Development Center for Maintenance of Composites

WP4: Non-Destructive Inspection of Thick-Walled Composites

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Thick composite inspection

Marine

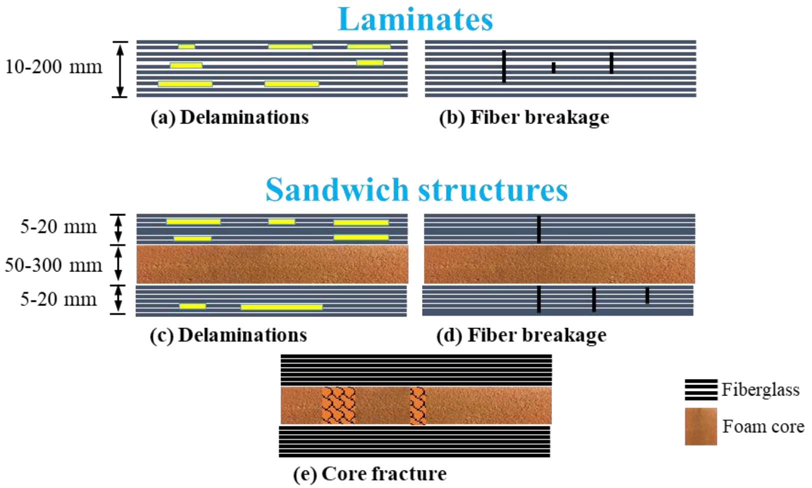
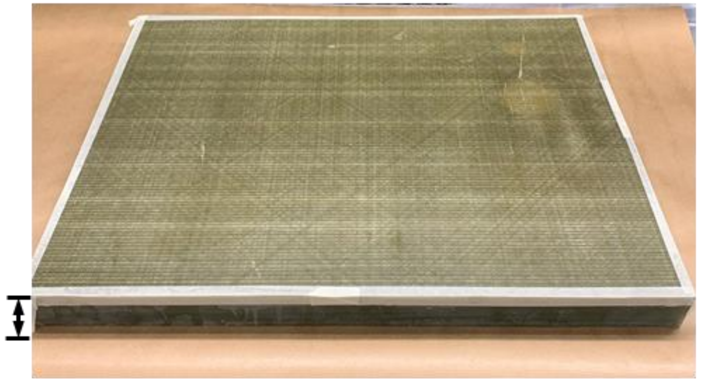


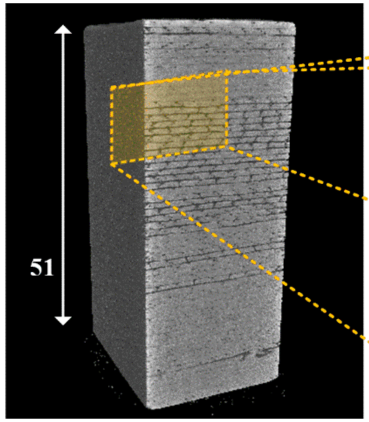
Illustration of common defects in marine composites
(Source: Damen)

Thick composites (e.g., 50-60 mm thickness)

