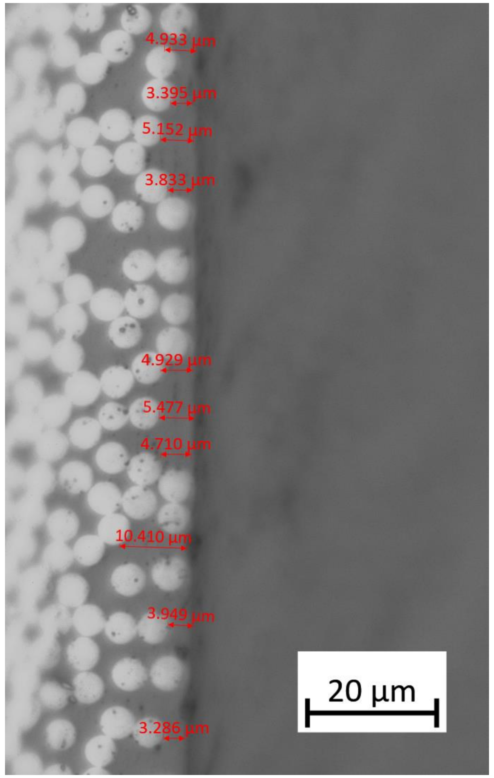
Micrographs

CERTEST

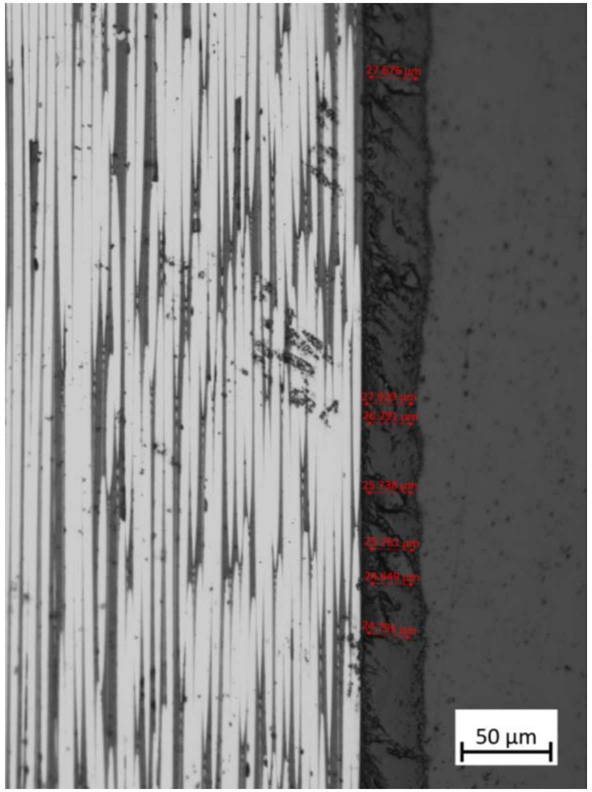
$[0,45\text{-}45,0,0,0]_S$ – RRL = 8µm



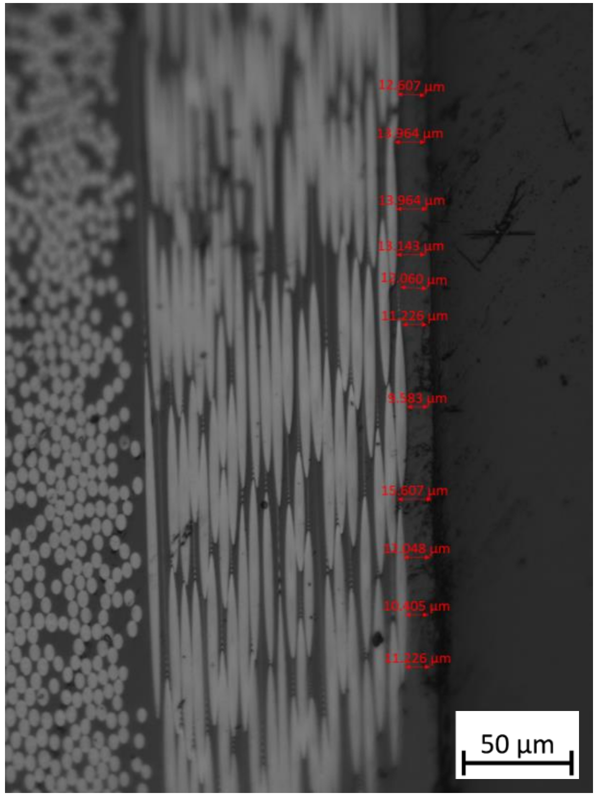
$[0,0,0,45\text{-}45,0]_S$ – RRL = 5 µm



$[0,45\text{-}45,0,0,0]_S$ – RRL =25 µm

