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Thermography for full-field stress and damage analysis of composite components

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Summary

- TSA overview
- Motivation
- Validation of FEA –case studies
- Damage Analysis
- Non crimp and woven materials

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Motivation

- Accurate definition of material/structural behaviour – large variations in values in literature for nominally identical materials
- Particularly important in composite materials – variations depend on manufacturing process etc
- Essential to accurately validate FEA using full-field experimental mechanics techniques
- Tools for damage analysis and NDE

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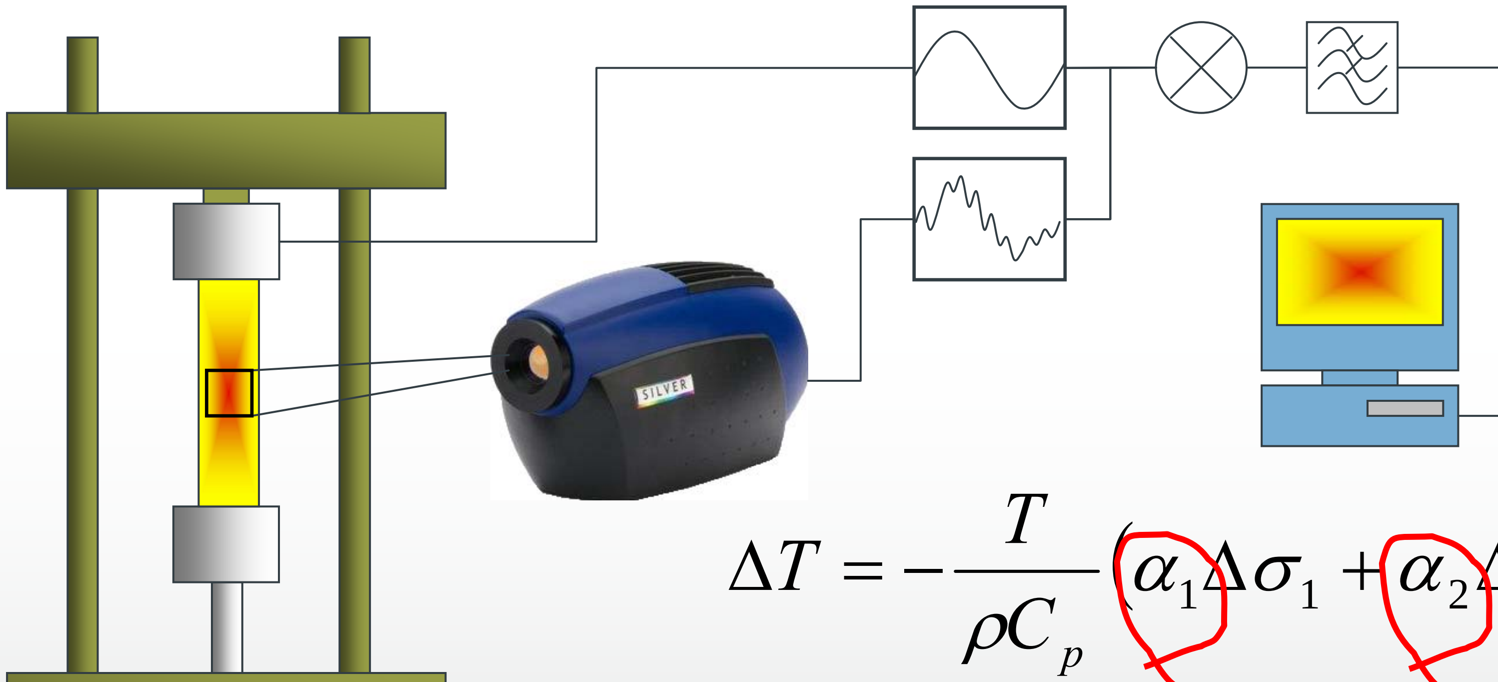
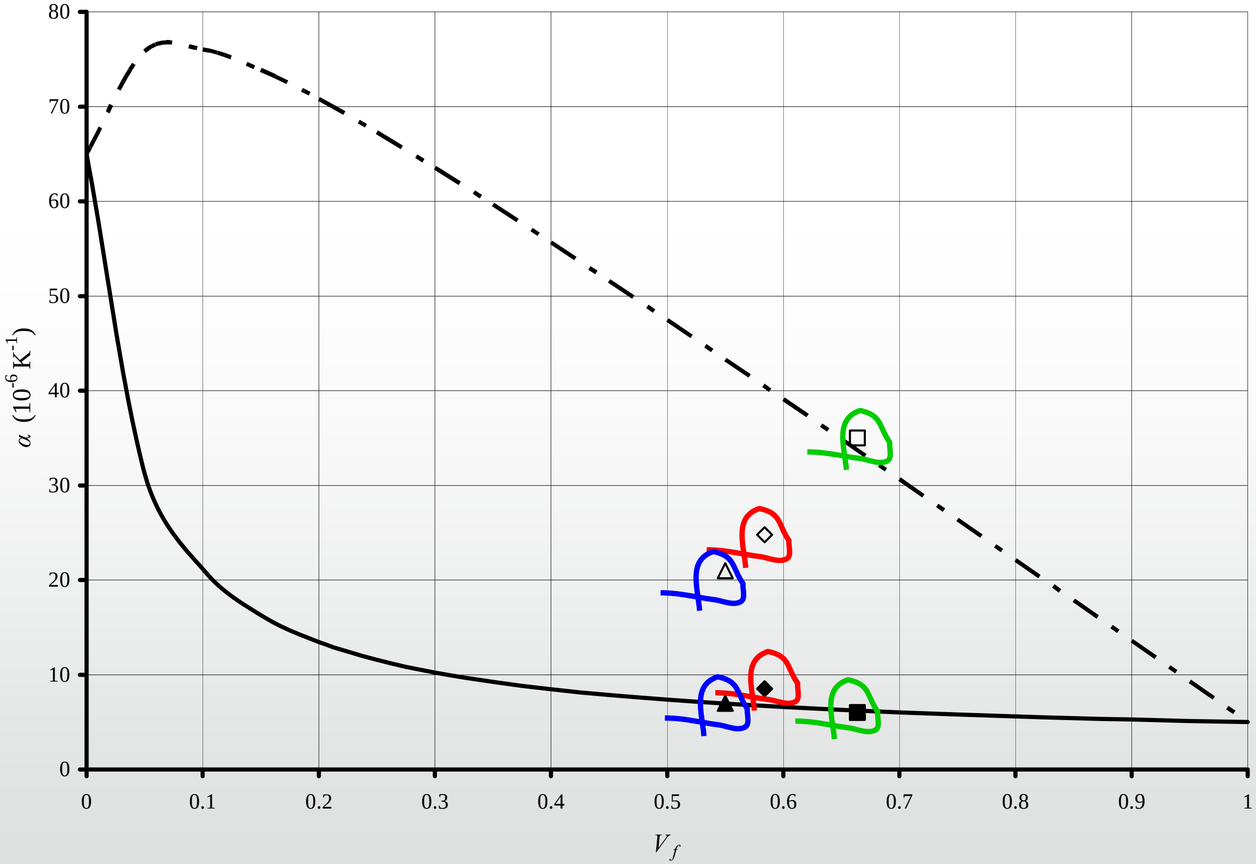
Thermoelastic stress analysis



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

Wang, W.J., Dulieu-Barton, J.M. and Li, Q. "Assessment of non-adiabatic behaviour in thermoelastic stress analysis of small scale components", Experimental Mechanics, in press. DOI: 10.1007/s11340-009-9249-2.
Sambasivam, S., Quinn, S and Dulieu-Barton, J.M., "Identification of the source of the thermoelastic response from orthotropic laminated composites", 17th International Conference on Composite Materials (ICCM17), 2009, Edinburgh, 11 pages on CD.

Coefficient of thermal expansion



Harwood and Cummings 1991

Vacuum infused Fruehmann et al JSA 2008

Daniel and Ishai 1994

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Derivation of stresses from TSA-calibration

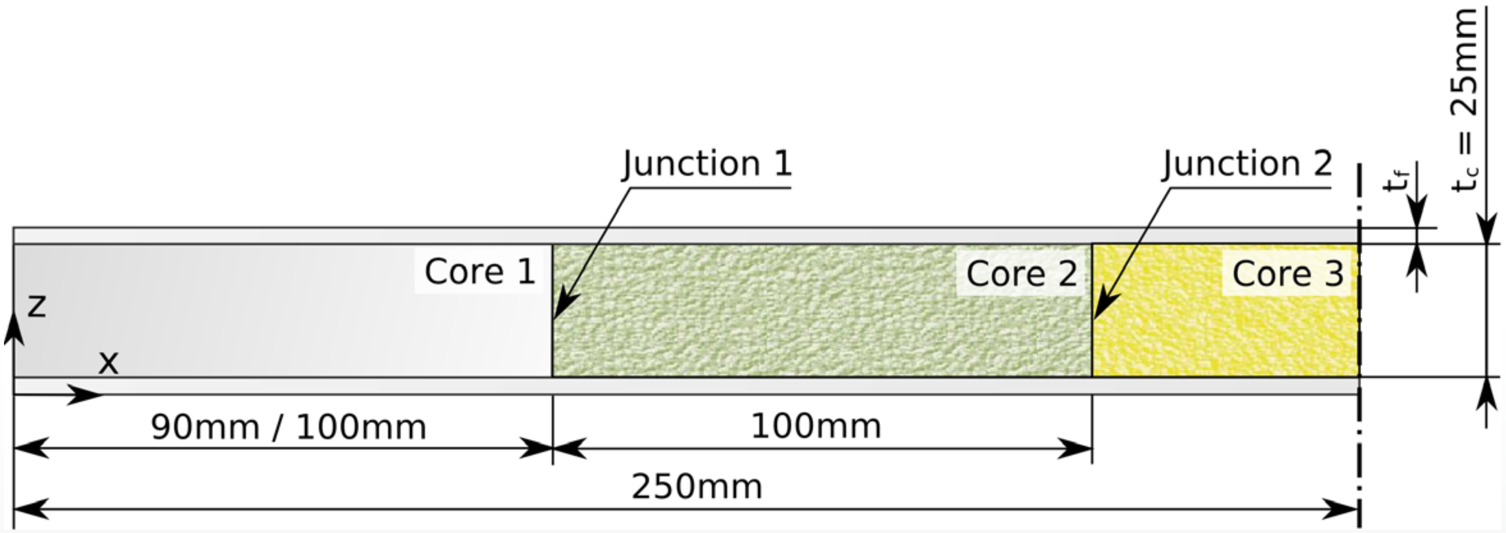
$$\Delta T = K_2 T \Delta\sigma_1 + K_2 T \Delta\sigma_2$$

$$K_1 = \alpha_1 / \rho C_p \qquad K_2 = \alpha_2 / \rho C_p$$

$$\underbrace{\frac{\Delta T}{K_1 T}}_{\text{TSA}} = \underbrace{\Delta\sigma_1 + \frac{K_2}{K_1}\Delta\sigma_2}_{\text{FEA}} \Rightarrow \text{Stresses}$$

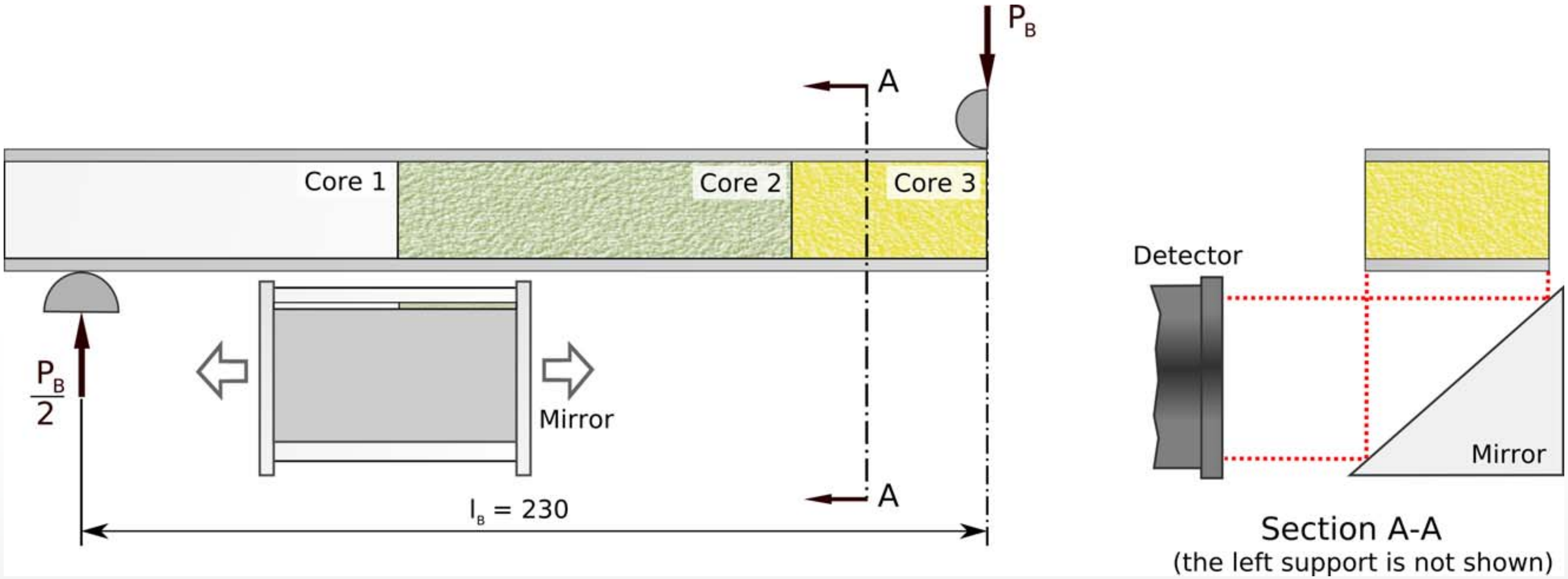
Emery, T.R., Dulieu-Barton, J.M., Earl, J.S. and Cunningham, P.R., "A generalised approach to the calibration of orthotropic materials for thermoelastic stress analysis", Composites Science and Technology, 2008, 68, 743-752.