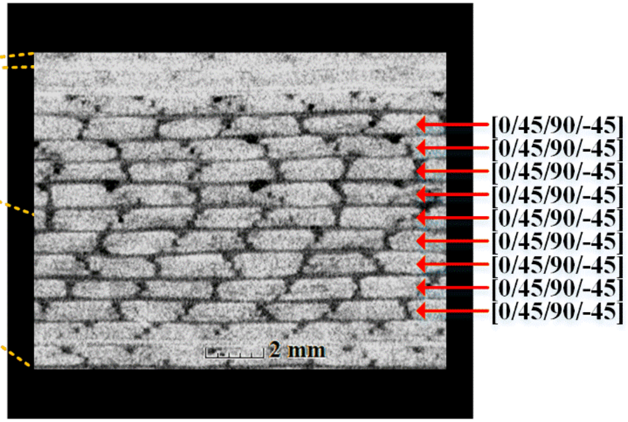
GFRP laminate in marine area

Thickness: 51 mm

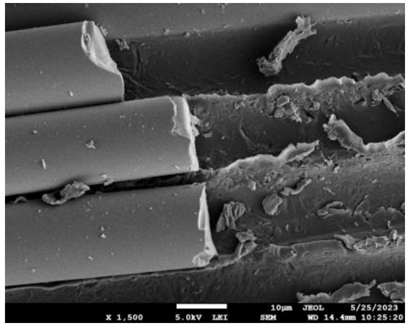




3D reconstructed CT scan



CT cross-sectional view showing internal stitched structure



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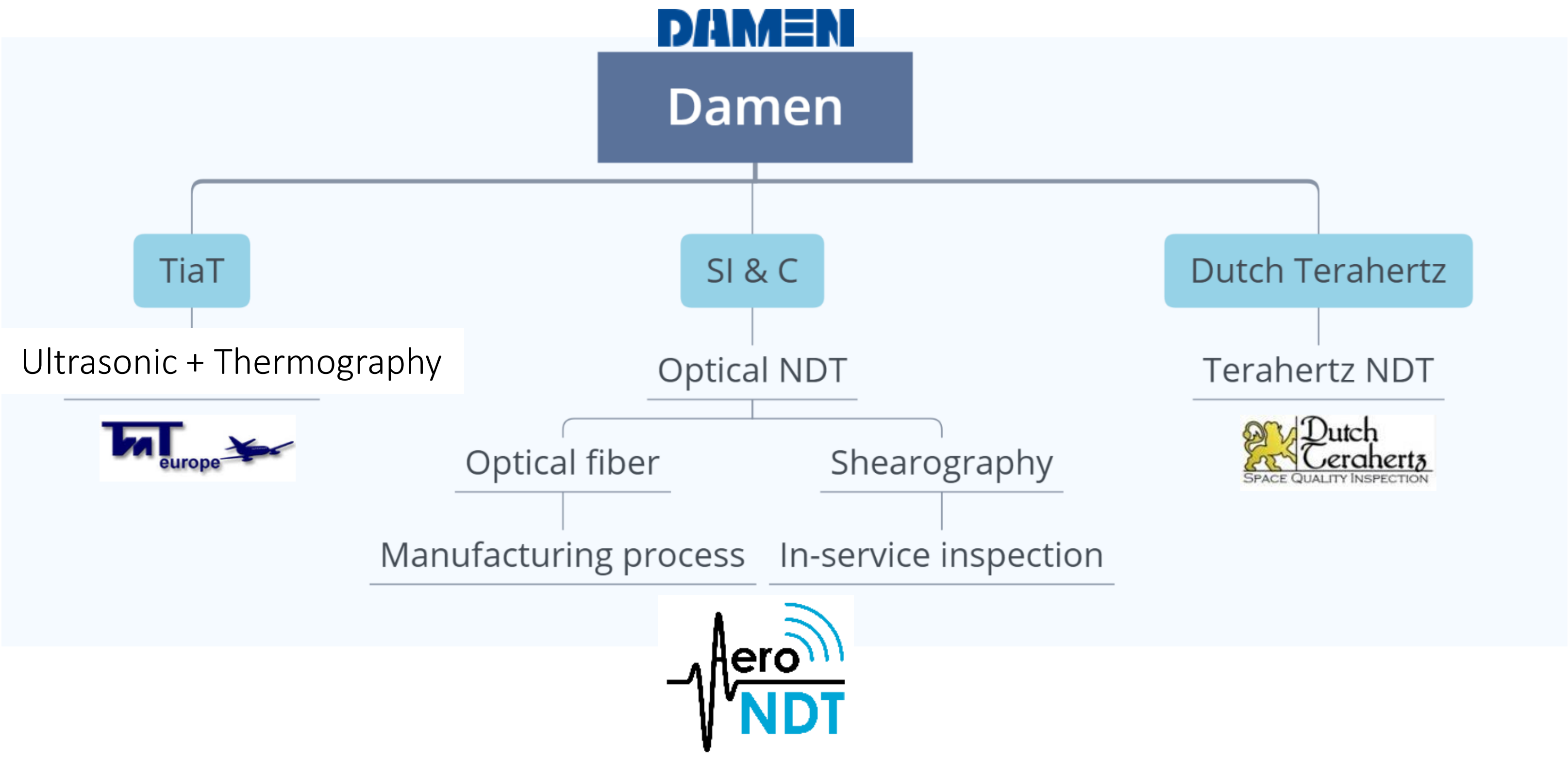

