Damage Quantification in Multi-directional Laminates using Thermoelastic Stress Analysis

Rafael Ruiz Iglesias

G. Ólafsson, O.T. Thomsen and J.M. Dulieu-Barton

Engineering and Physical Sciences Research Council

CERTIFICATION FOR DESIGN: RESHAPING THE TESTING PYRAMID

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

PRESENTATION OUTLINE

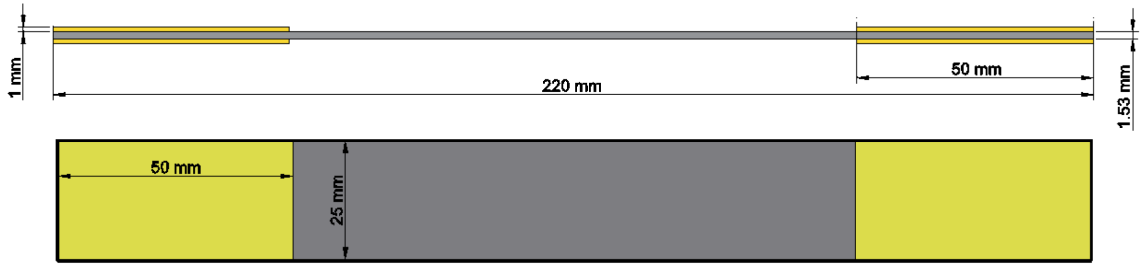
- Project inspiration
- Scientific background of TSA
- Principles behind the damage parametrisation
- Damage in multidirectional laminates
- Conclusions of the research and future work

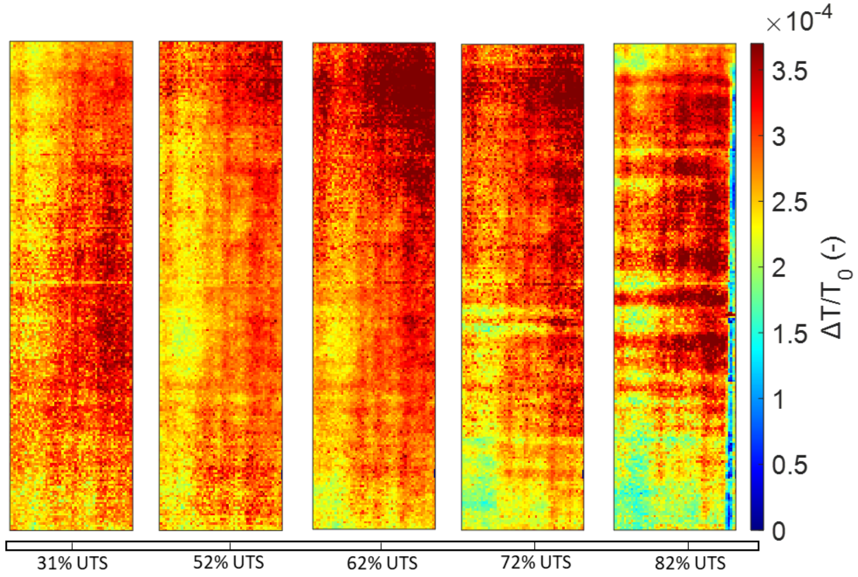
PROJECT AIMS AND OBJECTIVES

PREVIOUS WORK

Ruiz-Iglesias R., Ólafsson G., Thomsen OT., Dulieu-Barton JM.
Identification of Subsurface Damage in Multidirectional Composite Laminates Using Full-Field Imaging.
SEM 2022: Thermomechanics & Infrared Imaging, Inverse Problem Methodologies and Mechanics of Additive & Advanced Manufactured Materials, Volume 6. 2022. pp. 39–42. Available at: DOI:10.1007/978-3-031-17475-9_6

CFRP IM7/8552 $[90,0]_{3S}$ & $[0,90]_{3S}$





Analysis of the subsurface ΔT/T0 of CFRP $[0,90]_{3S}$ using the DIC surface ply model

Engineering and Physical Sciences Research Council

CERTIFICATION FOR DESIGN: RESHAPING THE TESTING PYRAMID

University of BRISTOL

PROJECT AIMS AND OBJECTIVES

PREVIOUS WORK

Ruiz-Iglesias R., Ólafsson G., Thomsen OT., Dulieu-Barton JM.
Identification of Subsurface Damage in Multidirectional Composite Laminates Using Full-Field Imaging.
SEM 2022: Thermomechanics & Infrared Imaging, Inverse Problem Methodologies and Mechanics of Additive & Advanced Manufactured Materials, Volume 6. 2022. pp. 39–42. Available at: DOI:10.1007/978-3-031-17475-9_6

AIM & OBJECTIVES → **Novel full-field damage parametrization methodology using TSA**

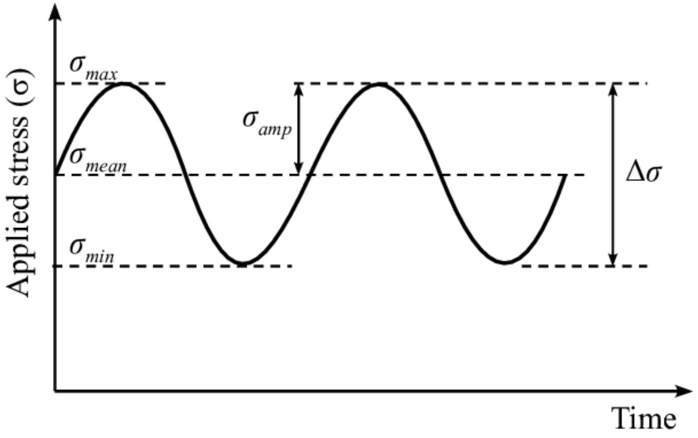
- Exploit the **non-adiabatic thermoelastic response** to detect surface and subsurface damage in laminated composites.
- **Damage quantification using TSA** of CFRP **$[0,90]_{3S}$, $[90,0]_{3S}$**, **$[0,45,-45,0,0,0]_S$ and $[0,0,0,45,-45,0]_S$** configurations.
- **Compare** TSA damage quantification with the stiffness degradation at different damage levels (obtained with DIC).
- **Work In Progress**: Applying all the knowledge to **quantify damage in real structures** (e.g C-Spar)

Engineering and Physical Sciences Research Council
CERTIFICATION FOR DESIGN: RESHAPING THE TESTING PYRAMID
University of BRISTOL

T_0 ~ *Mean temperature*
ρ ~ *Density*
C_p ~ *Specific heat capacity*
α_1 *and* α_2 ~ *Thermal expansion coefficients in 1,2*
$\Delta\sigma_1$ *and* $\Delta\sigma_2$ ~ *Stress variation in 1,2*
$[Q]_{1,2}$ ~ *Stiffness matrix*
$[T]$ ~ *Transformation matrix*
$[\Delta\varepsilon_{xy}]$ ~ *Strain variation in x,y*

SCIENTIFIC BACKGROUND

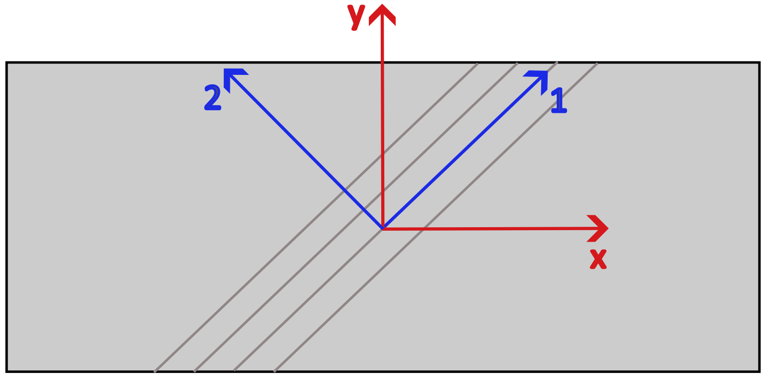
Stress variation (Δσ) is required to obtain the thermoelastic response of a material:



$$\Delta T = \frac{-T_0}{\rho C_p}(\alpha_1\Delta\sigma_1+\alpha_2\Delta\sigma_2) = \frac{-T_0}{\rho C_p}\left([\alpha]_{1,2}^T[Q]_{1,2}[T][\Delta\varepsilon]_{xy}\right)$$