Sandwich structures and core junctions



Type	Face Material	t_f [mm]	width [mm]	Core Material 1	Core Material 2	Core Material 3
1	Aluminium alloy	1.0	45.6	Aluminium alloy	Rohacell 51WF	Rohacell 200WF
2	PMMA	1.5	47.2	PMMA	Dynathane 1000	Rohacell 51WF
3	GFRP-CSM	1.2	46.8	PMMA	Dynathane 1000	Rohacell 51WF
4	GFRP-NCF	2.8	49.0	Aluminium alloy	Rohacell 51WF	Rohacell 200WF

Sandwich structures and core junctions



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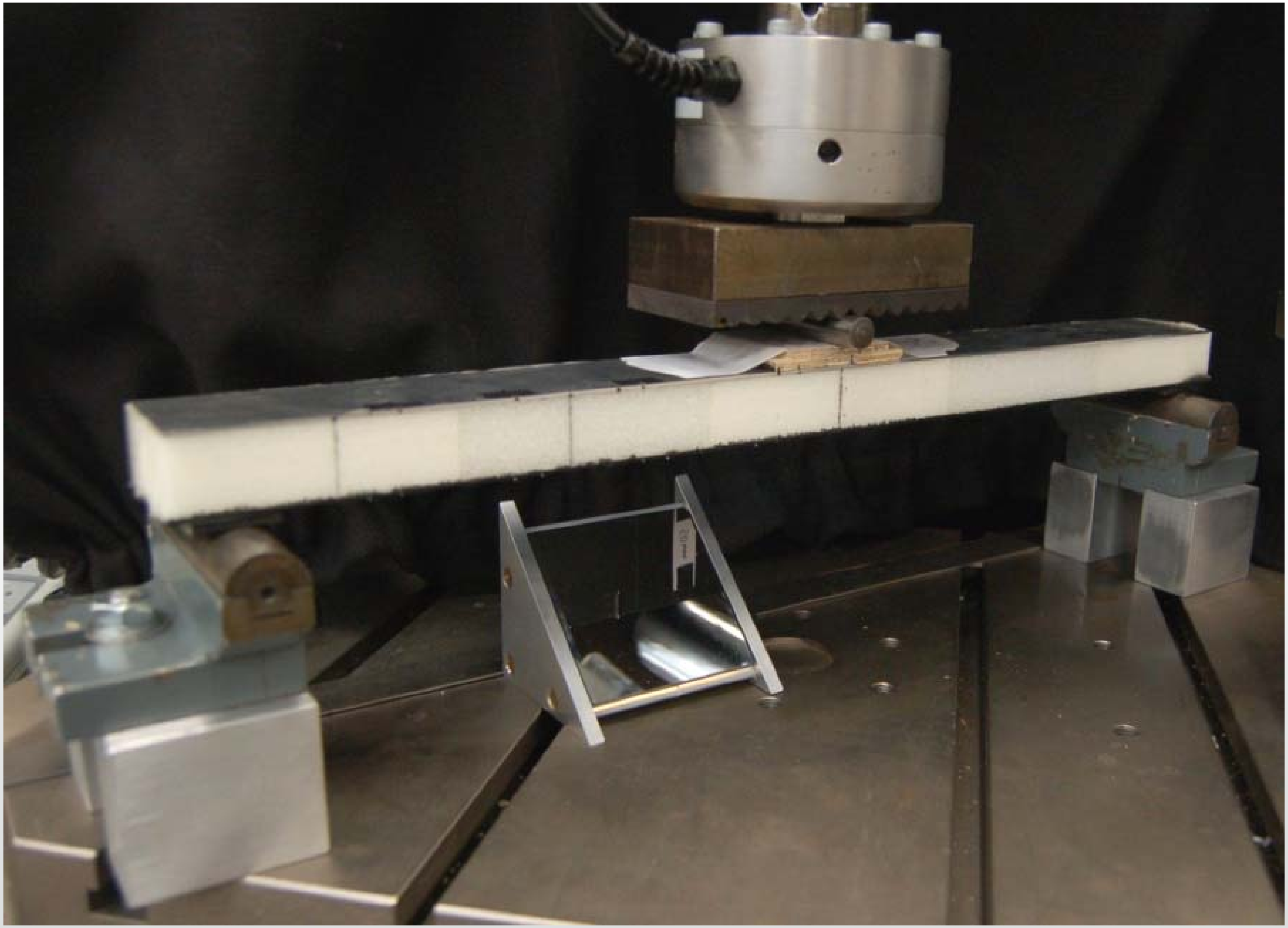
Experiment



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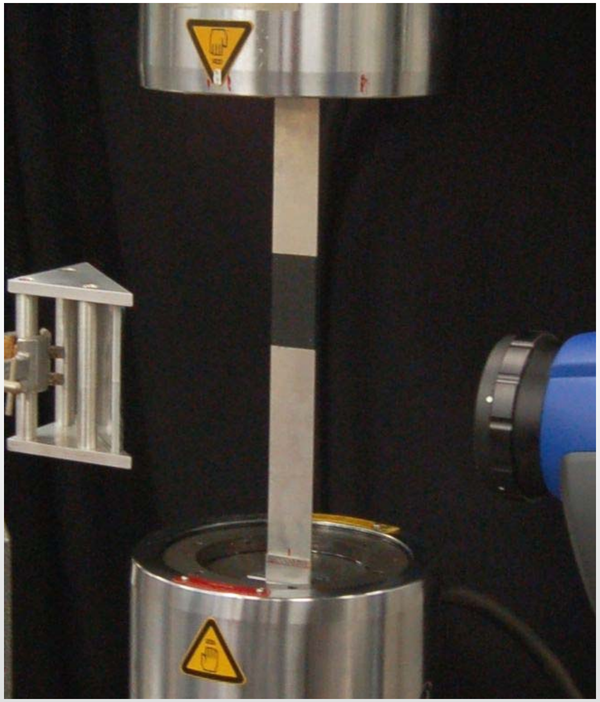
Calibration of the face sheet material

Isotropic CSM material $\Delta T = KT\Delta(\sigma_1 + \sigma_2)$

Orthotropic NCF material $\Delta T = K_1 T\Delta\sigma_1 + K_2 T\Delta\sigma_2$



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Material properties and calibration constants

Material	Young's modulus [MPa]	Poisson's ratio
Aluminium alloy 7075-T6	71700	0.32
PMMA (Degussa Plexiglas XT)	3100	0.41
GFRP-CSM	13000	0.30
GFRP-NCF, $[0/+45/90/-45 / +45/90/-45/0]_2$	19200	0.29
Rohacell 51WF	75 [10]	0.32 [11]
Rohacell 200WF	350 [10]	0.38 [11]
Dynathane 1000 (PU rubber foam)	5.5	0.22

Material	Mean stress [MPa]	Stress range [MPa]	Frequency [Hz]	A, A^* [MPa/DL]	A_M, A_M^{**} [MPa/DL]
Aluminium alloy	20.0, 40.0	10.0, 20.0	10, 30, 50	6.06 (5.3%)	6.45 (2.5%)
PMMA	5.4, 10.8	3.2, 6.4	6, 10	1.31 (6.1%)	1.33 (3.8%)
GFRP-NCF	10.0, 20.0	5.0, 10.0	6, 10	5.63 (11.2%)	5.35 (9.9%)
GFRP-CSM	10.0, 20.0	5.0, 10.0	6, 10	3.74 (3.7%)	3.87 (6.7%)

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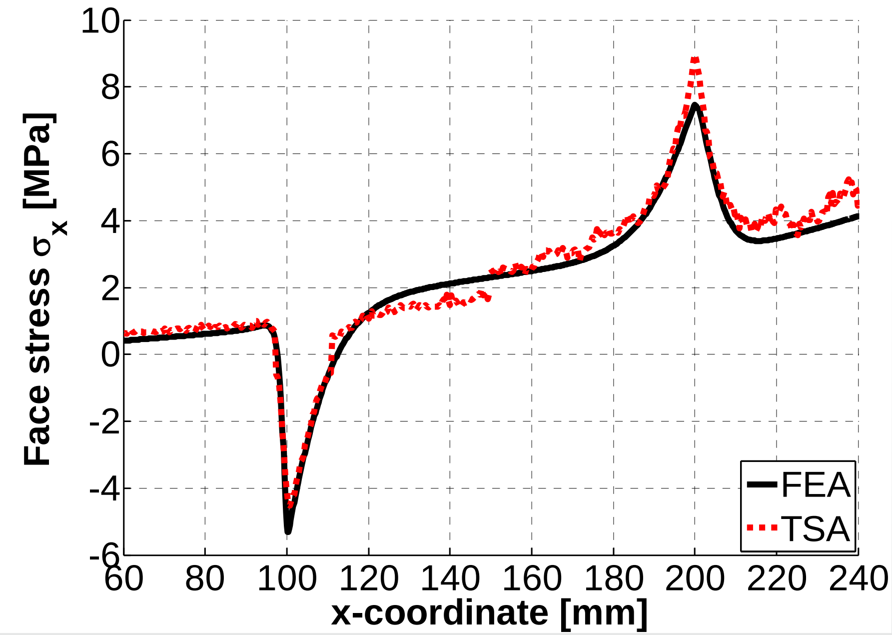
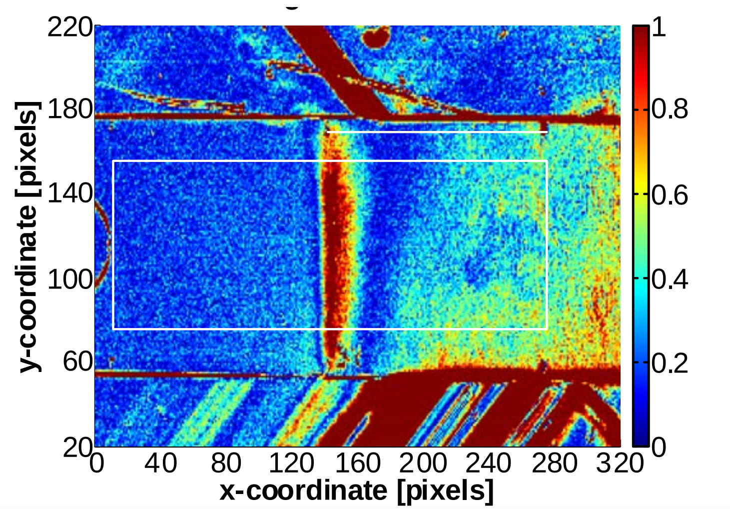
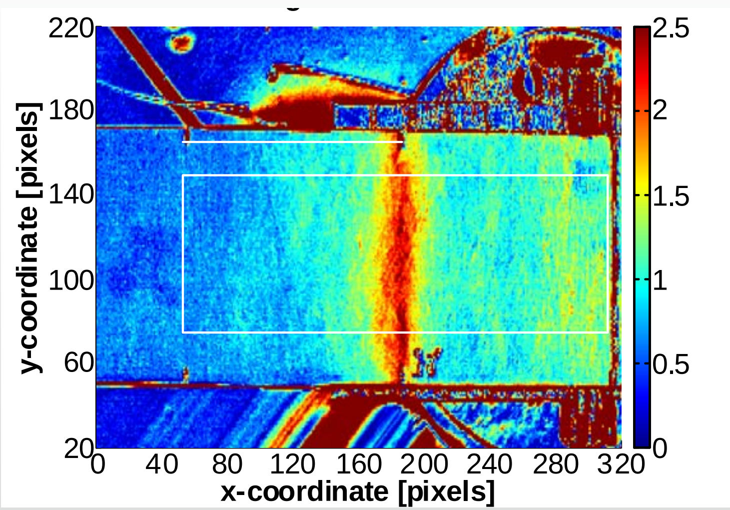
Results from CSM face sheet