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Fibre Bragg Grating (FBG)

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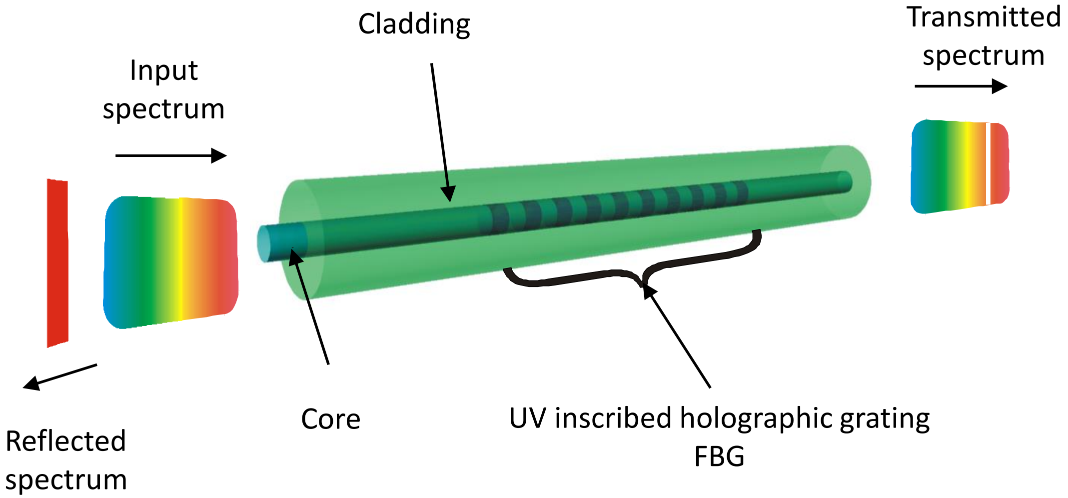
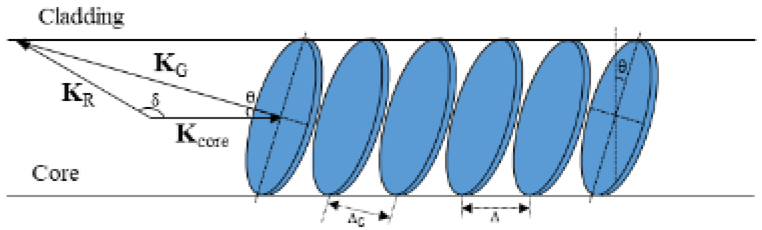
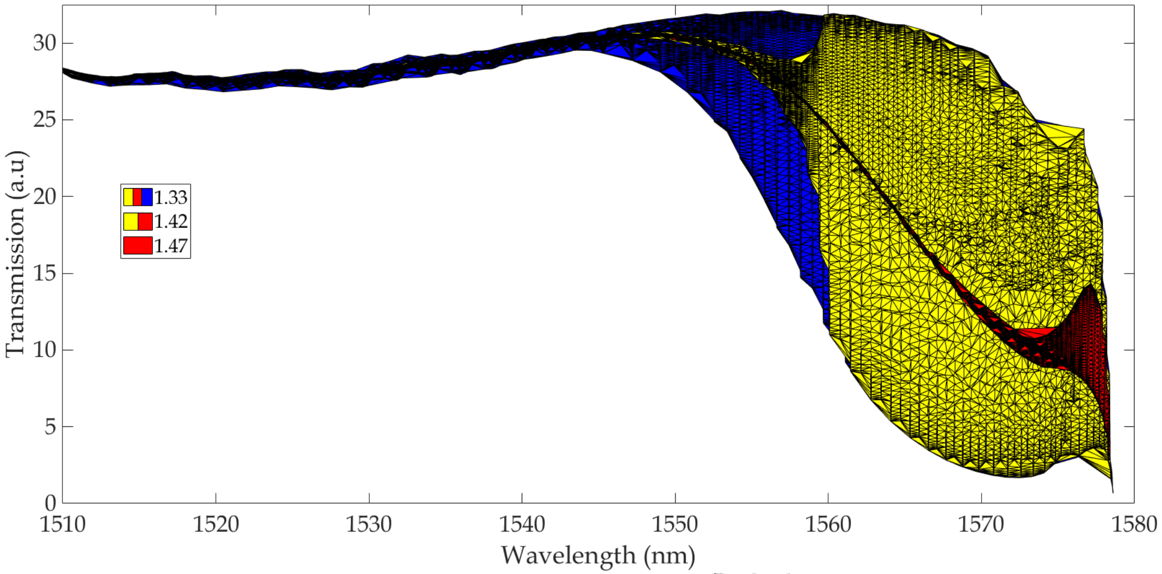
- Each FBG sensor reflects narrow wavelength spectrum
- Wavelength shifts due to strain change