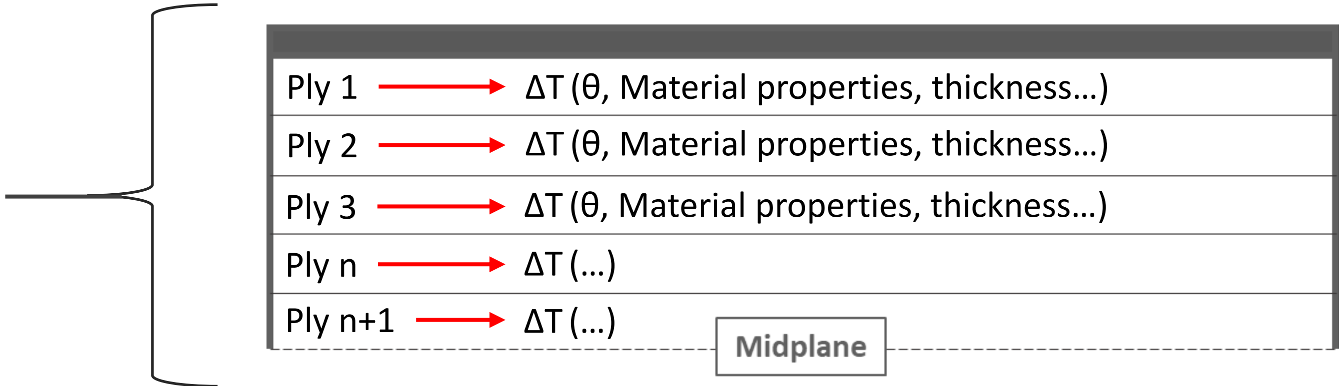
Simplified for orthotropic composite lamina (as $\alpha_6 = 0$)

We are looking for HEAT TRANSFER to obtain SUBSURFACE INFO!



1,2: Ply coordinate system

x,y: Laminate coordinate system



Cross-section of multi-directional symmetric laminate

SCIENTIFIC BACKGROUND

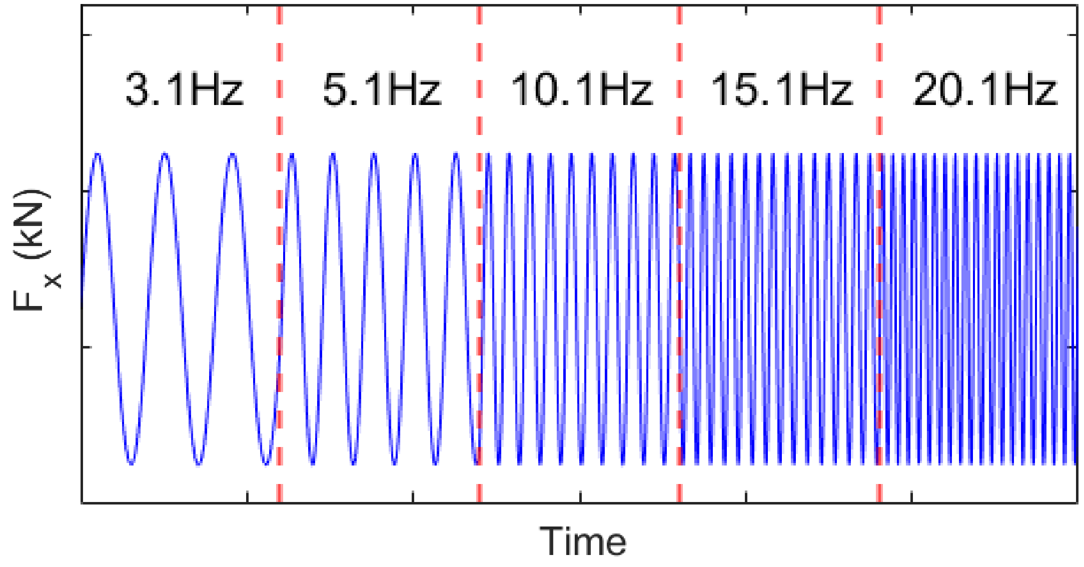
Thermoelastic Stress Analysis on…

GFRP RP-528: Adiabatic for all the layups (Not subsurface contribution) [1]

CFRP IM7/8552 → HEAT TRANSFER OCCURING <u>AT LOWER FREQUENCIES</u> [1,2]

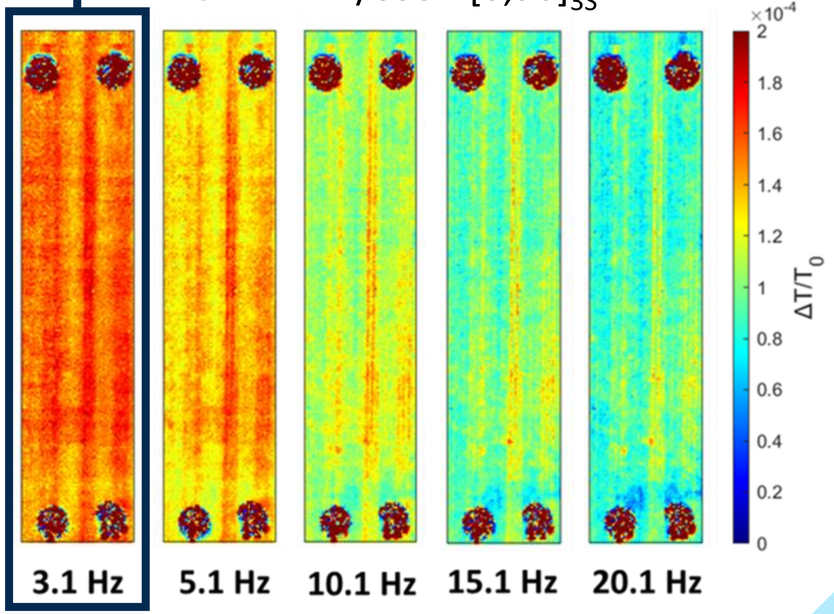
Subsurface Features (e.g. Damage)

Frequency Range



Example

Undamaged
CFRP IM7/8552 $[0,90]_{3S}$



[1] Jiménez-Fortunato I., Bull DJ., Thomsen OT., Dulieu-Barton JM. On the source of the thermoelastic response from orthotropic fibre reinforced composite laminates. *Composites Part A: Applied Science and Manufacturing. Elsevier Ltd; 1 October 2021; 149(106515): 1–15.*

[2] Ruiz-Iglesias R., Ólafsson G., Thomsen OT., Dulieu-Barton JM. Identification of Subsurface Damage in Multidirectional Composite Laminates Using Full-Field Imaging. *SEM 2022: Thermomechanics & Infrared Imaging, Inverse Problem Methodologies and Mechanics of Additive & Advanced Manufactured Materials, Volume 6. 2022. pp. 39–42. Available at: DOI:10.1007/978-3-031-17475-9_6*

HOW IS DAMAGE QUANTIFIED?