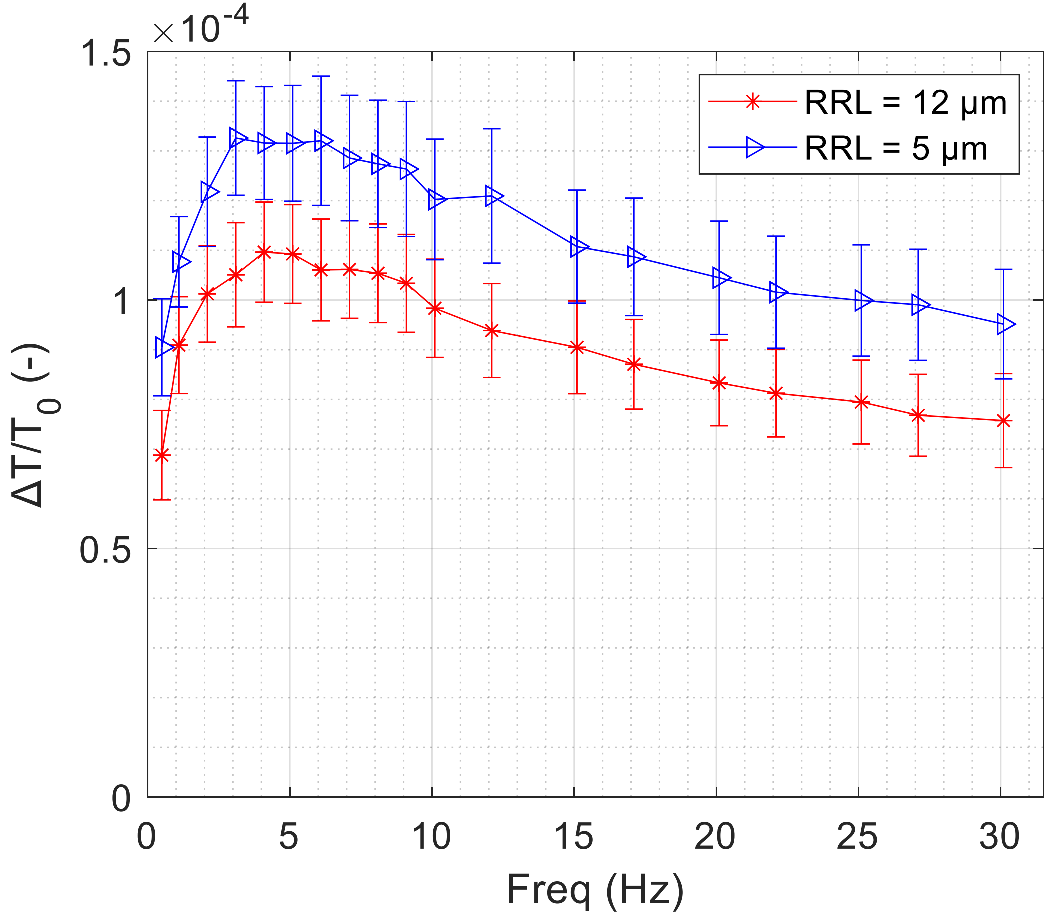


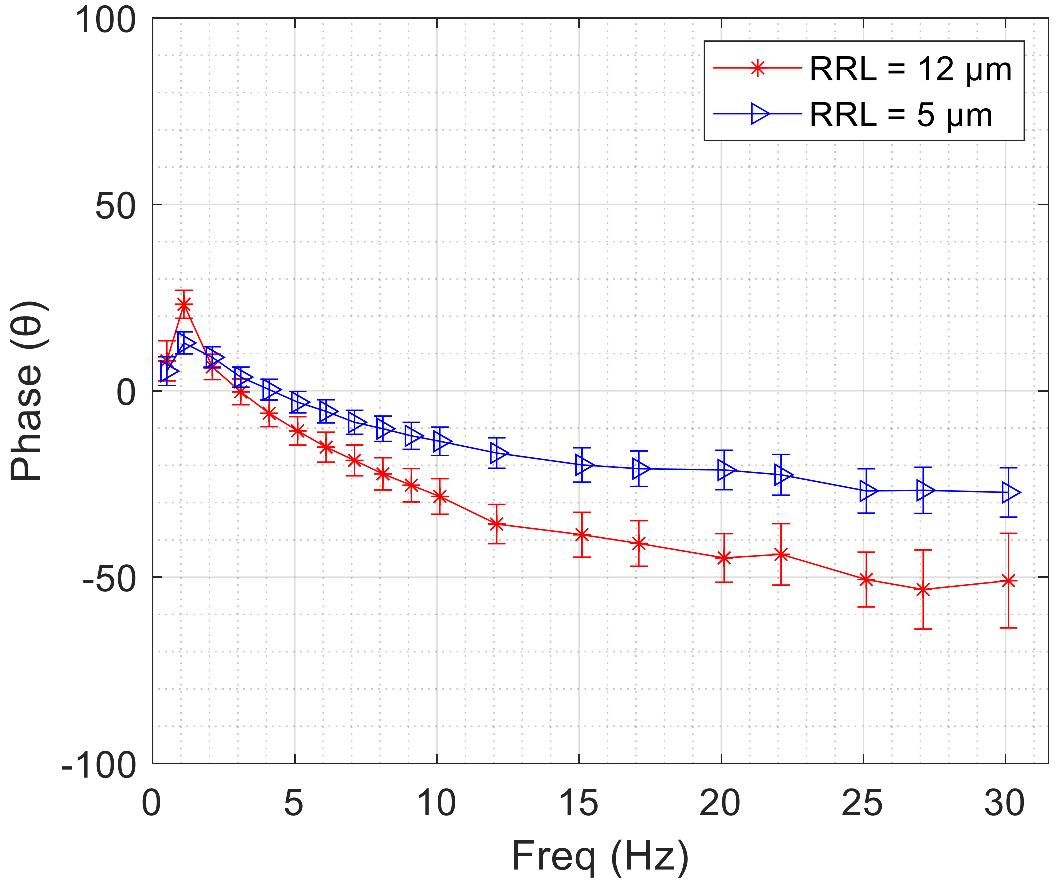
$[0,0,0,45\text{-}45,0]_S$ – RRL = 12 µm



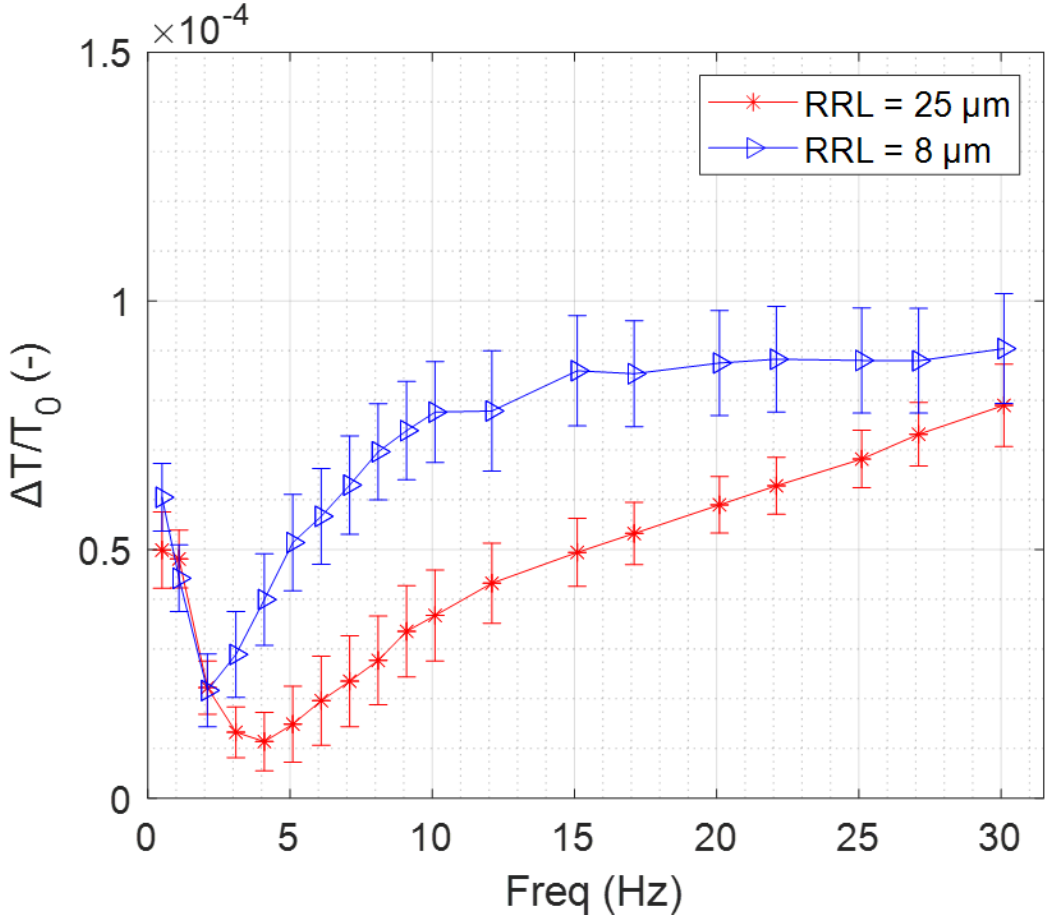
University of Bristol · University of Bath · University of Southampton · University of Exeter