- Tilted Fibre Bragg grating (TFBG)





- Temperature and strain – Bragg resonance peak
- Temperature and strain – Ghost resonance peak
- External refractive index – area of the cladding resonances peaks envelope

L. Fazzi, R.M. Groves "Demodulation of a tilted fibre Bragg grating transmission signal using α-shape modified Delaunay triangulation" Measurement 166 (2020): 108197

Tilted Fibre Bragg Grating (TFBG): experiments

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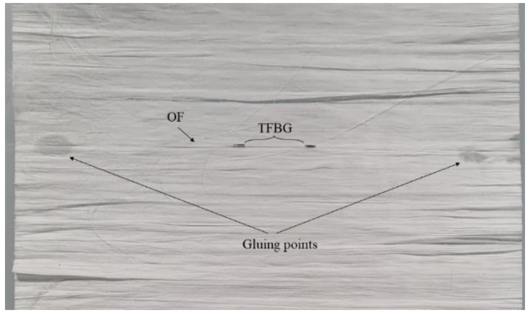
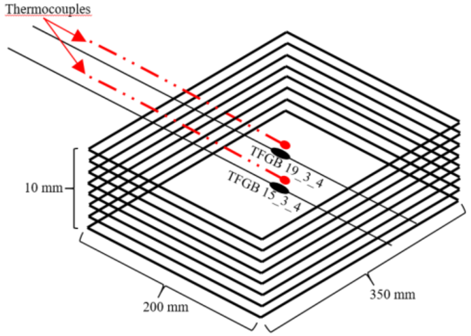
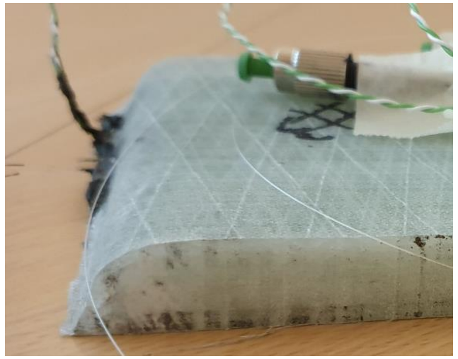
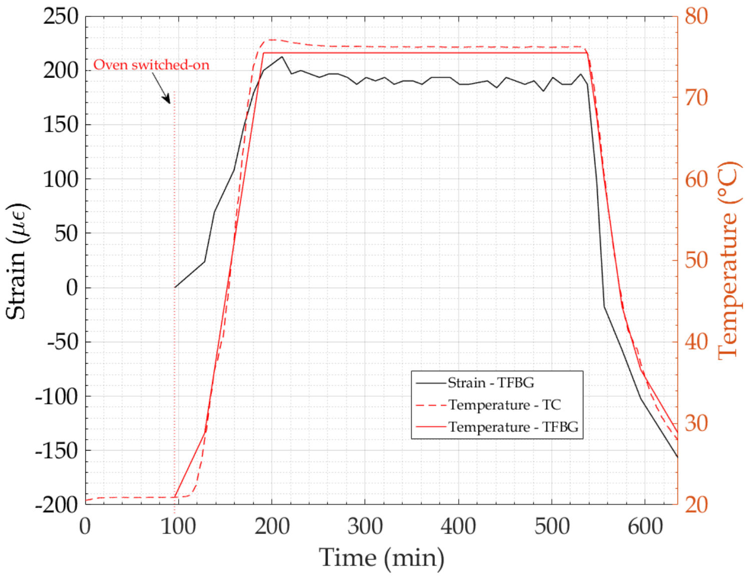
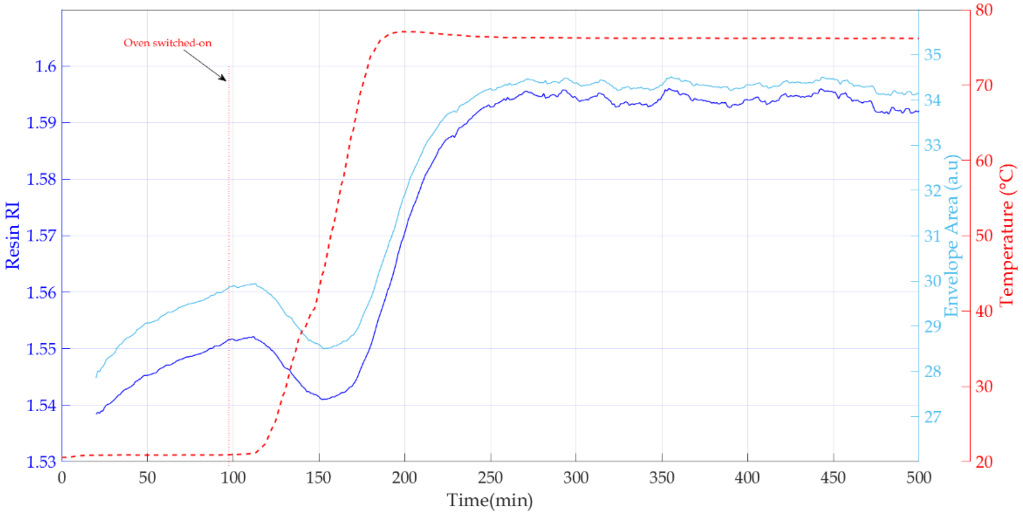