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

- It was developed based in the law of conservation of mass, momentum and energy.
- It relates the density, the internal energy per unit mass and the heat absorbed per unit mass for damaged and undamaged materials.
- Experiments were carried out on **GFRP $[0,90,0,90,0]_S$ at a loading frequency of 10.1 Hz**

$$\Delta T = -\frac{T_0}{\rho C_p} \cdot (\alpha_x \sigma_x + \alpha_y \sigma_y)$$

In pure tension: $(\alpha_x\sigma_x + \cancel{\alpha_y\sigma_y})$

i.e. the ***laminate stress***

$$\frac{\Delta T}{T_0} = K_{Undamaged} \cdot \frac{\Delta \sigma_x}{(1 - D)^2}$$

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

** Undamaged: D=0*

** Damaged: D ≠ 0*

D: Damage parameter

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

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

NOVELTY OF THIS RESEARCH

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

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

UKRI Engineering and Physical Sciences Research Council

CERTEST CERTIFICATION FOR DESIGN: RESHAPING THE TESTING PYRAMID

University of BRISTOL

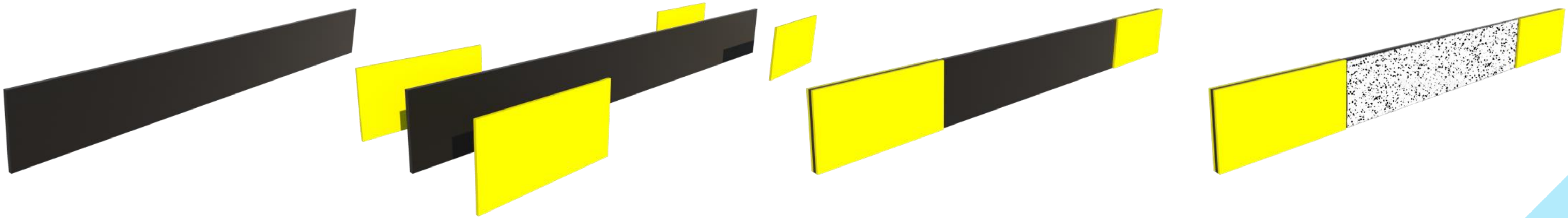
EXPERIMENTAL PLAN – MATERIAL (CFRP IM7/8552)

Tension mode → uniform strain state through the laminate thickness

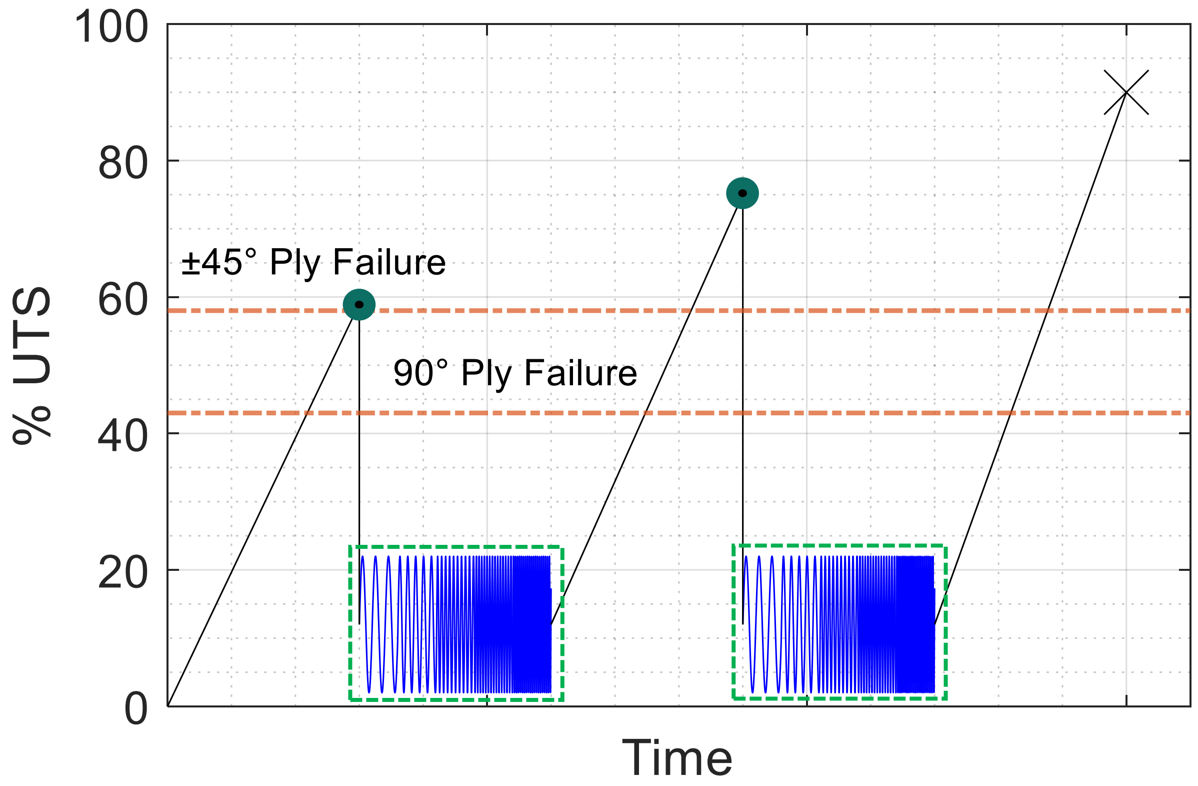
Configuration	Loading scenario	$FPF_{Tsai\text{-}Wu}$ (MPa)	Ply failing	Failure Mode	Applied cyclic Stress (MPa)	UTS_{LaRC03} (MPa)
$[90,0]_{3S}$ & $[0,90]_{3S}$	Tension Loading	542.60	90°	Matrix failure	162.66 ± 141.33	1245.63
$[0,45,-45,0,0,0]_S$ & $[0,0,0,45,-45,0]_S$	Tension Loading	914.87	±45°	Shear	123.46 ± 111.11	1548.42

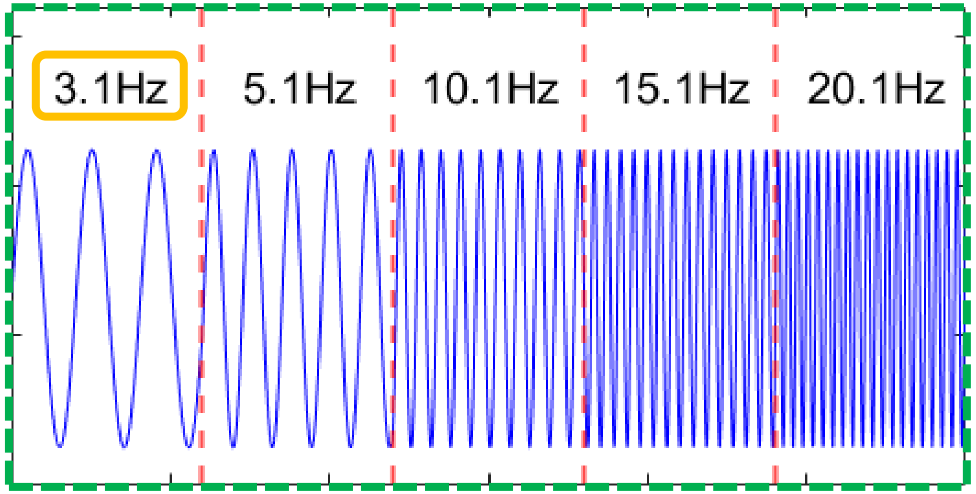
- *Different plies breaking and different failure mechanisms*
- *Low cyclic stress must be applied*

Coupon Preparation



EXPERIMENTAL PLAN





WE ARE USING TSA AND DIC

…Why DIC?