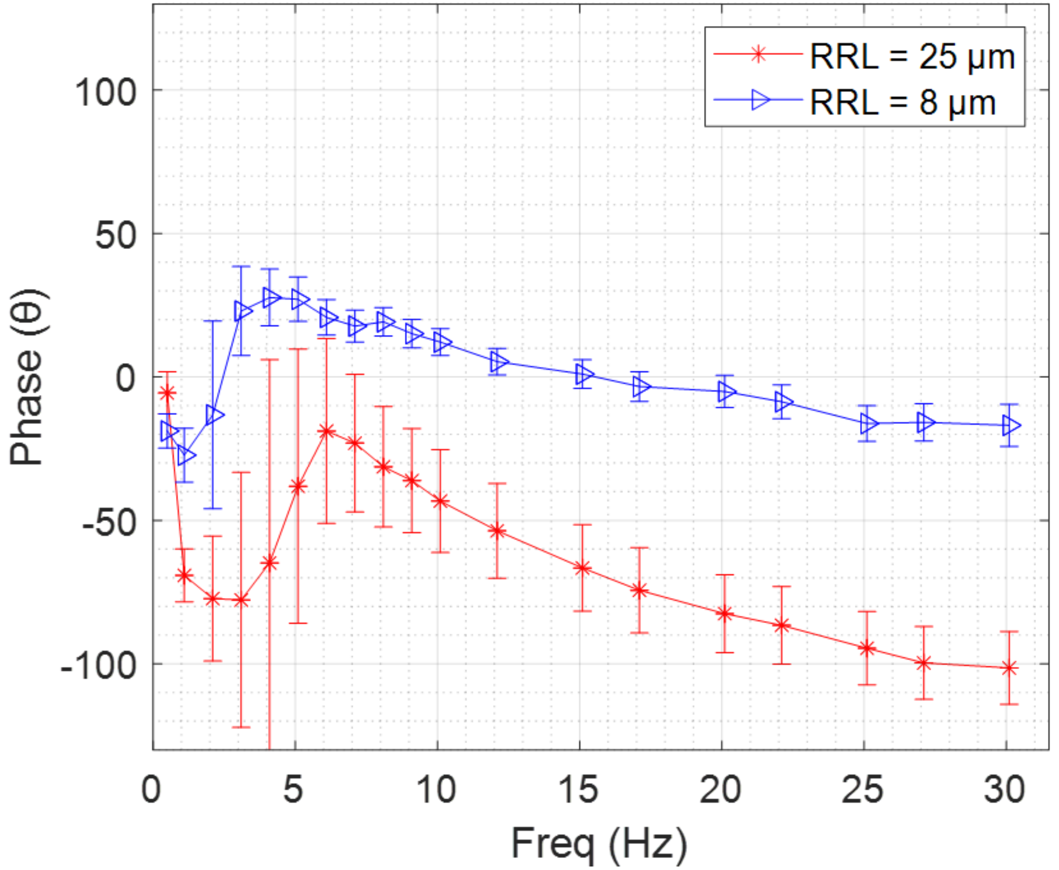
Experimental Results: $[0,0,0,45\text{-}45,0]_S$





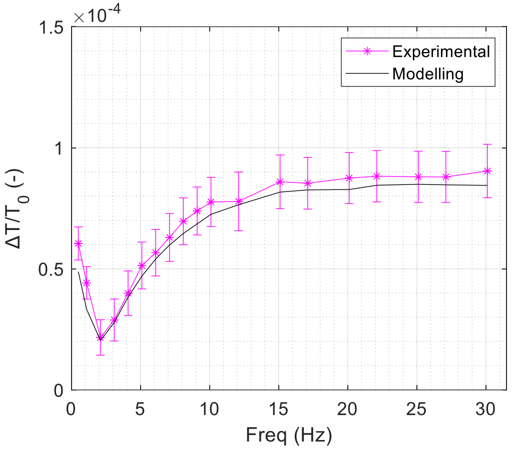
Experimental Results: $[0,45\text{-}45,0,0,0]_S$