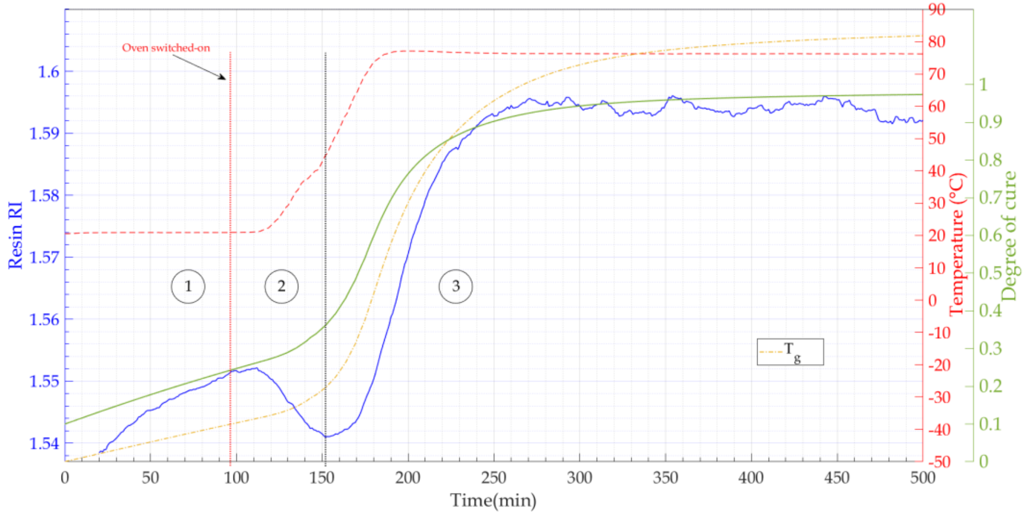




Temperature and strain trends during the composite curing time measured trough the embedded TFBG and TC



Envelope area and resin RI trend during the composite curing time