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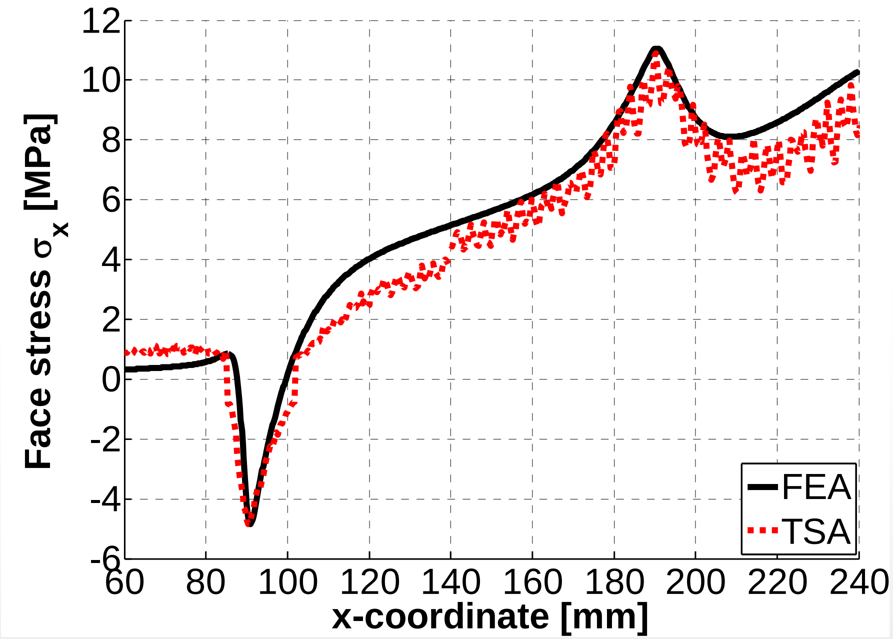
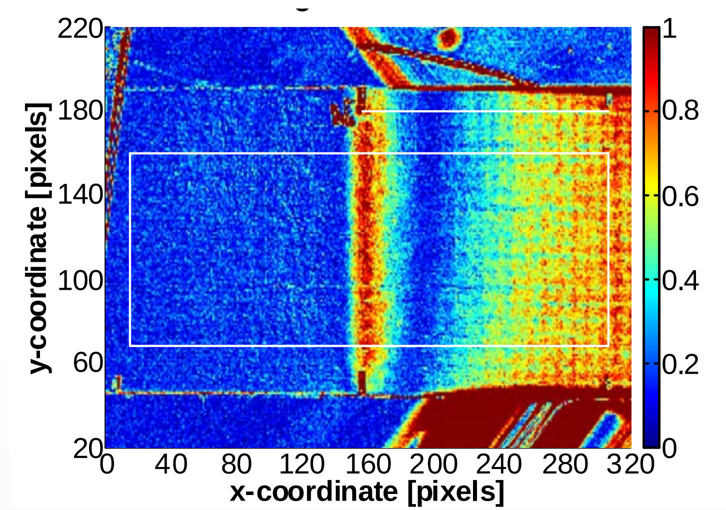
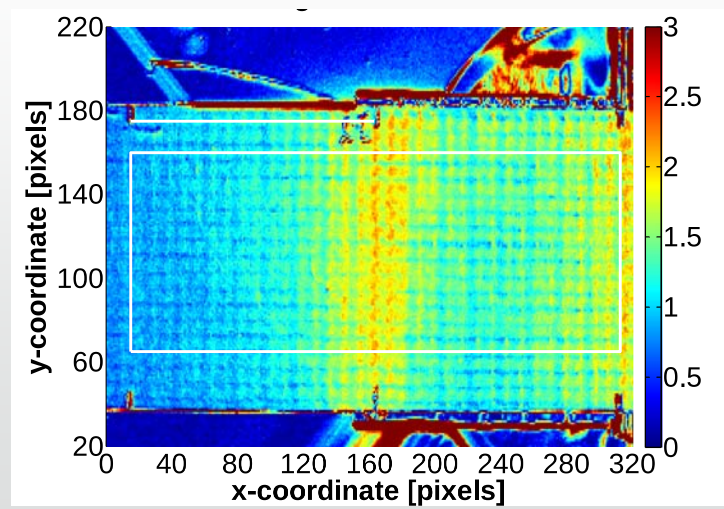
Results from NCF face sheet



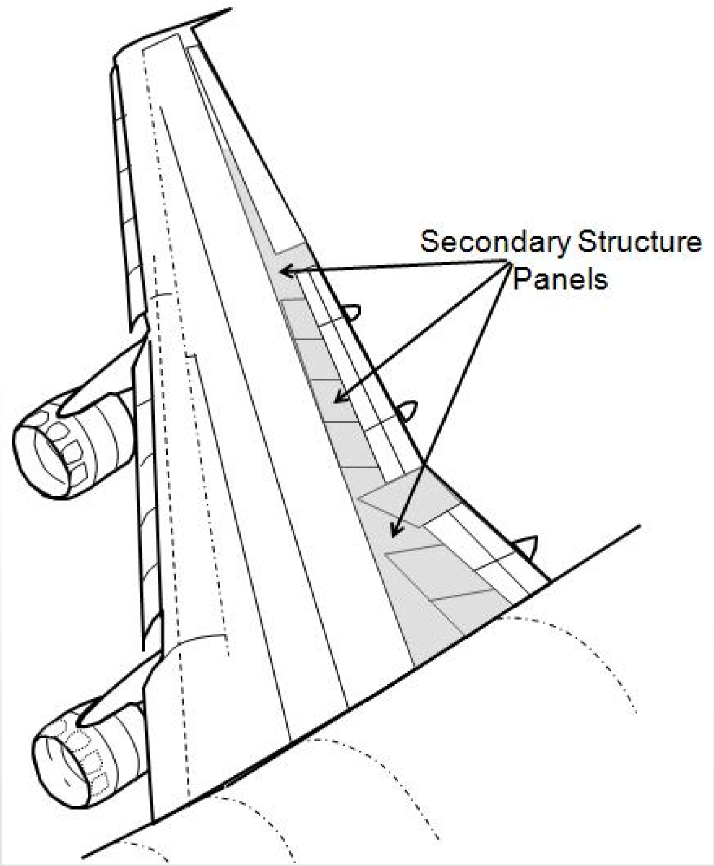




Johannes, M. Dulieu-Barton, J.M., Bozhevolnaya, E., Thomsen, O.T., "Characterisation of local effects at core junctions in sandwich structures using thermoelastic stress analysis" Journal of Strain for Engineering Design, 2008, 43, 469-492.

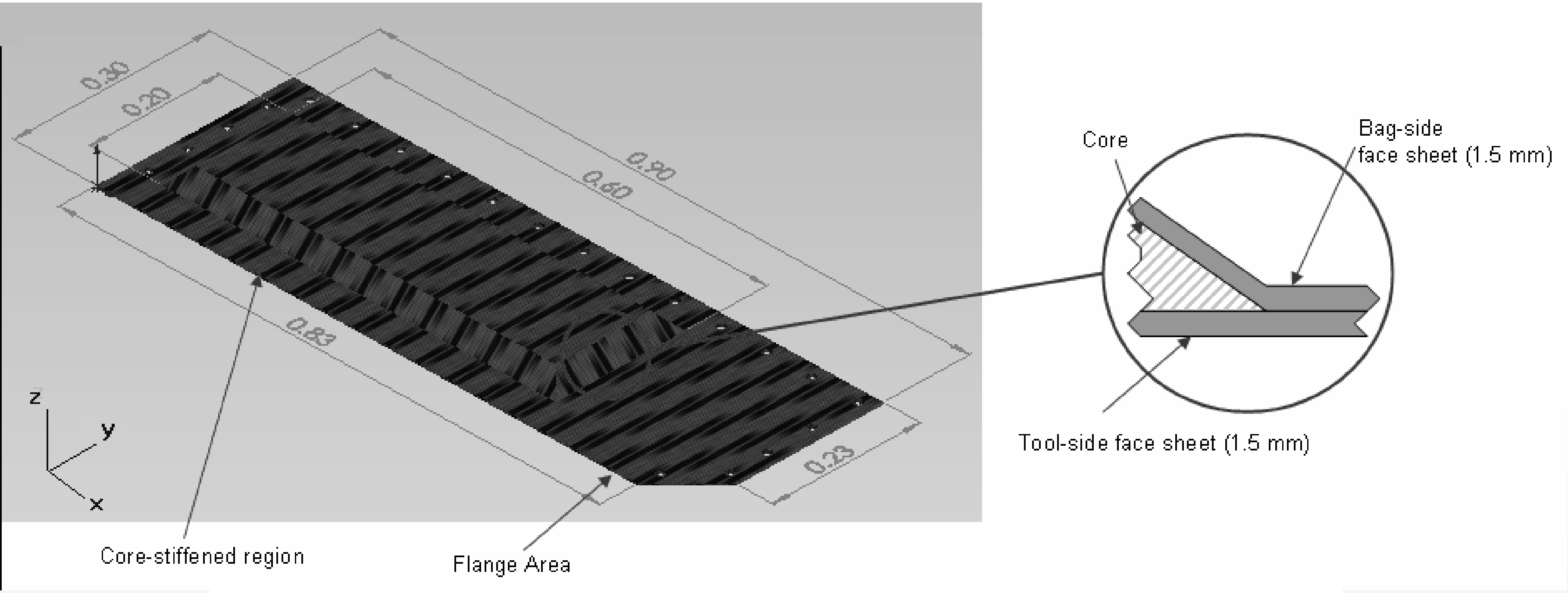
Stresses in secondary aircraft structure

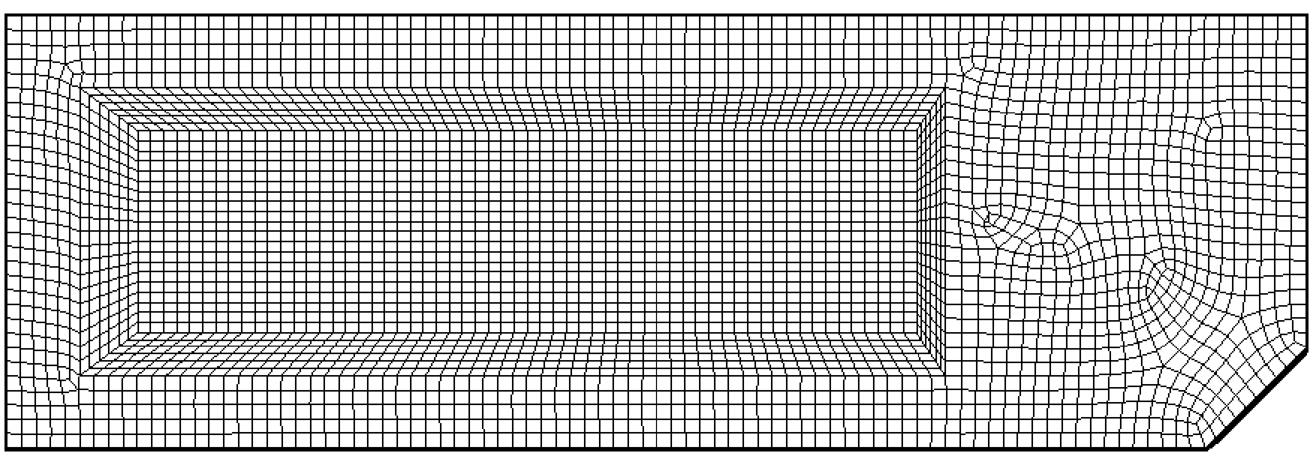
- Increased use of composite materials in aircraft structure
  - weight saving
  - improved life time
- Development of new manufacturing techniques and new materials