To obtain D_{YM}

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

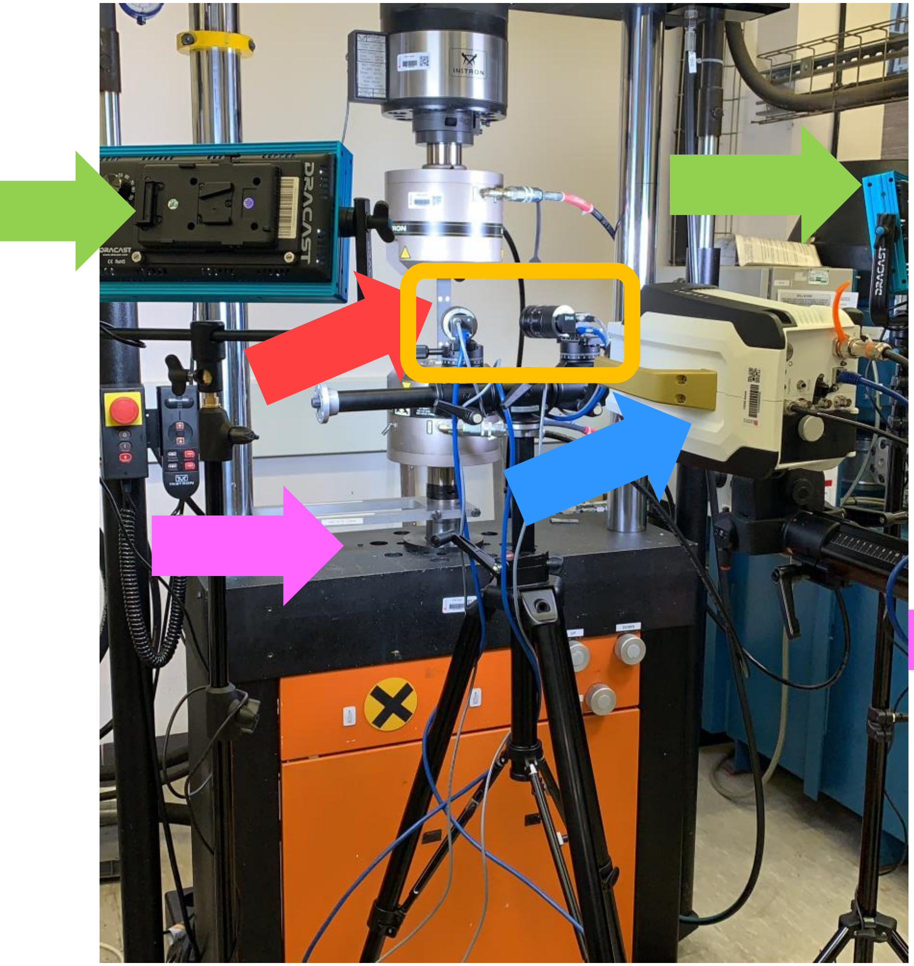
Cyclic Loading → Observe the plies condition **(Inspection)**

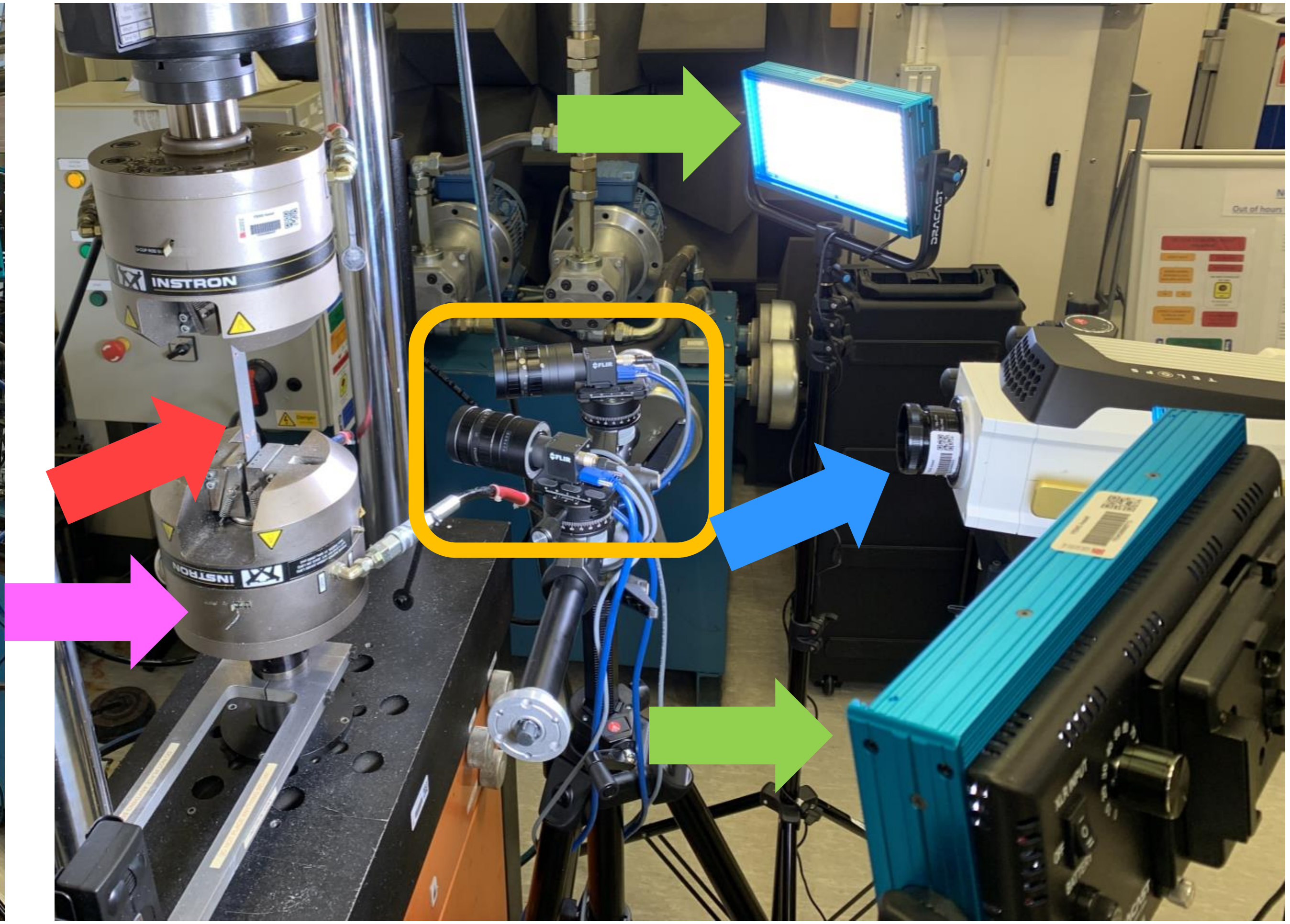
Engineering and Physical Sciences Research Council