through the TFBG sensor with TC temperature



Comparison between αr and the resin RI with TC temperature and Tg evolution

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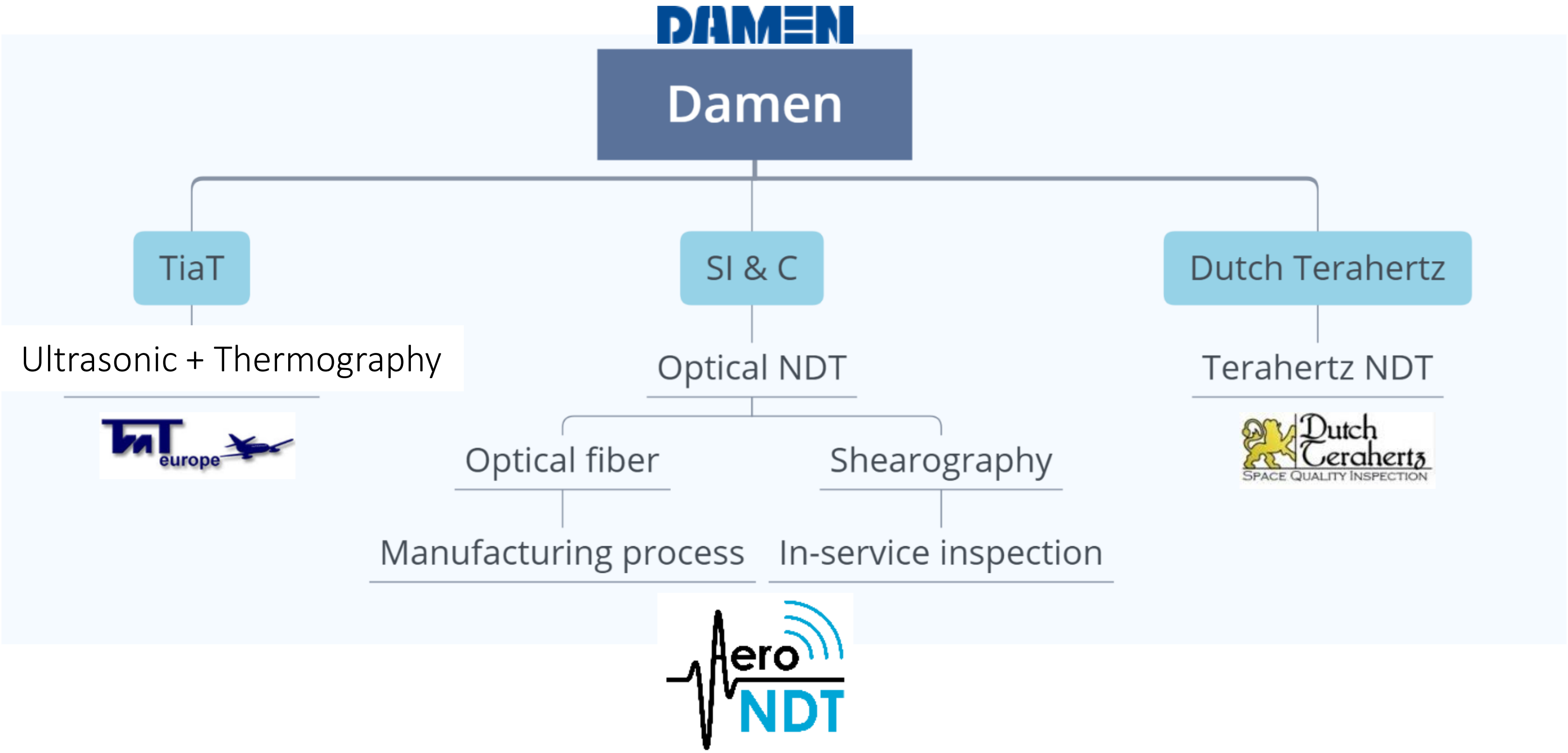