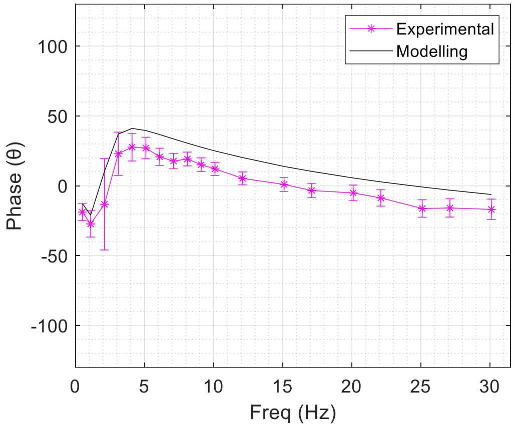




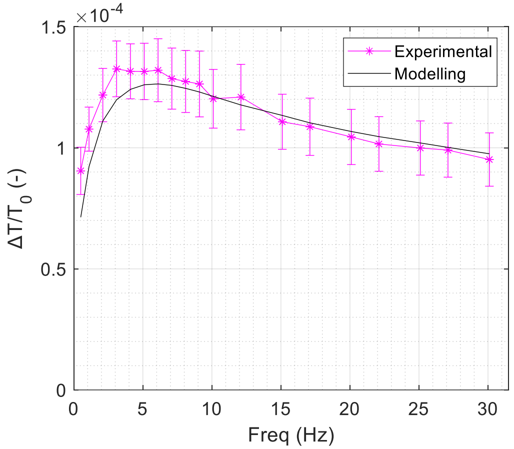
Experiments vs Model results

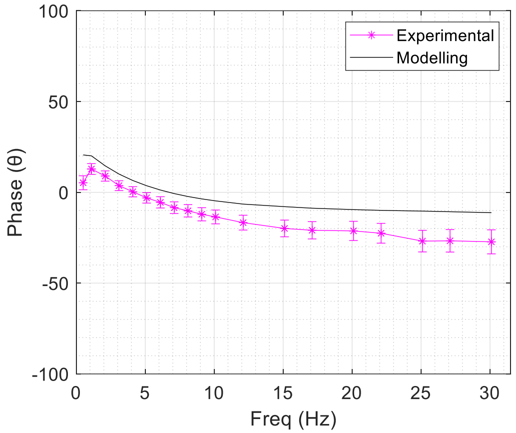
$[0,45\text{-}45,0,0,0]_S$ – RRL =8μm



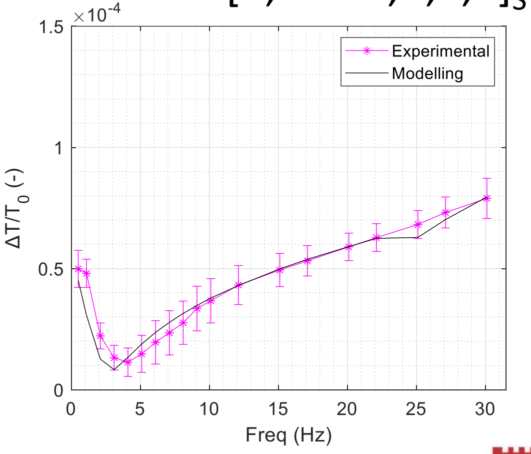


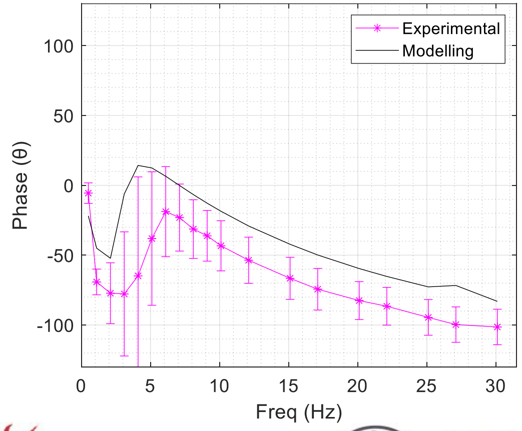
$[0,0,0,45\text{-}45,0]_S$ – RRL = 5 μm



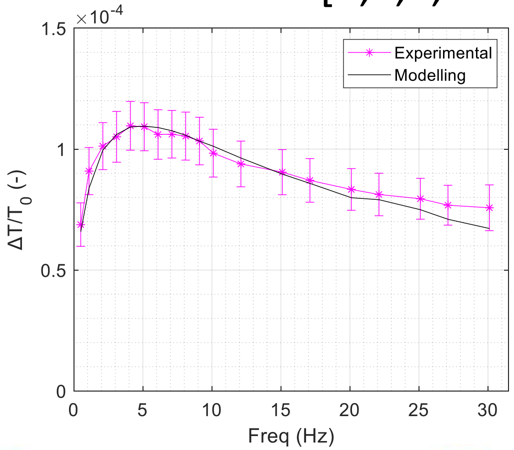


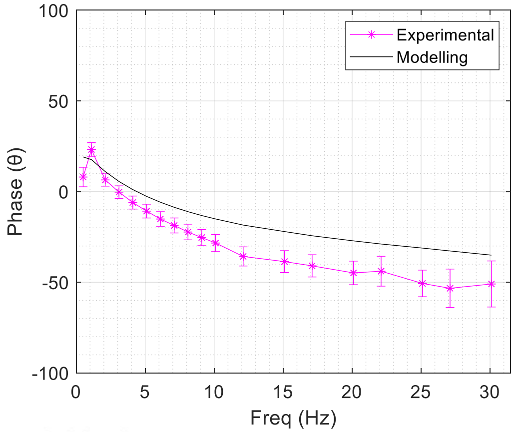
$[0,45\text{-}45,0,0,0]_S$ – RRL =25 μm



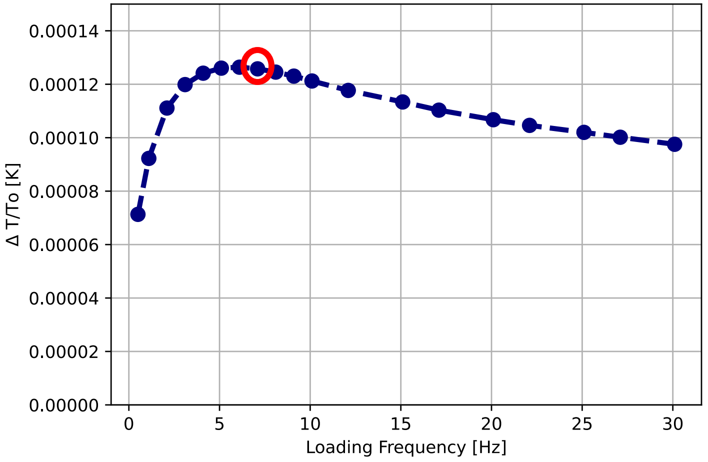


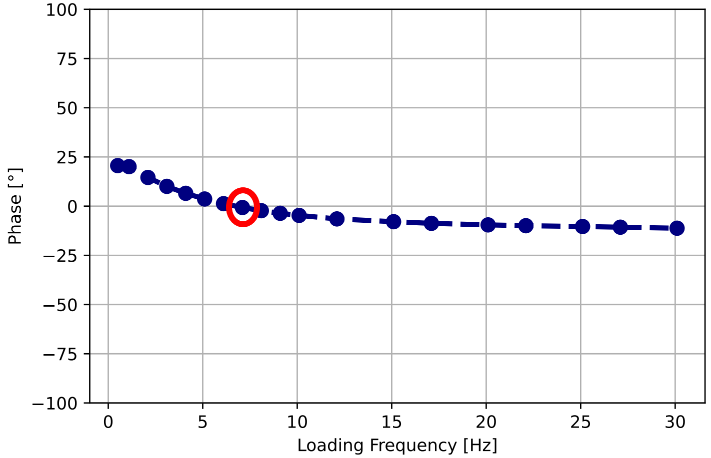
$[0,0,0,45\text{-}45,0]_S$ – RRL = 12 μm