CERTIFICATION FOR DESIGN: RESHAPING THE TESTING PYRAMID

University of BRISTOL

EXPERIMENTAL ARRANGEMENTS





SAMPLE

DIC CAMERAS

TSA CAMERA

LIGHTS

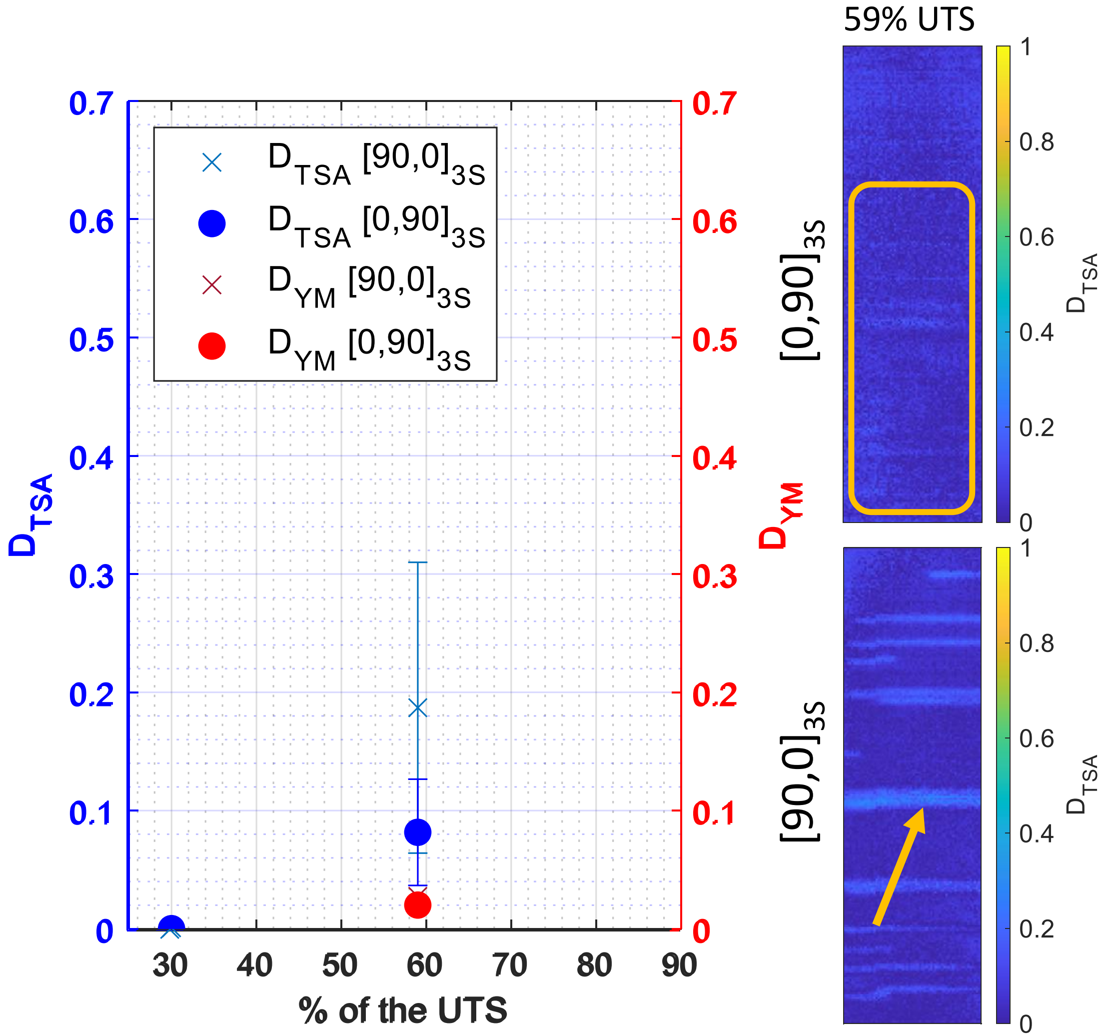
HYDRAULICS

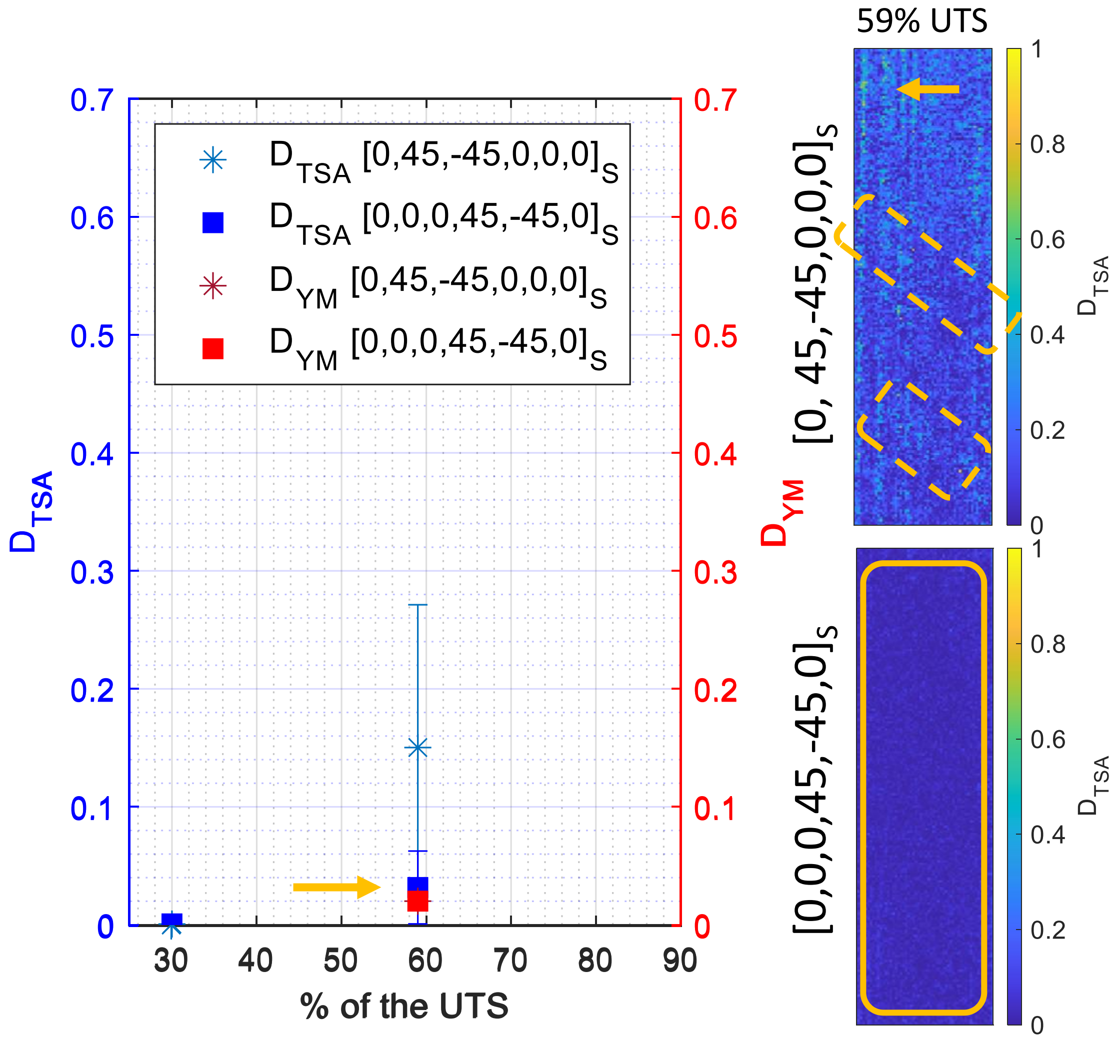
UKRI Engineering and Physical Sciences Research Council