Crump, D.A., Dulieu-Barton, J.M. and Savage, J., “The manufacturing procedure for aerospace secondary sandwich structure panels” Journal of Sandwich Structures and Materials, in press. DOI :10.1177/1099636209104531

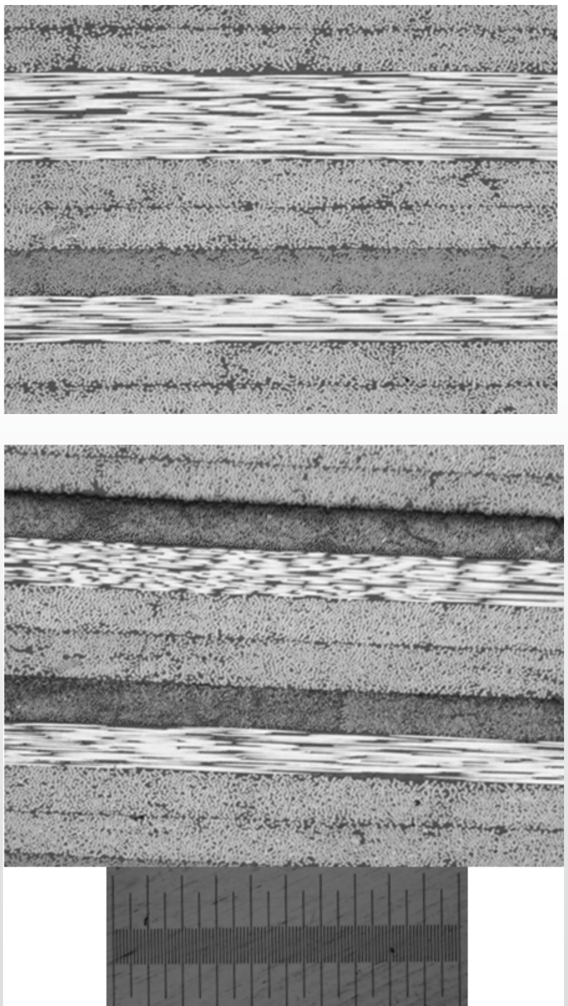
Generic panel



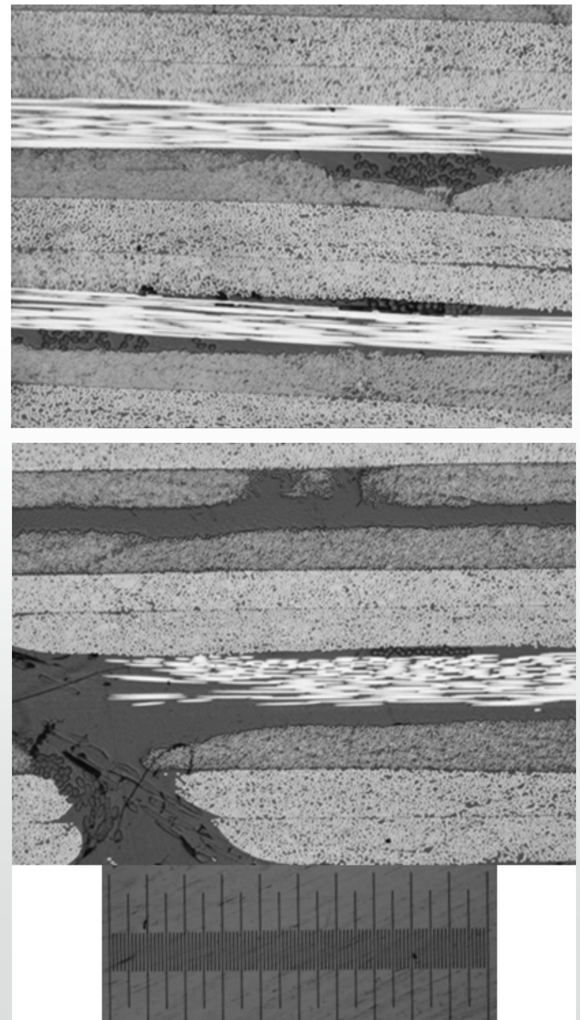


Face sheet material characterisation

UD prepreg/autoclaved



NCF RFI Oven cure



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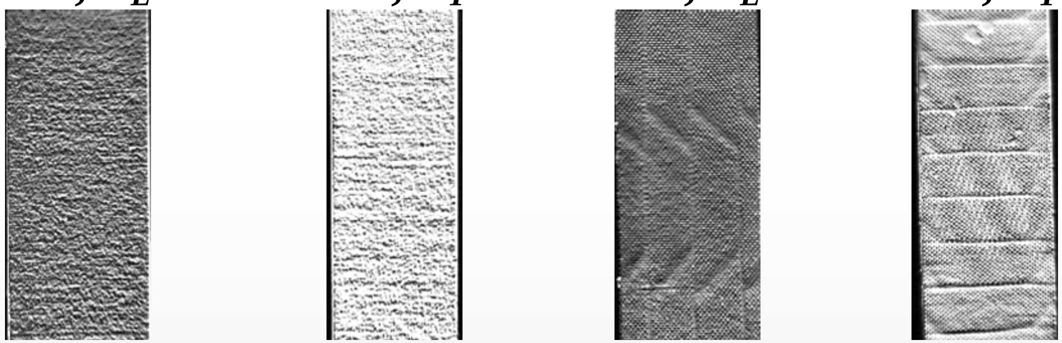
Thermoelastic constants

	M1, K_L	M1, K_T	M2, K_L	M2, K_T
				
Thermoelastic constant MPa^{-1}(x 10^{-6})	1.592 ± 0.83	3.112 ± 1.19	1.58 ± 0.81	2.837 ± 1.55

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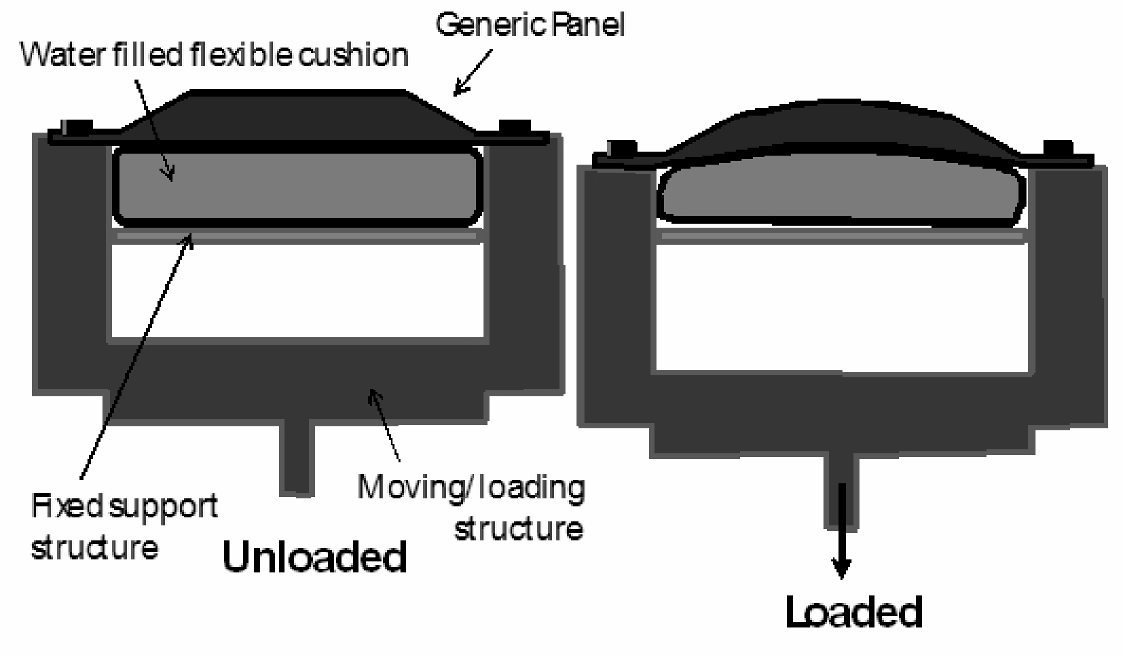
Representative loading

- Allow full scale pressure load applied to generic panel
- Panel is pulled over water filled cushion
- Applied to standard test machine
- Allows cyclic loading
- Allows optical access



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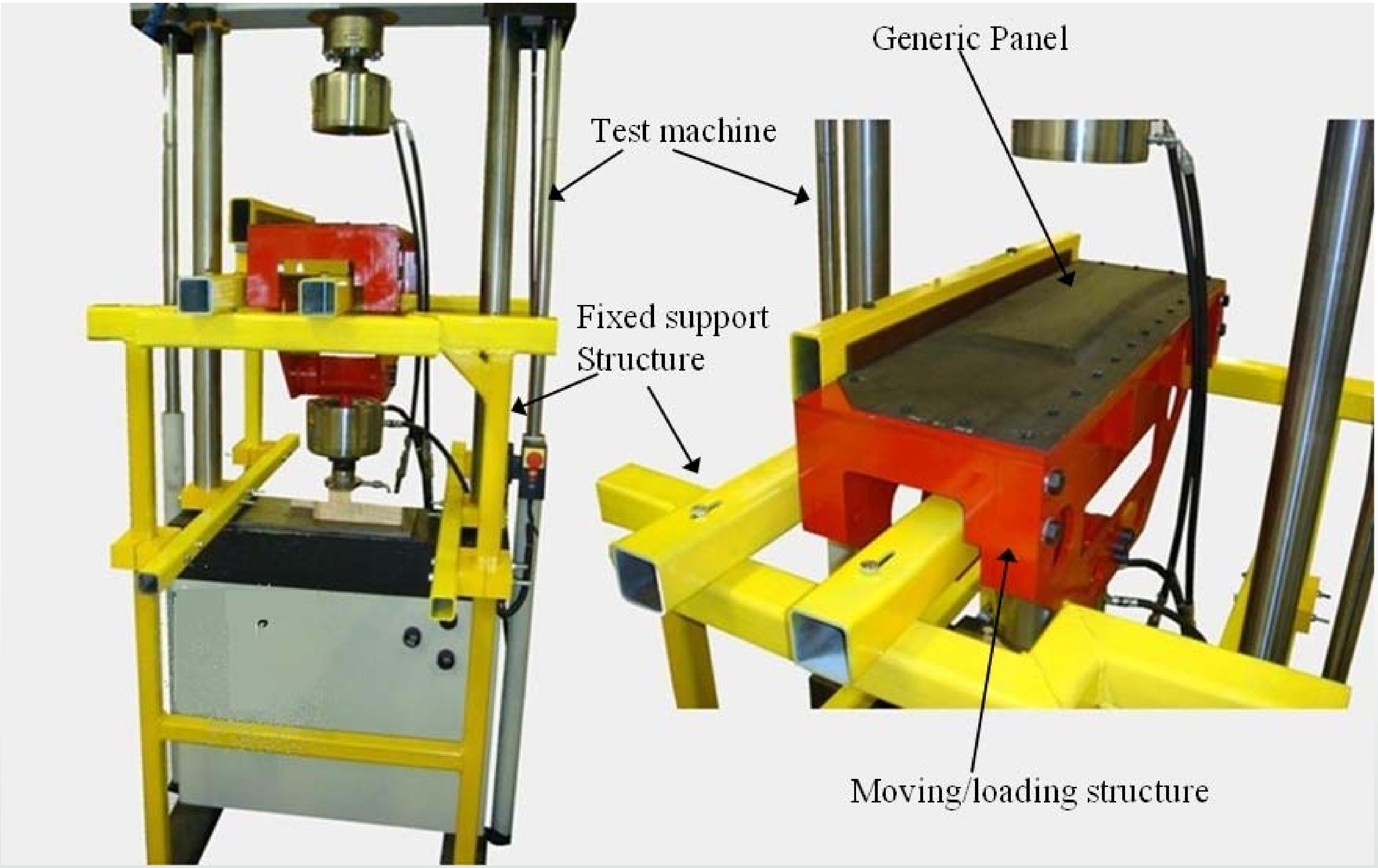
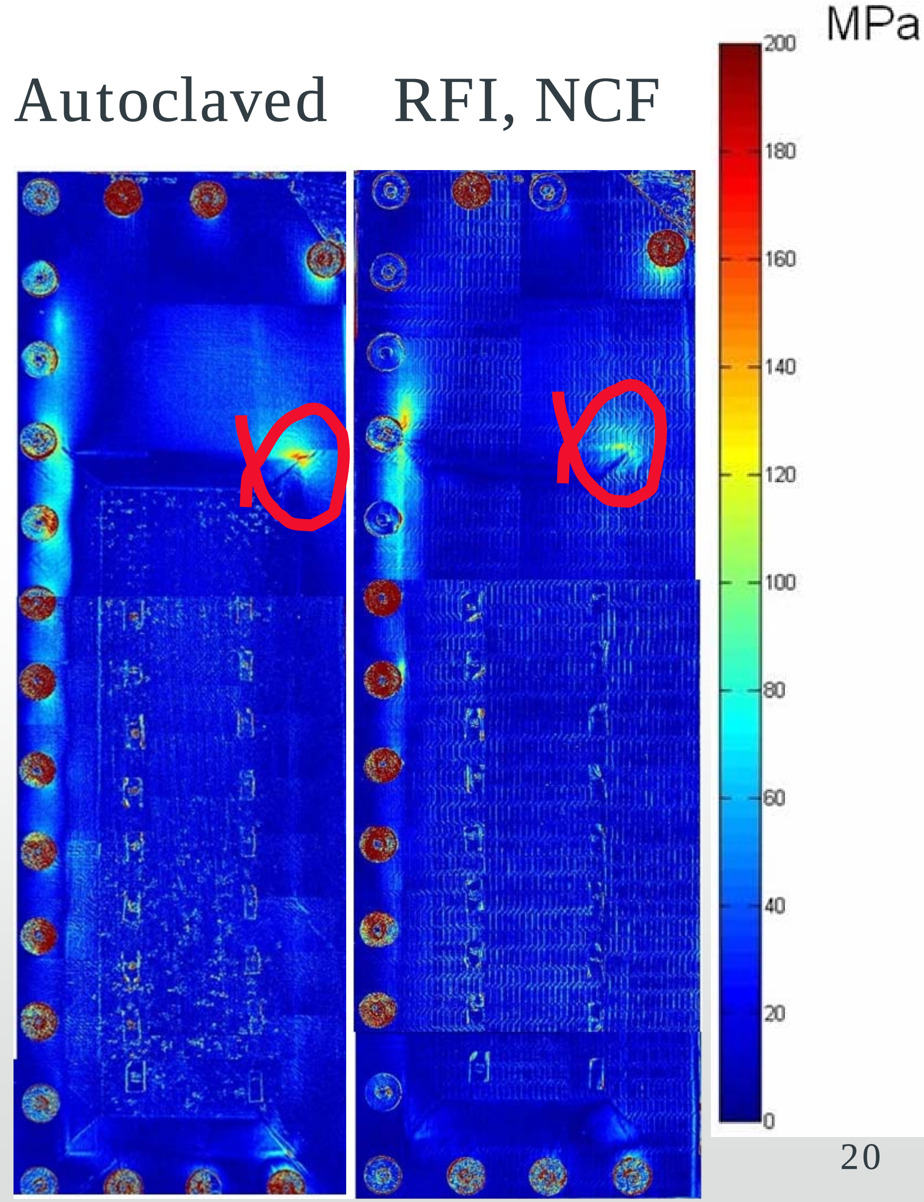
Full scale testing of a generic panel