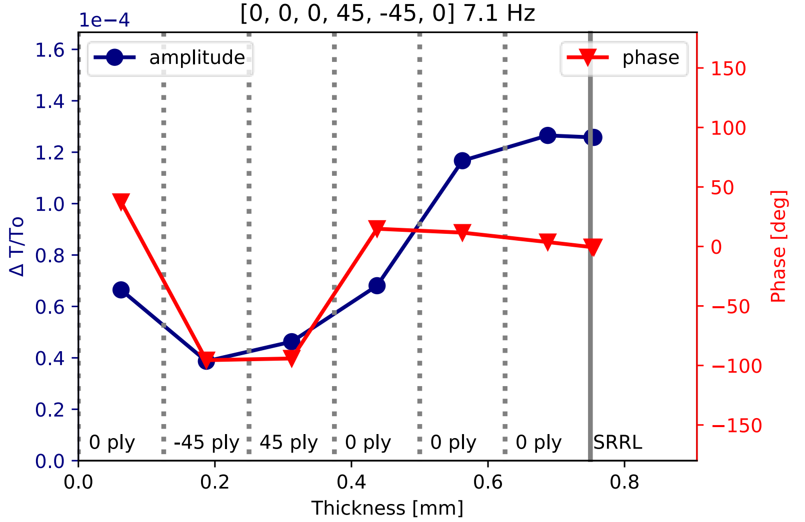


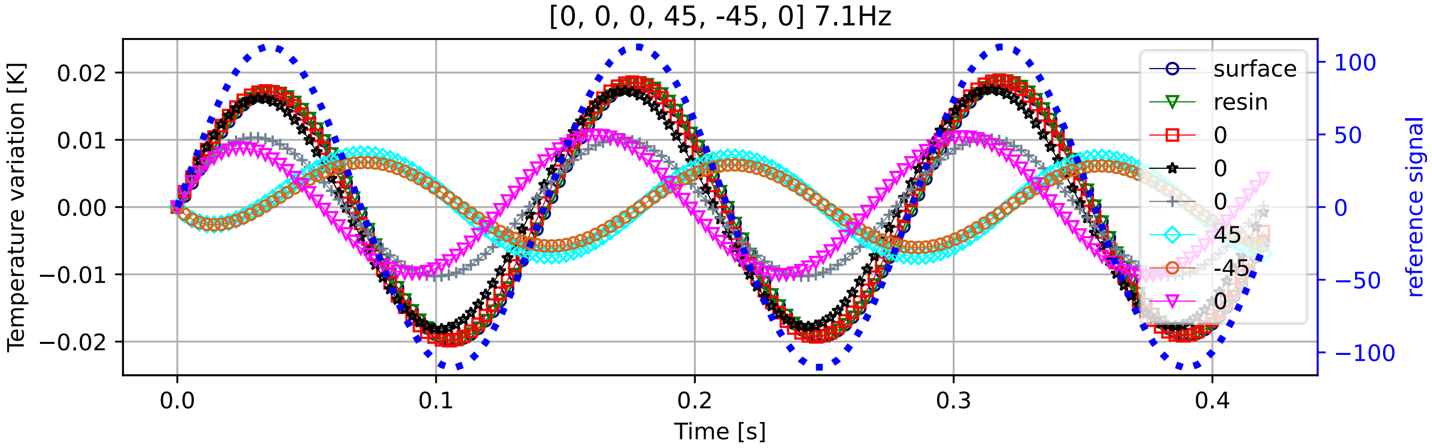


Numerical results: [0, 0, 0, 45, -45, 0]$_S$, 7.1 Hz





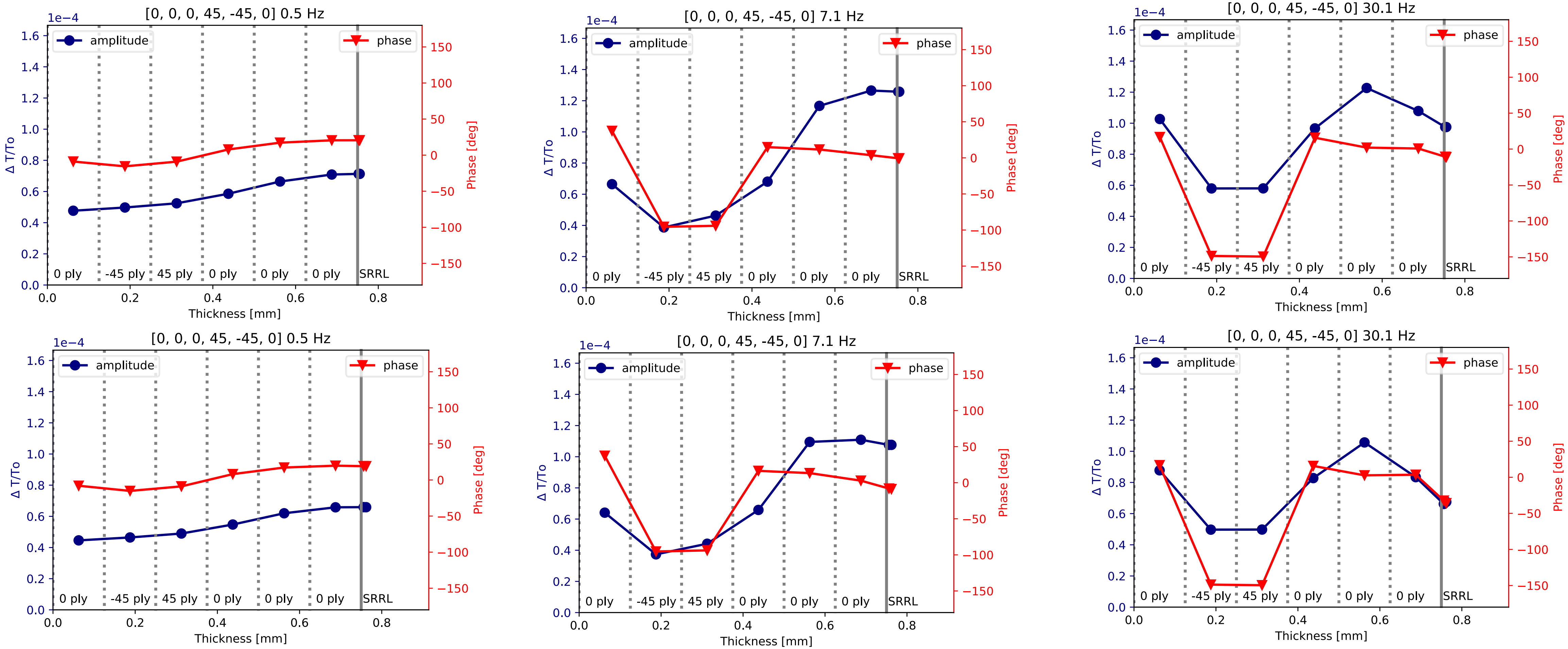




Numerical results: [0, 0, 0, 45, -45, 0]$_S$

SRRL 5 µm

SRRL 12 µm



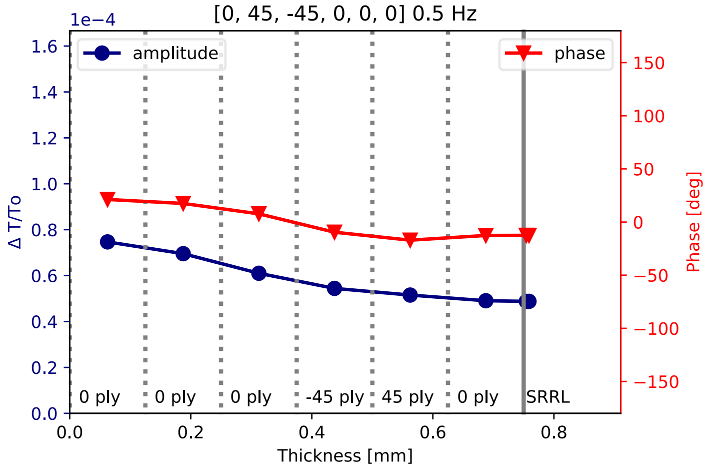
0.5 Hz

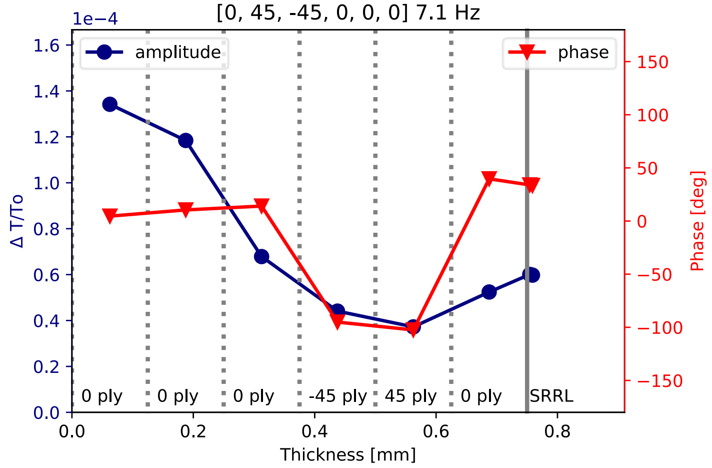
7.1 Hz

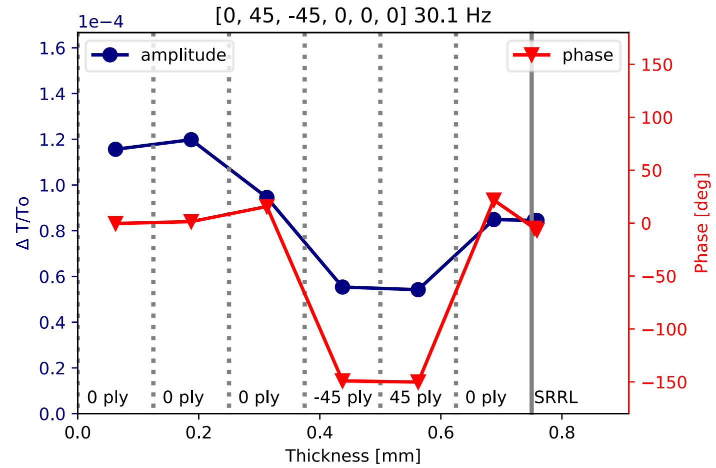
30.1 Hz

Numerical results: $[0, 45, -45, 0, 0, 0]_S$

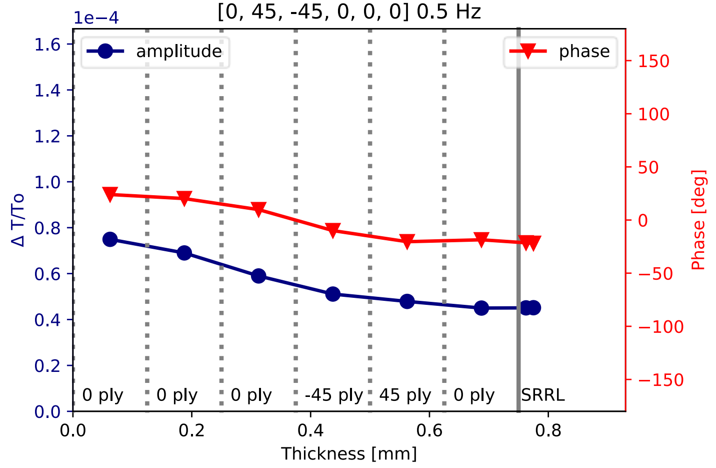
SRRL 8.8 µm