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Literature / past

	Defect	Technique	Composite
Manufacturing	Fibre bunching, waviness	Ultrasonics Radiography Microwave	Monolithic laminate
	Layup irregularities, ply orientation	Ultrasonics Eddy-current	 CFRP only
	Fibre volume fraction	Ultrasonics Microwave Eddy-current	 CFRP only
	Voids/porosity	Ultrasonics Radiography Thermography	
	Foreign inclusions	Microwave Radiography Ultrasonics	GFRP only
	Bondline integrity	Radiography Ultrasonics Thermography Optical interferometry	 Near-surface Near-surface
In-service	Delamination	Ultrasonics Thermography Optical interferometry	 Near-surface Near-surface
	Fibre breakage	Acoustic emission	
	Skin-to-core disbonding	Optical interferometry Thermography Resonance Ultrasonics	Sandwich structure
	Core crush	Radiography Thermography	Sandwich structure
	Water presence	Microwave Radiography Thermography Capacitive imaging	Honeycomb sandwich
	Global strain state	Vibration analysis Strain sensing	
	Surface-breaking cracks	Most techniques	

	Defect	Laser Shearography	Ultrasonic Inspection	Infrared Thermography	Digital Tap Hammer
Delamination	Min. Size Detected	2 inches	2 inches	3 inches	3 inches
	Max. Depth Detected	1- 2 plies	1 ply	2 – 3 plies	2 – 3 plies
	Overall Effectiveness	good esp. for kissing bonds	can't detect kissing bonds	can't detect kissing bonds	can't detect kissing bonds
Water Ingress	Min. Size Detected	2 inches	4 inches	2 inches	4 inches
	Max. Depth Detected	skin/core interface	skin/core interface	skin/core interface	skin/core interface
	Overall Effectiveness	good	use higher frequency transducer	very good	fair
Impact Damage	Min. Size Detected	1 inch	2 inches	1 inch	3 inches
	Max. Depth Detected	skin/core interface	1- 2 plies	skin/core interface	skin/core interface
	Overall Effectiveness	very good	good	good	only edge delaminations found
Void	Min. Size Detected	2 inches	2 inches	1 inch	defect not detected
	Max. Depth Detected	¼ inch	½ inch	¾ inch	
	Overall Effectiveness	fair with thick laminates	good for uniform laminates	very good	not effective
System limitations:		Requires good reflective surface – not good with matt finish black parts or clear gel coat; not good with thick or highly curved parts	Requires good calibration sample and uniform laminate; small probe area	Known good laminate required for baseline data; defect must produce a thermal gradient	Only effective with larger defects
Equipment cost:		≈ $100,000	≈ $40,000	≈ $10,000	≈ $1,500