CERTEST CERTIFICATION FOR DESIGN: RESHAPING THE TESTING PYRAMID

University of BRISTOL

Damage Quantification: Multidirectional laminates



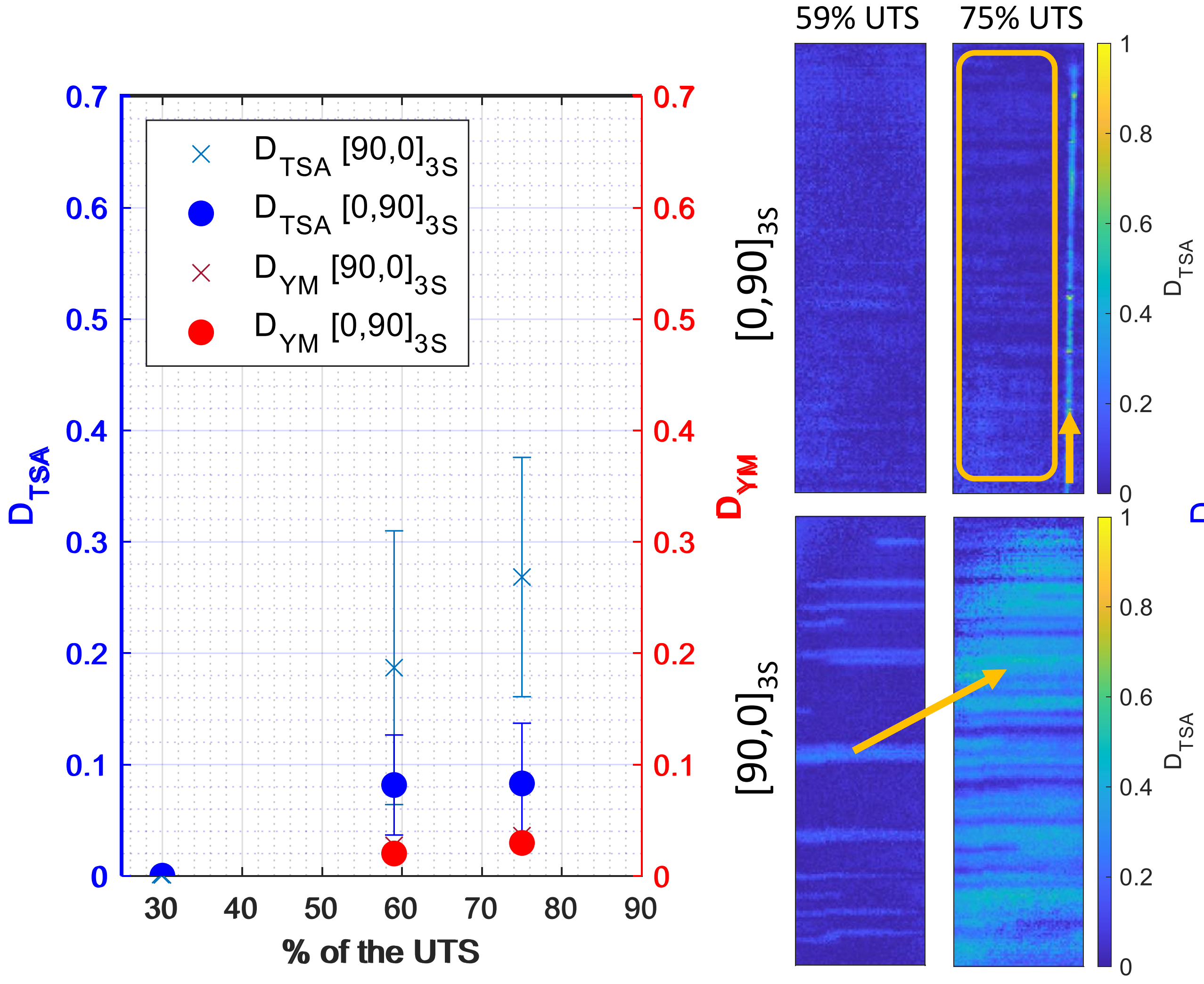


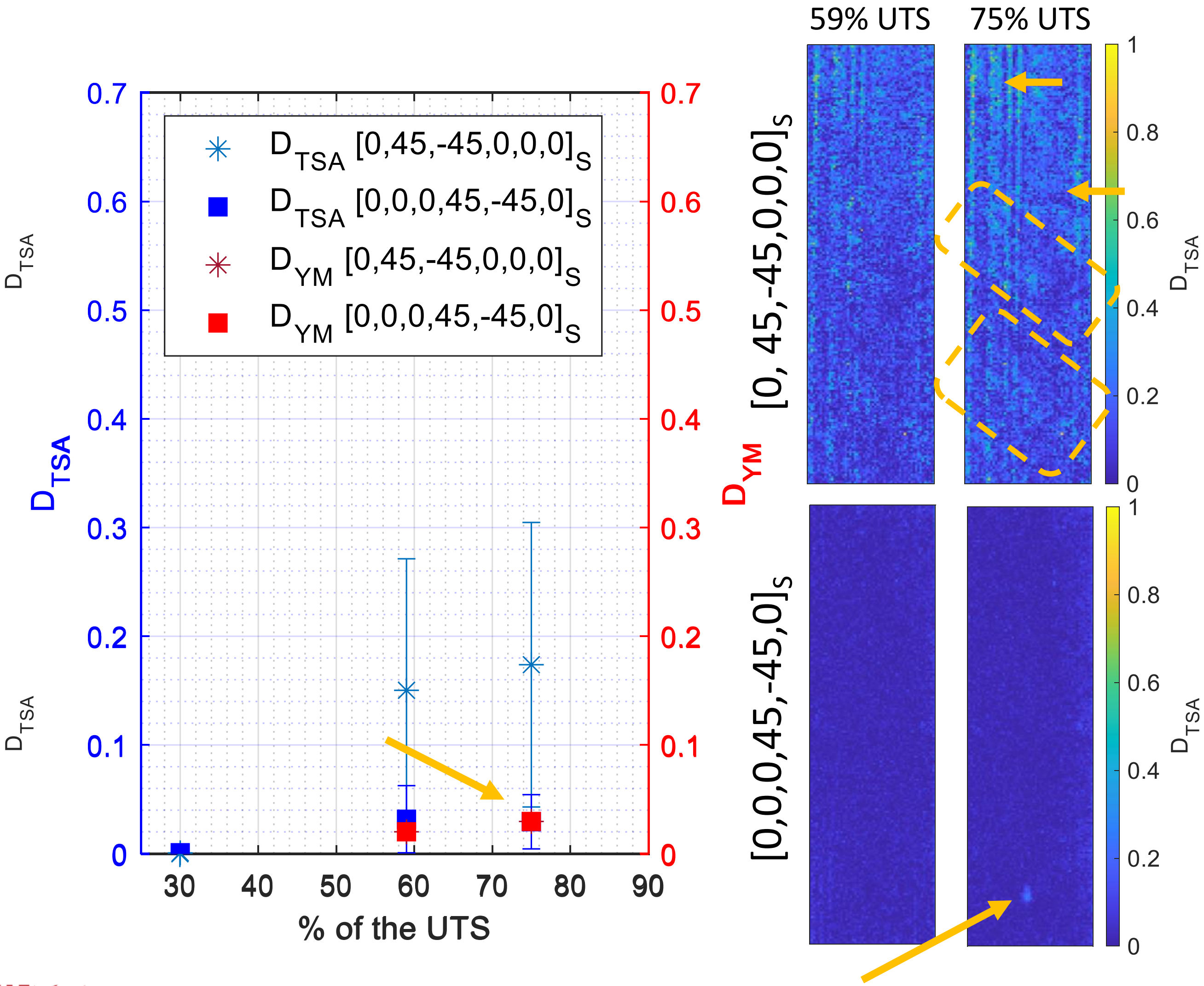
Engineering and Physical Sciences Research Council