Crump, D.A., Dulieu-Barton, J.M. and Savage, J., "Design and commission of an experimental test rig to apply a full-scale pressure load on composite sandwich panels representative of aircraft secondary structure", Measurement Science and Technology, 2010, 21, (16pp). DOI: 1088/0957-0233/21/1/015108

Results

- Standard autoclaved prepreg offered a panel with a maximum deflection of 6.3 mm whilst RFI, NCF panel deformed by 4.6 mm.
- The measured stress response indicated a reduction in stress peak when using RFI and NCF.



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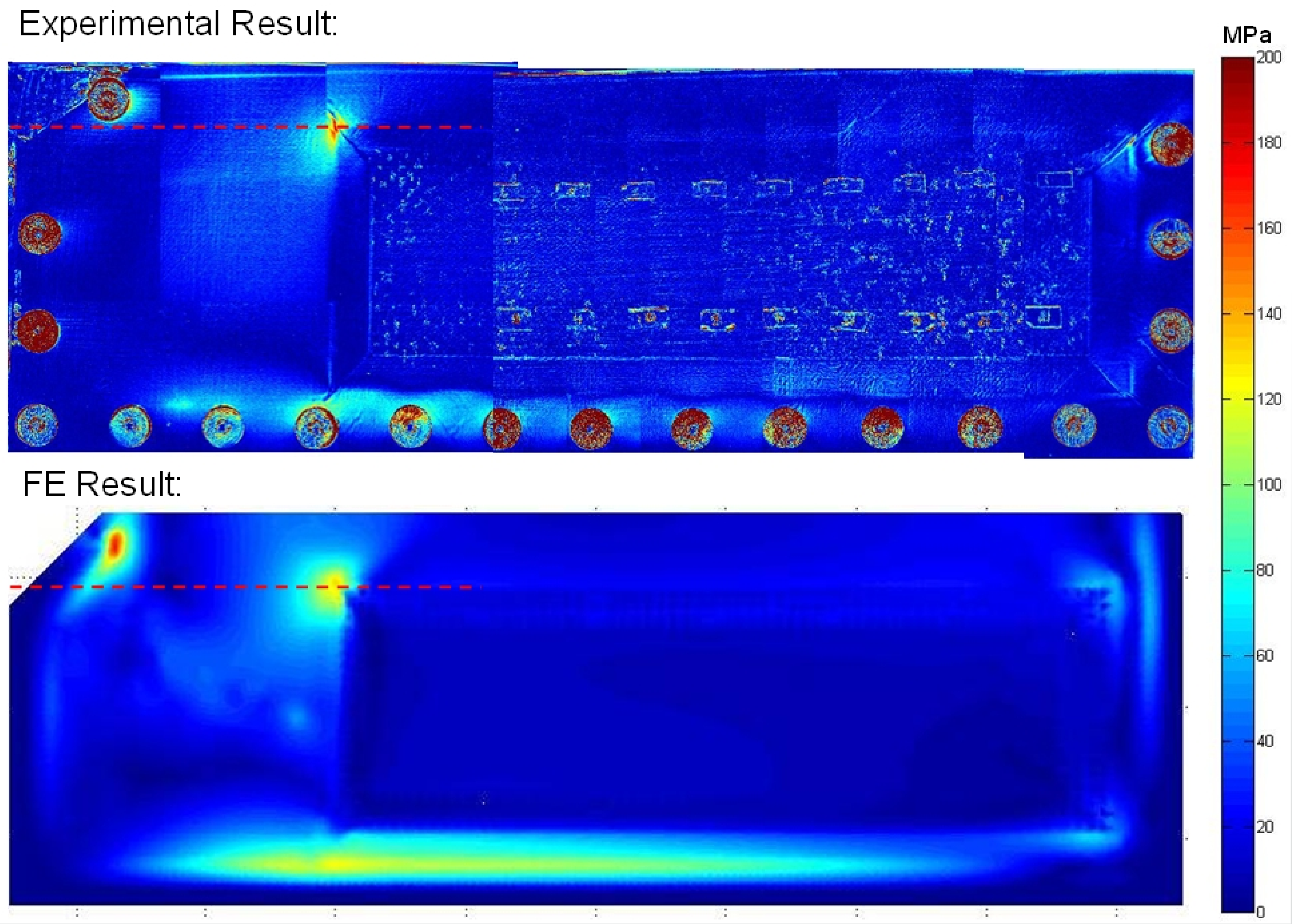
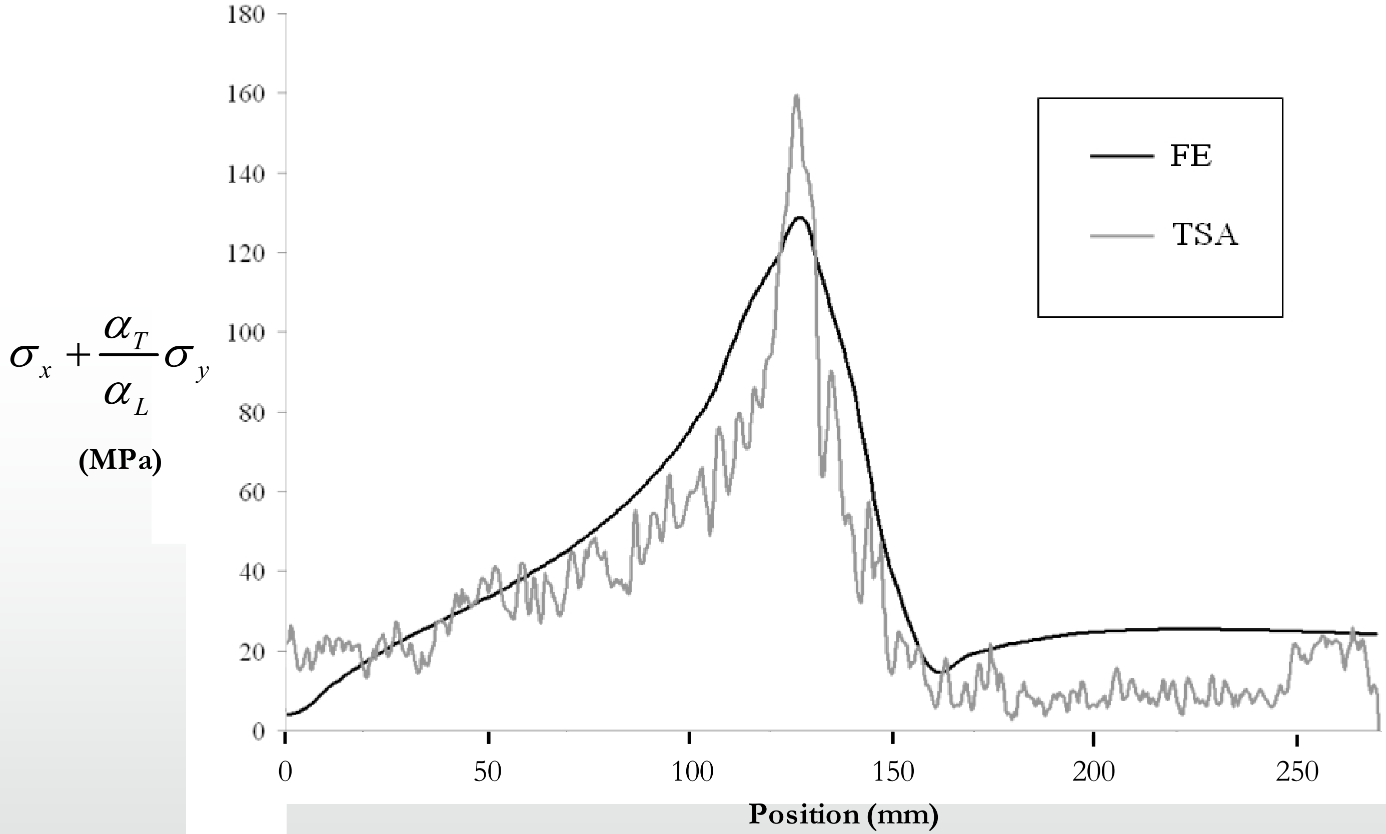
Comparison of TSA and FEA