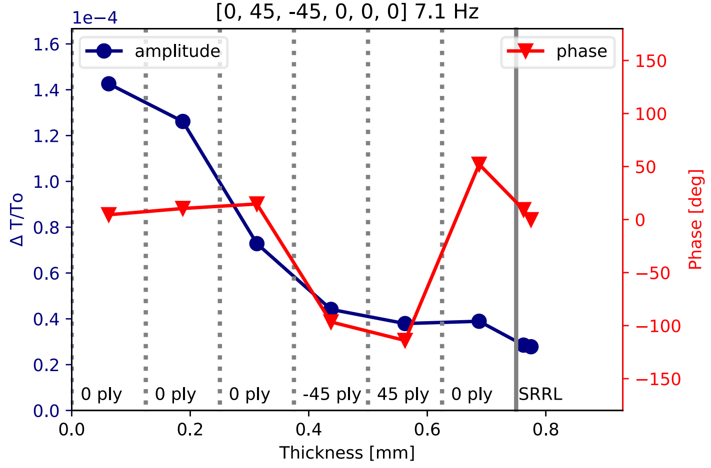


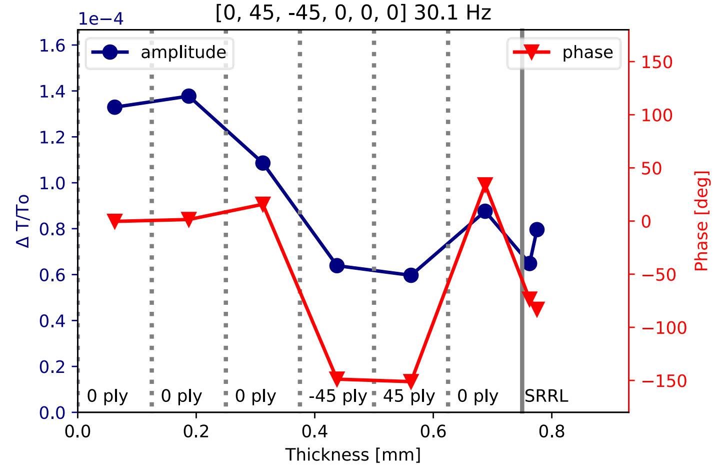




SRRL 25 µm





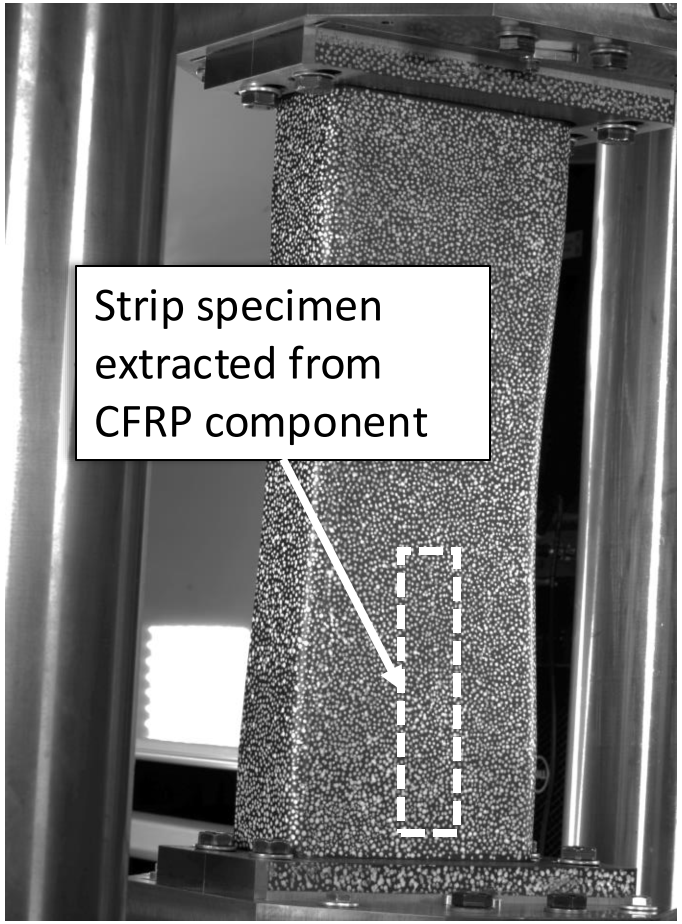


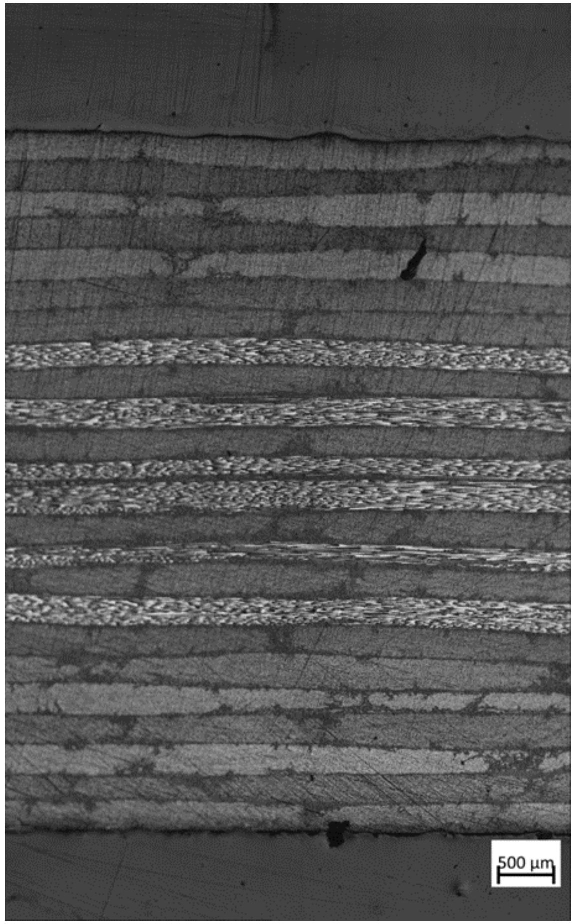
0.5 Hz

7.1 Hz

30.1 Hz

C-Spar coupon: $[(45/-45)_3/(0/90)_3]_S$



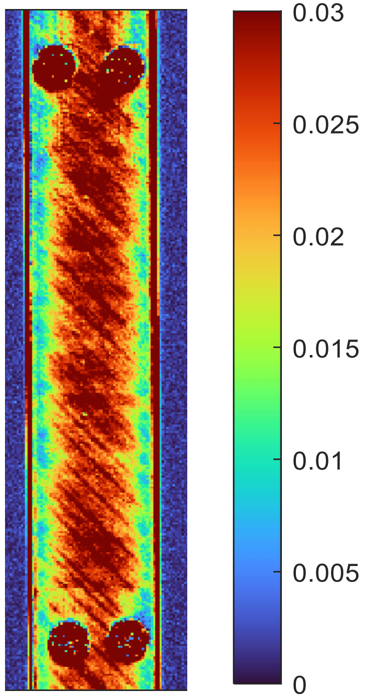


Layup: $[(45/-45)_3/(0/90)_3]_S$

Measured RRL thickness ≈ 20 µm

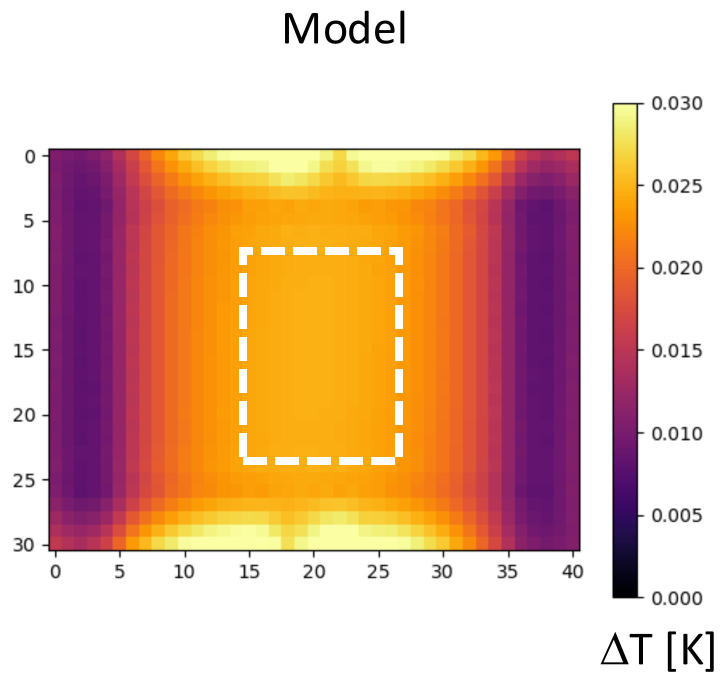
Unknown material properties

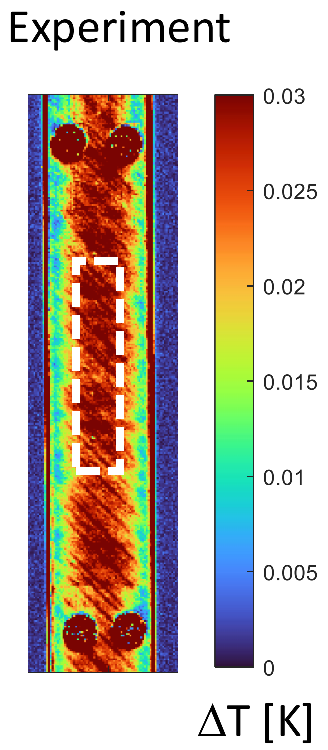
Thermoelastic response (ΔT)