CERTIFICATION FOR DESIGN: RESHAPING THE TESTING PYRAMID

University of BRISTOL

Damage Quantification: Multidirectional laminates



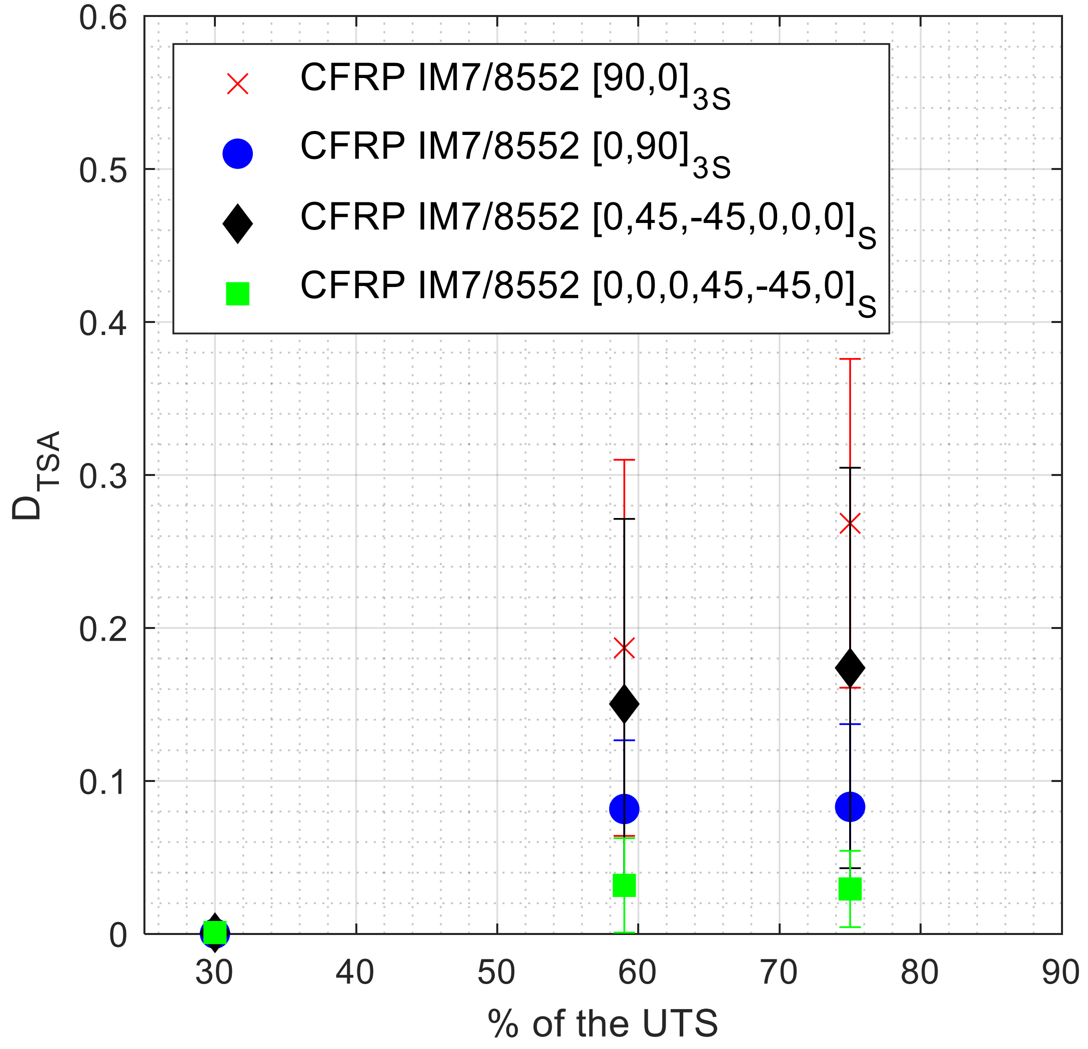


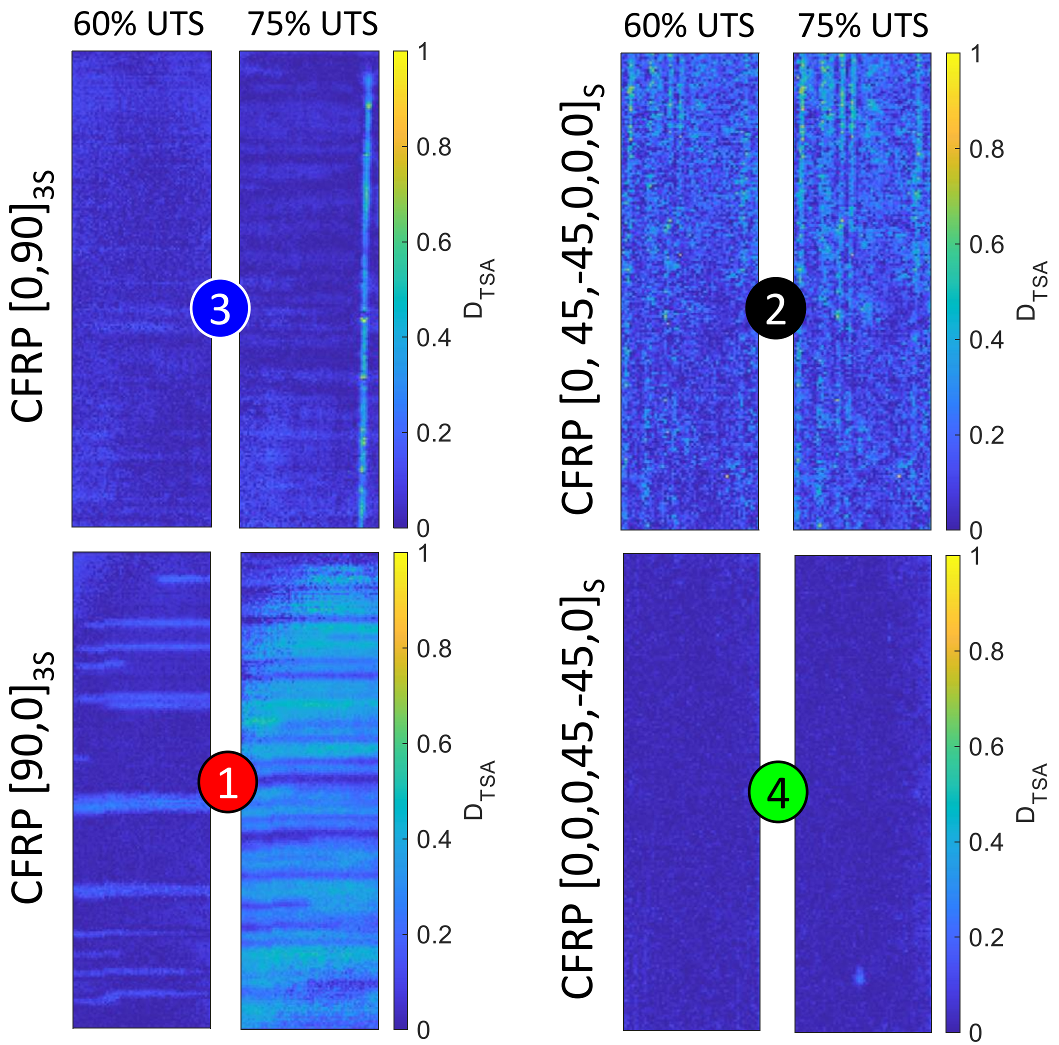
Engineering and Physical Sciences Research Council

CERTIFICATION FOR DESIGN: RESHAPING THE TESTING PYRAMID

University of BRISTOL

TSA Damage Quantification: All the laminates





UKRI Engineering and Physical Sciences Research Council
CERTEST CERTIFICATION FOR DESIGN: RESHAPING THE TESTING PYRAMID
University of BRISTOL

CONCLUSIONS OF THE RESEARCH

- Full-Field damage parametrization using TSA **at low frequencies provides** information about both surface and subsurface
- Compared with the stiffness degradation parametrisation, D_{TSA} provides more information about the laminate's status

1. $[90,0]_{3S}$ wasn't more damaged than $[0,90]_{3S}$ but it exhibited a higher D_{TSA}
2. $[0,45,-45,0,0,0]_{S}$ wasn't more damaged than $[0,0,0,45,-45,0]_{S}$ but it exhibited a higher D_{TSA}

TSA provides a better measure of a **reduction in structural performance** when the damage is close to the surface

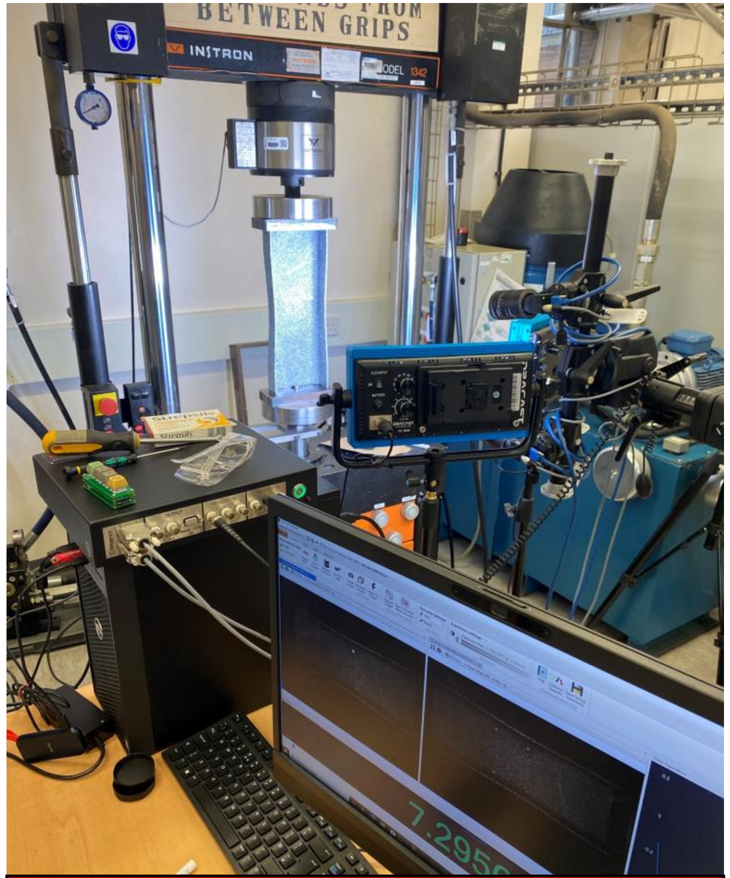
FUTURE WORK

- WIP: Damage parametrization of a real structure: **C-Spar**
- Subject specimens to different stress states (e.g. bending) → Not only tension in real structures stress state