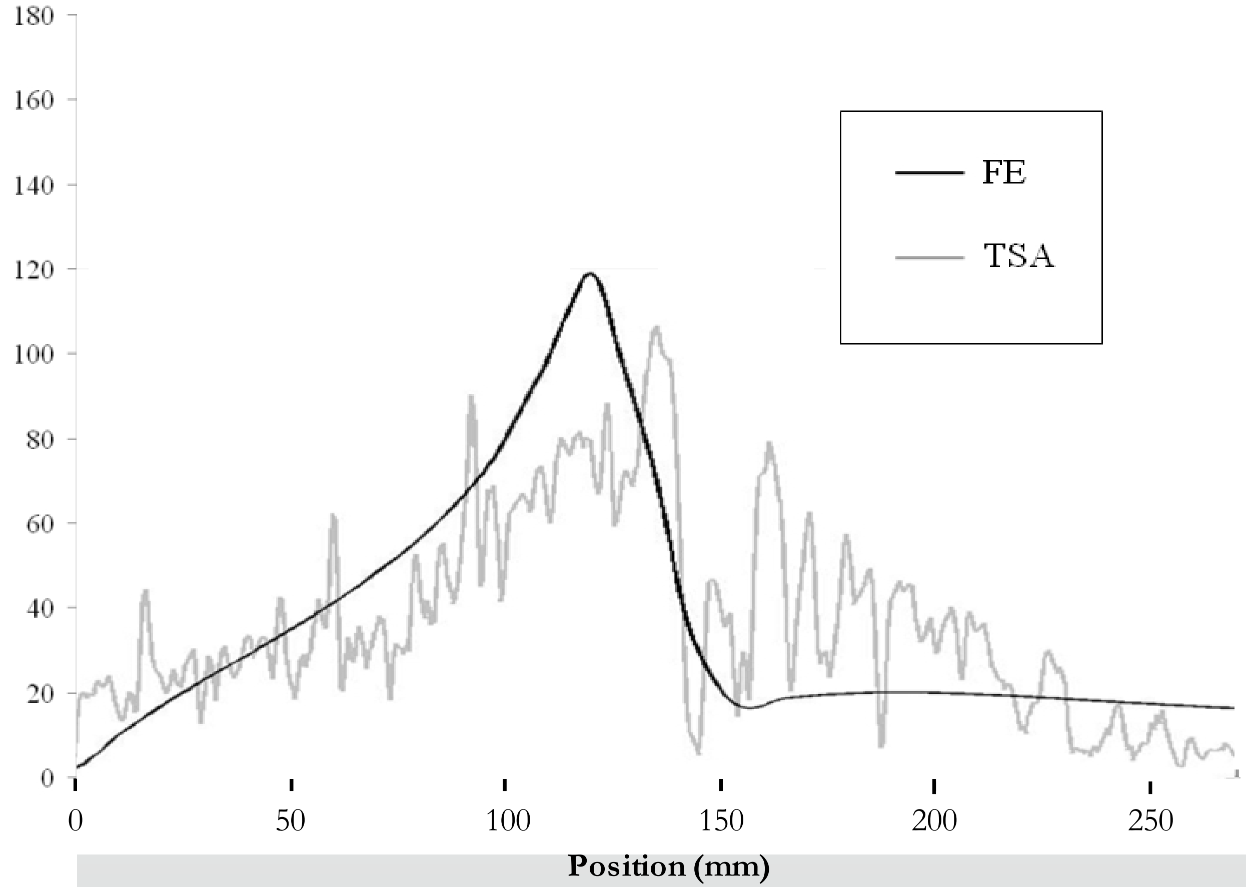
Autoclaved


$\sigma_x + \frac{\alpha_T}{\alpha_L}\sigma_y$
(MPa)
180
160
140
120
100
80
60
40
20
0
0
50
100
150
200
250
Position (mm)
FE
TSA

NCF -RFI

$$\sigma_x + \frac{\alpha_T}{\alpha_L}\sigma_y$$

(MPa)



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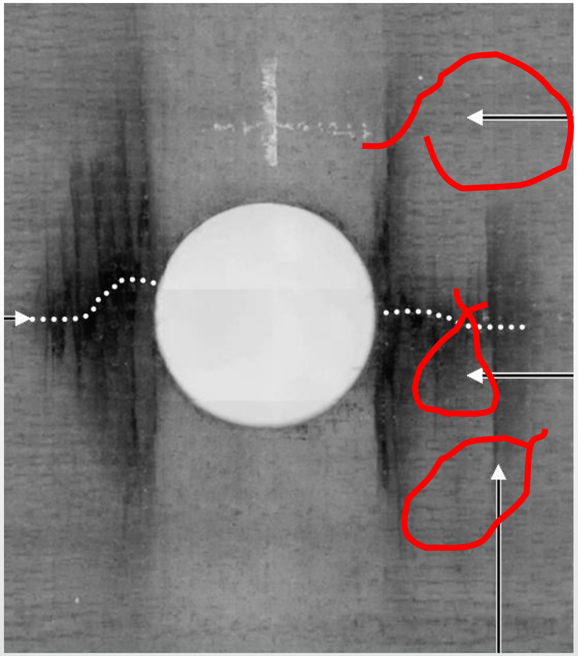
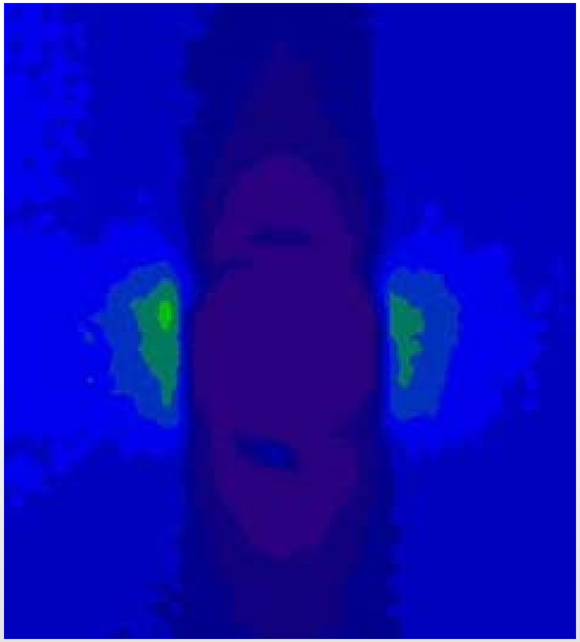
Damage studies in Cross ply laminate

$[(0/90)_3, 0, (90/0)_3]$





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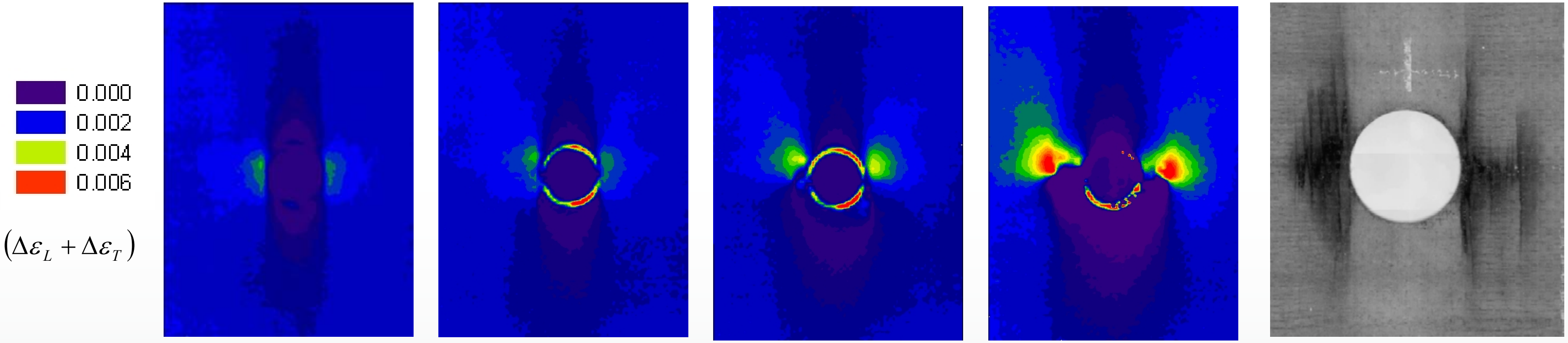
Cross ply



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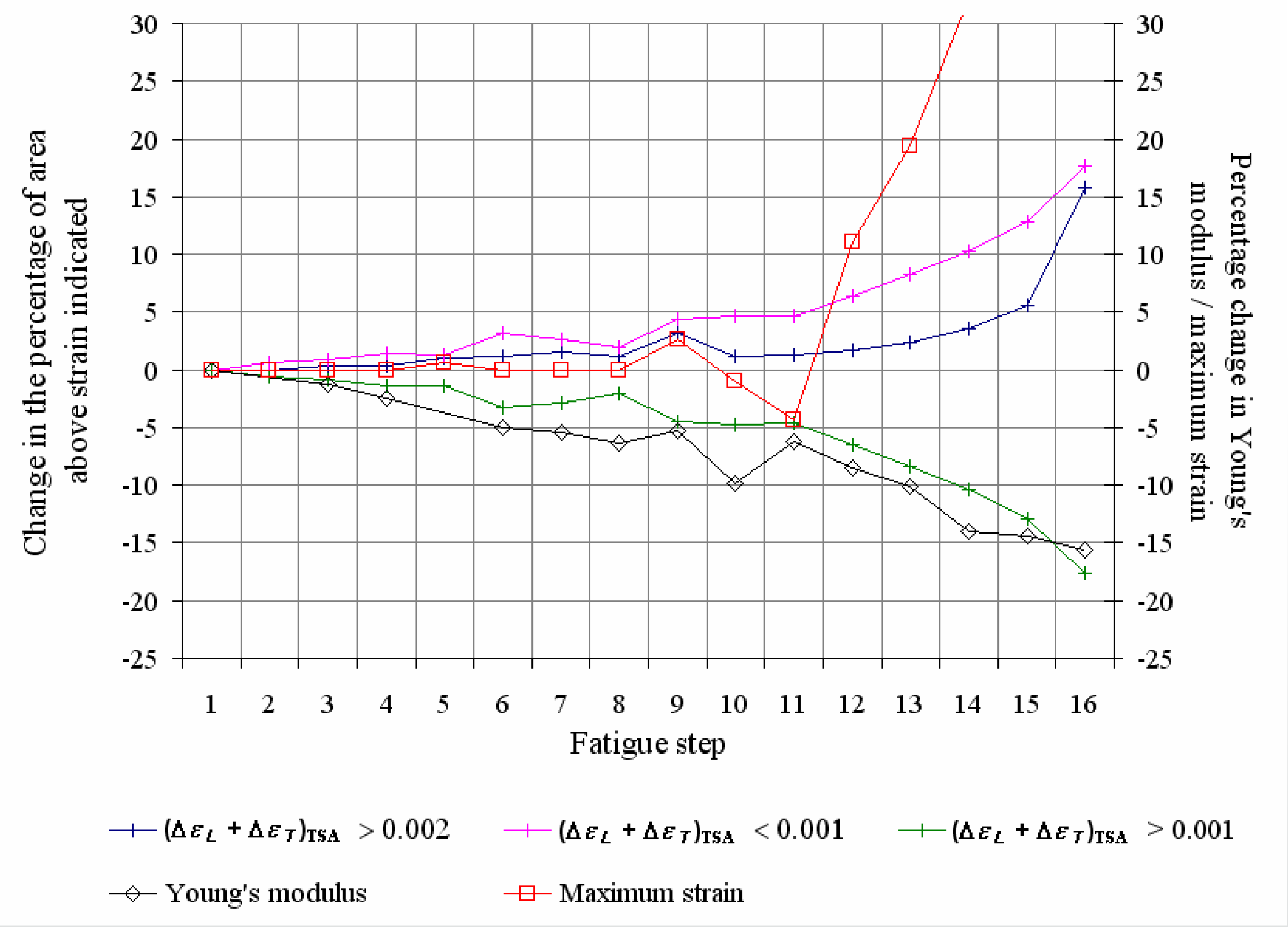
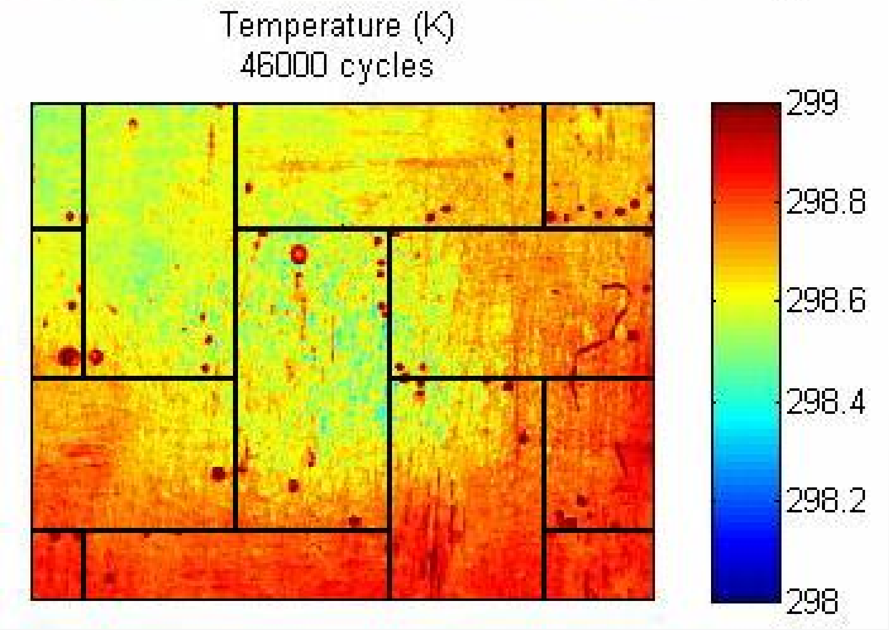
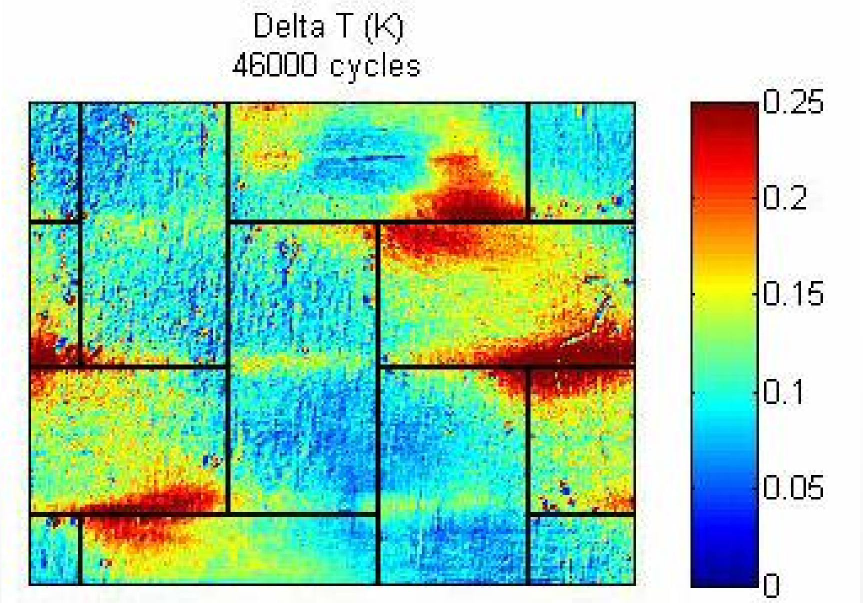
Damage indicator