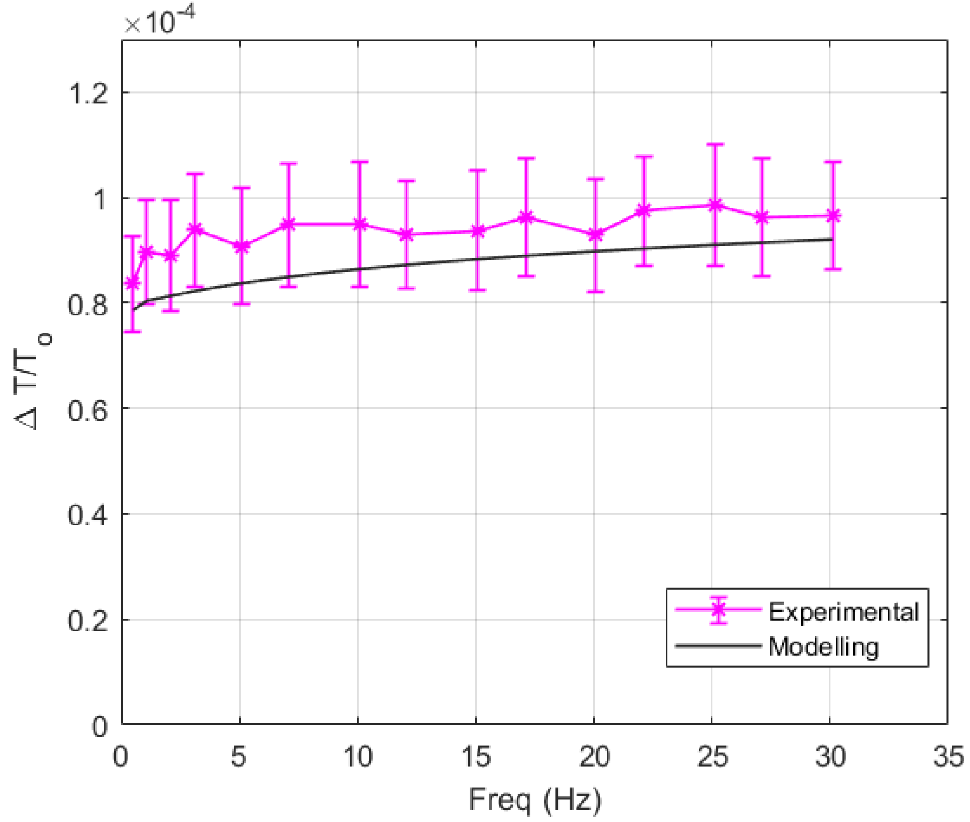


C-Spar coupon: results

Thermoelastic response (ΔT) at 10 Hz







Conclusions

- Thermoelastic response in CFRP laminates is highly dependent on testing parameters (i.e., loading frequency), material properties →non adiabatic phenomena in the thickness direction.
- Small variations in the thickness of the surface resin layer can strongly affect the measured thermoelastic response.
- The proposed numerical model allows the interpretation of the through-the-thickness heat transfer phenomena and facilitates the use of TSA for full-field model validation on composites.
- The model is able to replicate non-uniform temperature distributions due to the presence of edge effects in complex layups.
- The model will be used to tune experimental setup and optimize testing parameters for the identification of subsurface damage using TSA.

UKRI Engineering and Physical Sciences Research Council
CERTEST
University of BRISTOL
UNIVERSITY OF BATH
University of Southampton
UNIVERSITY OF EXETER