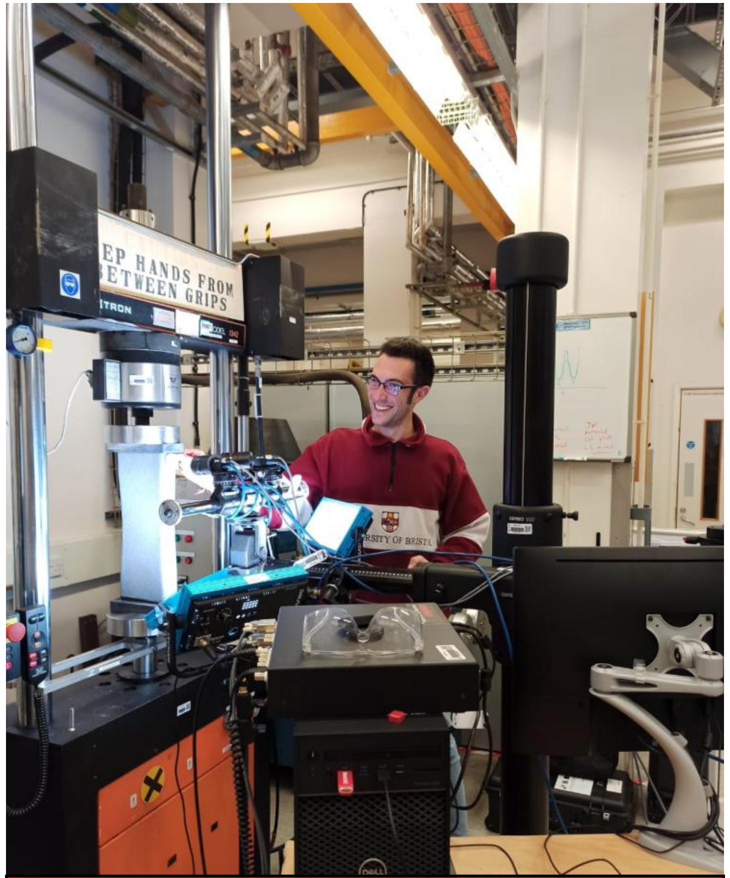
Engineering and Physical Sciences Research Council CERTIFICATION FOR DESIGN: RESHAPING THE TESTING PYRAMID University of BRISTOL

WIP: C-Spar // EXPERIMENTAL SETUP

C-Spar in the test machine



Speckled C-Spar



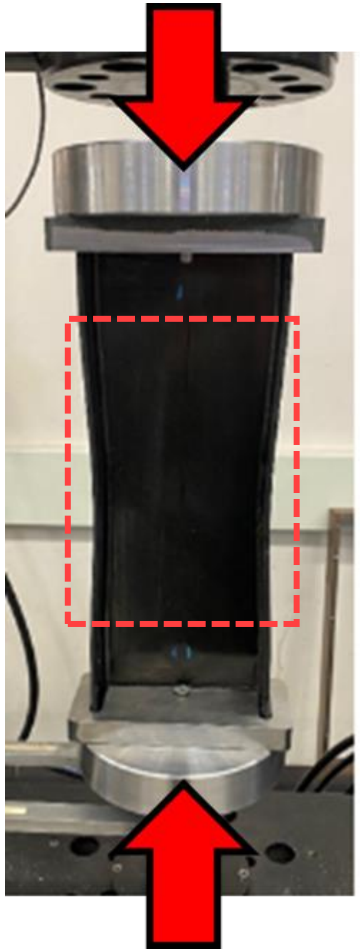
Rafa calibrating the tests

Engineering and Physical Sciences Research Council

CERTIFICATION FOR DESIGN: RESHAPING THE TESTING PYRAMID

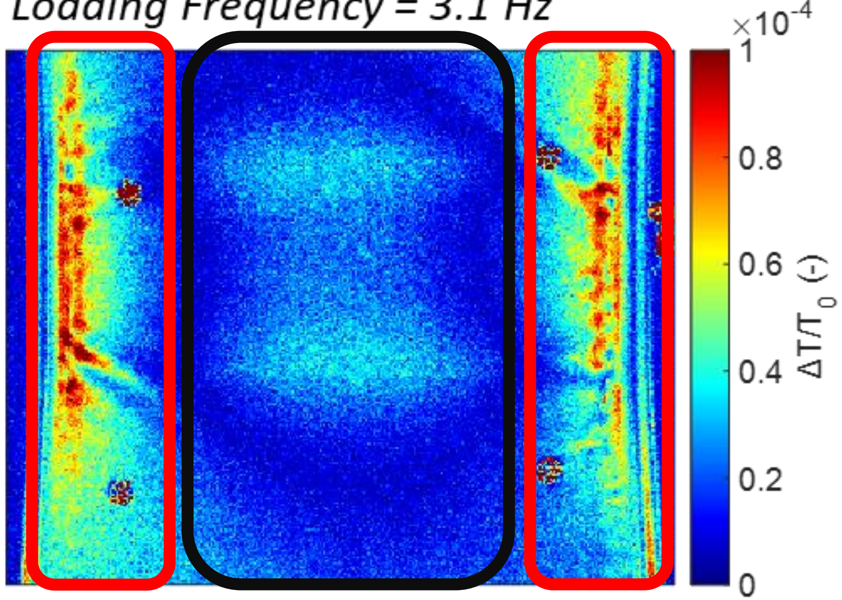
University of BRISTOL

WIP: C-Spar // Inside the web Inspection



Undamaged

Loading Frequency = 3.1 Hz

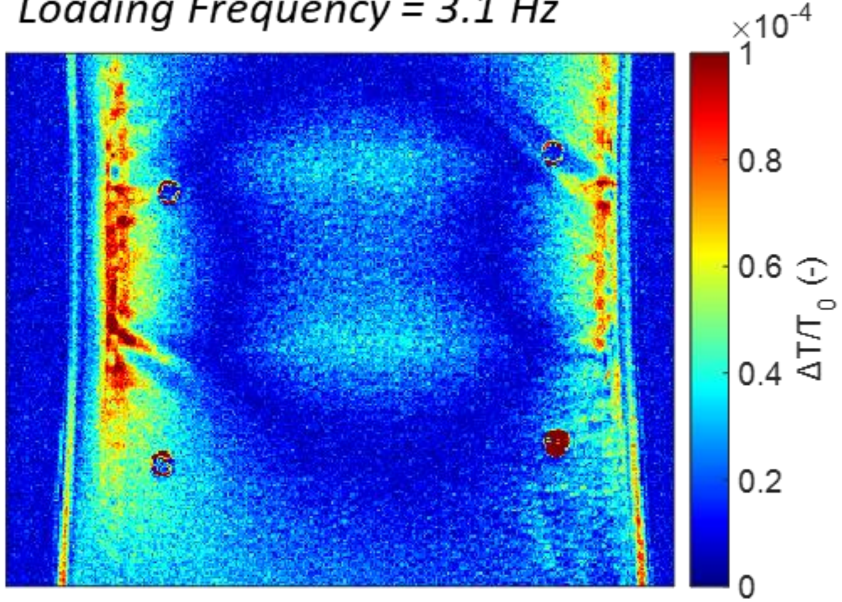


Wrinkles
High stress concentration areas

8 Shape: Buckling ~ *Bending*

Damaged

Loading Frequency = 3.1 Hz



Same pattern found as the undamaged

Damage parametrisation

**More complex stress state*

Engineering and Physical Sciences Research Council
CERTIFICATION FOR DESIGN: RESHAPING THE TESTING PYRAMID
University of BRISTOL

UKRI Engineering and Physical Sciences Research Council

CERTEST

CERTIFICATION FOR DESIGN: RESHAPING THE TESTING PYRAMID

University of BRISTOL

UNIVERSITY OF BATH

University of Southampton

UNIVERSITY OF EXETER

AIRBUS

BAE SYSTEMS

ROLLS ROYCE Rolls-Royce

GKN AEROSPACE

NATIONAL COMPOSITES CENTRE

cfms

The Alan Turing Institute

Contact email: rafael.ruiziglesias@bristol.ac.uk