Emery, T. R. and Dulieu-Barton, J.M., “Thermoelastic Stress Analysis of damage mechanisms in composite materials”, Composites Part A, in press. DOI: 10.1016/j.compositesa.2009.08.015

Thermography data-damage analysis



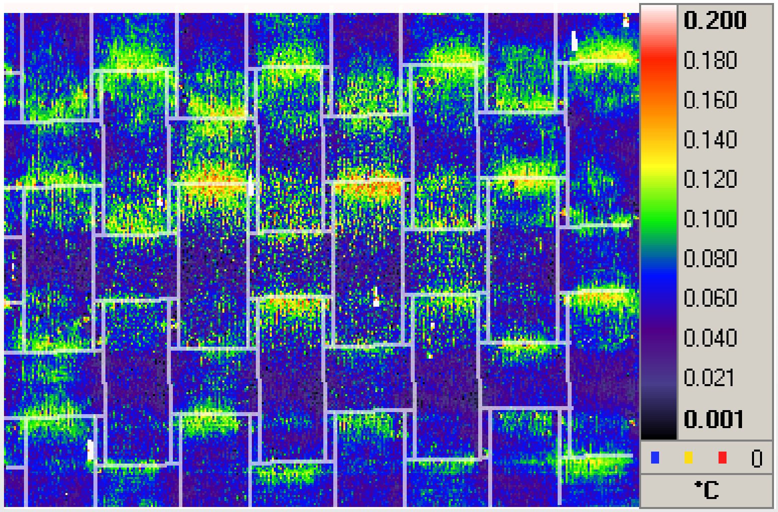


$$\Delta T = -\frac{T}{\rho C_p}\left(\alpha_1 \Delta\sigma_1 + \alpha_2 \Delta\sigma_2\right) \Rightarrow \frac{\Delta T}{T}$$

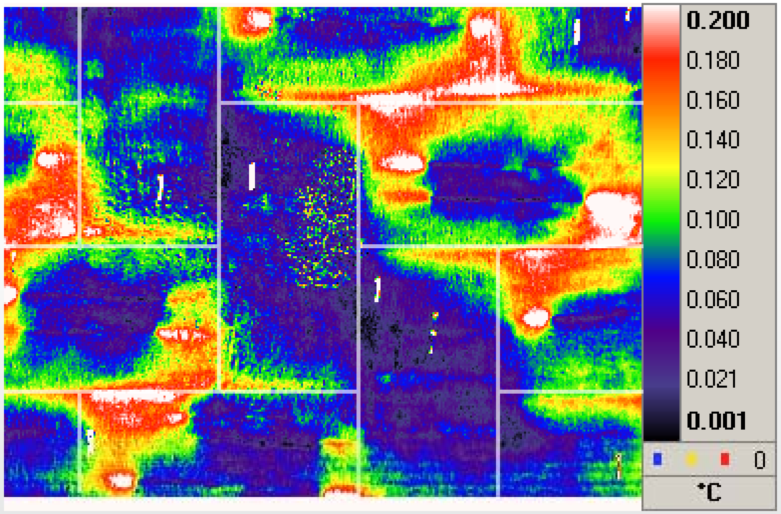
Application of TSA to woven composites

- It is possible to correlate the thermoelastic response to the weave pattern.

- The thermoelastic response changed with repeated testing at loads below 30 % of the failure stress



ΔT data from a single ply
of plain weave E-glass/epoxy



ΔT data from a single ply
of 2 x 2 twill weave E-glass/epoxy

Frühmann, R.K., Dulieu-Barton, J.M. and Quinn, S., “On the thermoelastic response of woven composite materials”, Journal of Strain Analysis for Engineering Design, 2008, 43, 435-450.

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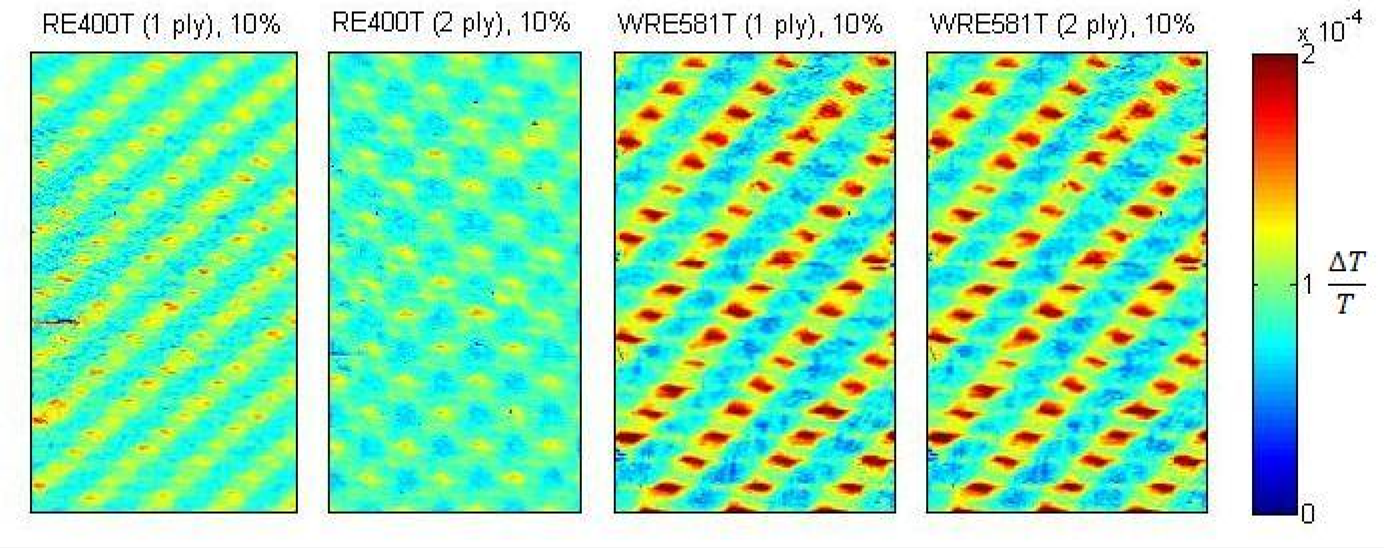
Global thermoelastic response

- The effect of stacking sequence is visible in the global TSA data.



TSA data from all four undamaged materials, at 10% loading

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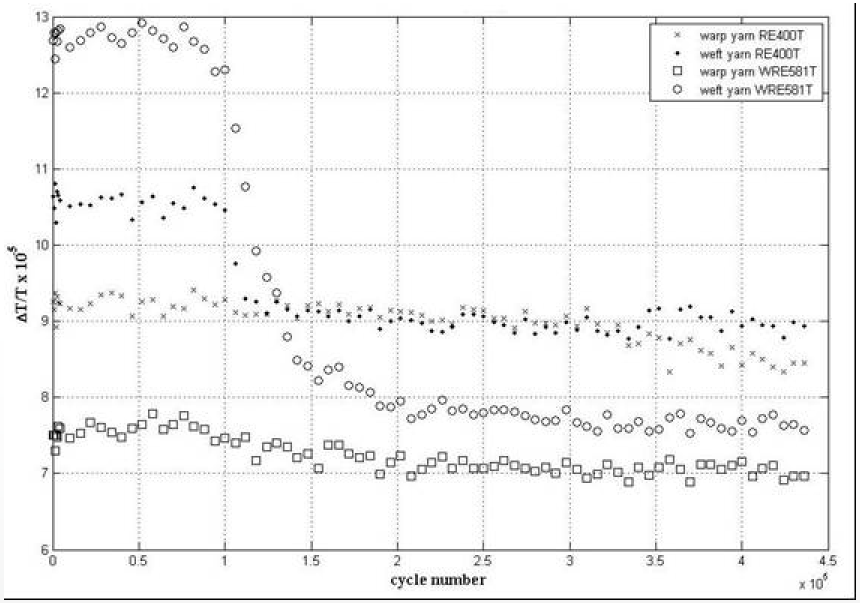
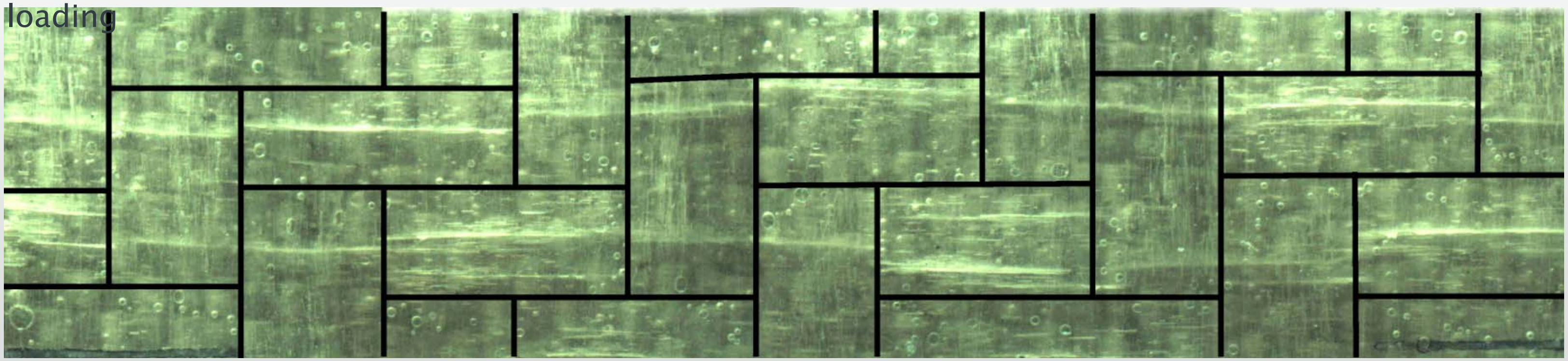
Meso-scale thermoelastic response

- Thermoelastic signal decay is concentrated in the weft cells.
- Cracks are found to form along the centre of the weft cells.



Time history of the thermoelastic response from a typical warp and weft yarn

Macroscope image
(x 10 magnification) of the WRE581T single ply material after 184000 cycles at 15% loading



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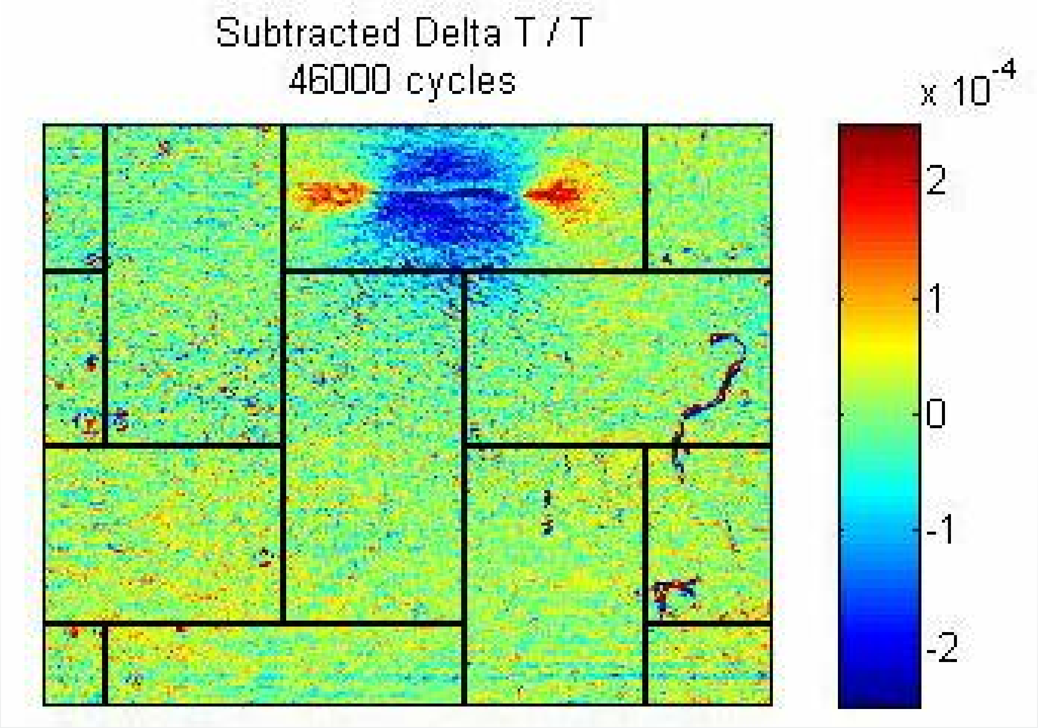
Data processing



$$\left(\frac{\Delta T}{T}\right)_{Damaged} - \left(\frac{\Delta T}{T}\right)_{Undamaged}$$

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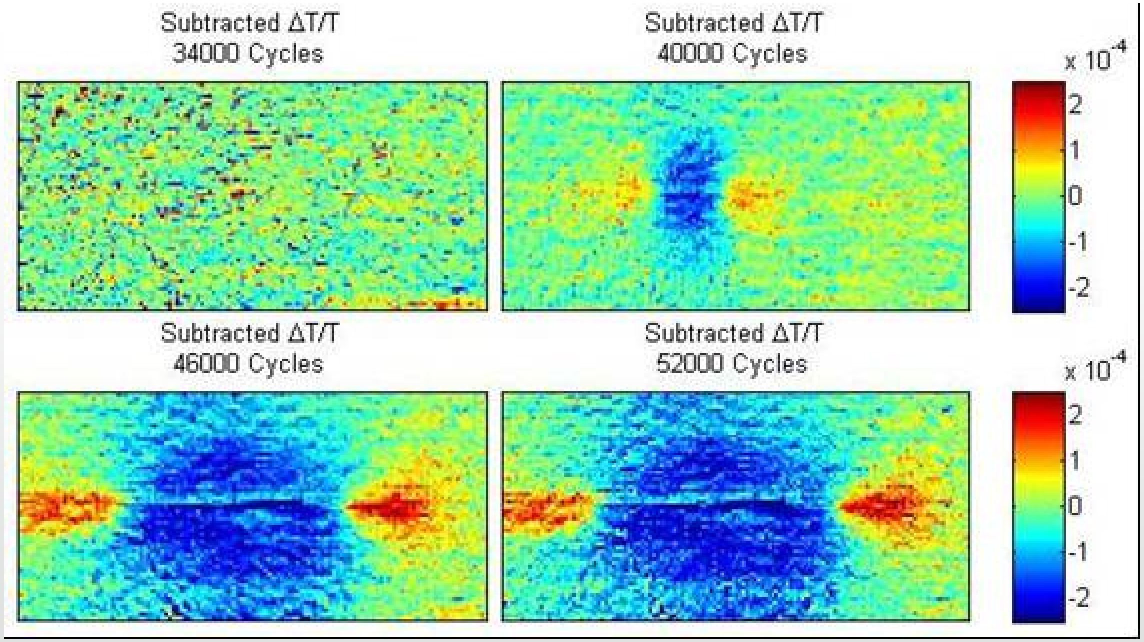
Damage identification

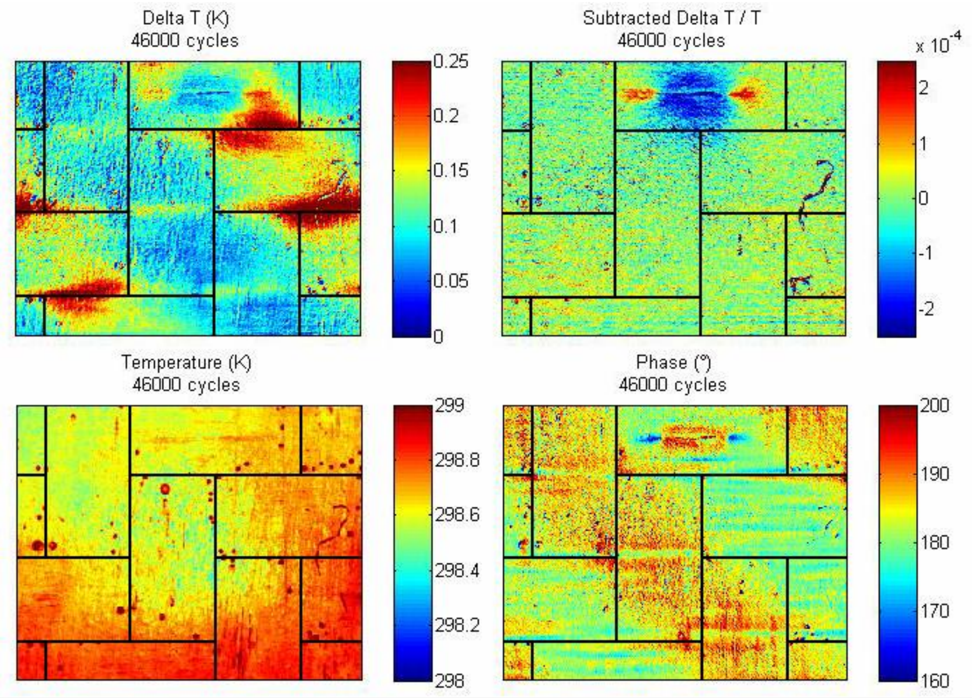
- The thermoelasic response was examined at the scale of the yarn.
- ‘Virgin’ data was subtracted to identify changes in the local thermoelastic response



Subtracted $\Delta T/T$ field from a single weft yarn

Overview

- Damage in textile composites can occur at very low stress levels, < 20 % of σ_f.
- Damage can be identified using TSA despite the heterogeneous thermoelastic material response.
- Phase data provides a means for damage identification without *a priori* knowledge of the thermoelastic field.

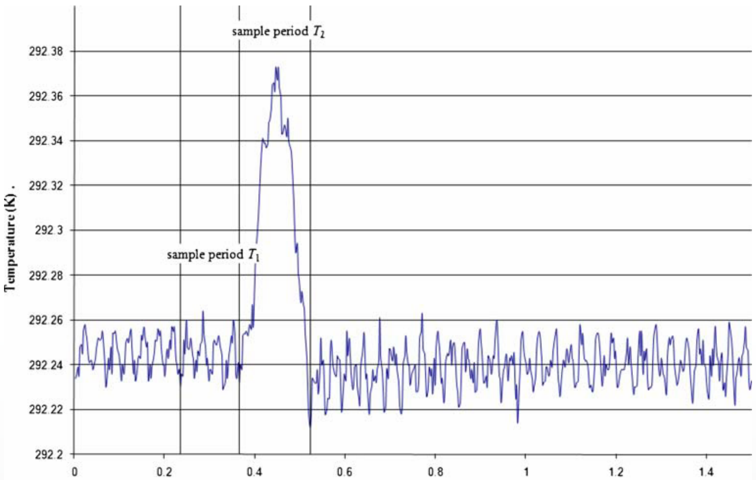


Complete set of high resolution TSA data from the WRE581T specimen loaded at 10 % of the failure stress

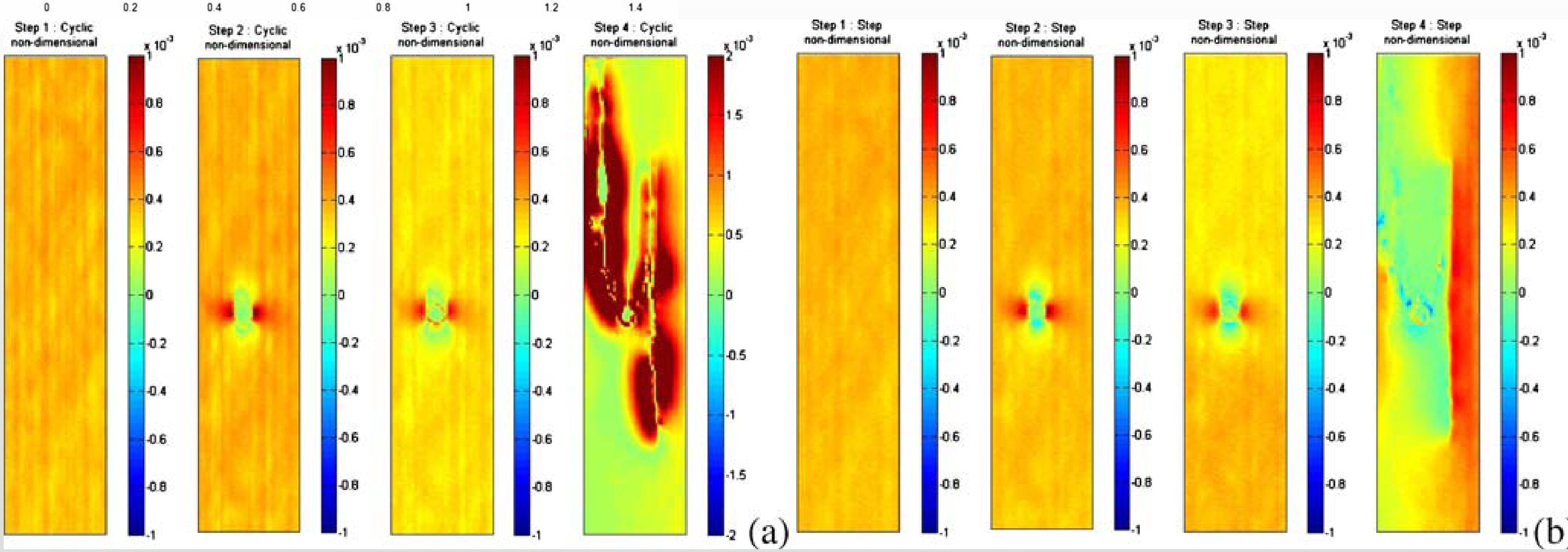
This work was supported by the UK Engineering and Physical Sciences Research Council -EPSRC

Frühmann, R.K., Dulieu-Barton, J.M. and Quinn, S., "Assessment of fatigue damage evolution in woven composite materials using infra-red techniques" Composites Science and Technology, in press. DOI: /10.1016/j.compscitech.2010.02.009

Field studies – transient loading



Frühmann, R.K., Dulieu-Barton, J.M. and Quinn, S., "Thermoelastic stress and damage analysis using transient loading" Experimental Mechanics, in press. DOI: 10.1007/s11340-009-9295-9



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Conclusions

- Demonstrated the necessity of accurate measured material property values for composite materials
- Shown how full-field experimental mechanics techniques can be used to validate FEA
- Presented convincing case studies that demonstrate the applicability and ease of using TSA
- Shown that TSA can be used over a range of scales for stress analysis and damage studies