Defects	Visual	Ultrasonics		Thermography		Laser Shearogrphy	
		A-Scan	C-Scan	Steady	Pulsed	Vacuum	Heat
Adhesive bond failure	0	A	A	B	A	A	B
Air bubble	C	C	C	C	B	C	B
Blister	A	C	C	C	B	C	C
Core crushing	C	B	B	B	A	B	C
Core shear failure	0	C	C	B	A	A	B
Crazing	A	0	0	C	C	C	C
Delaminations	C	B	A	C	B	A	B
Fiber failure	C	B	B	0	C	A	A
Kissing bond	0	B	A	B	A	A	B
Local impact damage	B	C	B	B	B	A	B
Matrix cracking	A	C	B	C	C	B	C
Moisture ingress	C	C	B	A	A	B	A
Ply waviness	B	0	0	0	C	C	C
Pit (or pinhole)	A	0	C	0	0	0	C
Porosity	B	0	C	C	B	0	C
Resin rich area	0	C	B	B	A	0	C
Resin starved area	0	C	B	B	A	0	C
Skin-to-core disbond	0	C	B	B	A	A	B
Surface cracking	A	0	0	C	C	C	C
Thermal damage	B	C	B	B	B	C	B
Voids	C	C	B	C	B	C	C

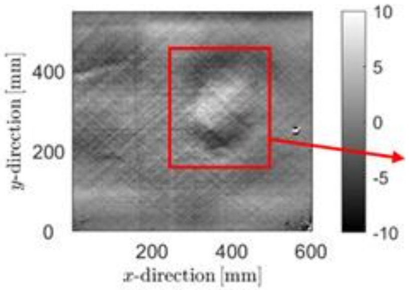
Ibrahim, M. E. "Nondestructive testing and structural health monitoring of marine composite structures." *Marine Applications of Advanced Fibre-Reinforced Composites*. Woodhead Publishing, 2016. 147-183.

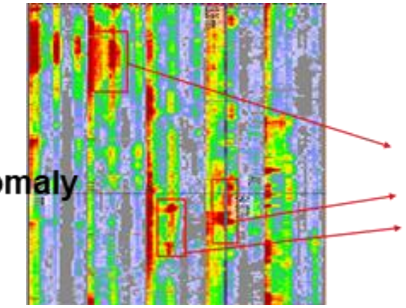
INSPECTION TECHNQIUES FOR MARINE COMPOSITE CONSTRUCTION AND NDE 2012
http://www.shipstructure.org/pdf/463.pdf

SSC Project 1464 Test Panel Program
http://www.shipstructure.org/pdf/463.pdf

Literature / past

Shearography	Ultrasonic testing	Thermography
Non-contact, full-field	Contact, scanning	Non-contact, full-field
Speckle interferometry	Ultrasonic waves	Thermal emission





Defects	Visual	Ultrasonics		Thermography		Laser Shearogrphy	
		A-Scan	C-Scan	Steady	Pulsed	Vacuum	Heat
Adhesive bond failure	0	A	A	B	A	A	B
Air bubble	C	C	C	C	B	C	B
Blister	A	C	C	C	B	C	C
Core crushing	C	B	B	B	A	B	C
Core shear failure	0	C	C	B	A	A	B
Crazing	A	0	0	C	C	C	C
Delaminations	C	B	A	C	B	A	B
Fiber failure	C	B	B	0	C	A	A
Kissing bond	0	B	A	B	A	A	B
Local impact damage	B	C	B	B	B	A	B
Matrix cracking	A	C	B	C	C	B	C
Moisture ingress	C	C	B	A	A	B	A
Ply waviness	B	0	0	0	C	C	C
Pit (or pinhole)	A	0	C	0	0	0	C
Porosity	B	0	C	C	B	0	C
Resin rich area	0	C	B	B	A	0	C
Resin starved area	0	C	B	B	A	0	C
Skin-to-core disbond	0	C	B	B	A	A	B
Surface cracking	A	0	0	C	C	C	C
Thermal damage	B	C	B	B	B	C	B
Voids	C	C	B	C	B	C	C

- To identify techniques capable of:
  - Reliable defect detection
  - High automation capabilities

Ibrahim, M. E. "Nondestructive testing and structural health monitoring of marine composite structures." *Marine Applications of Advanced Fibre-Reinforced Composites*. Woodhead Publishing, 2016. 147-183.

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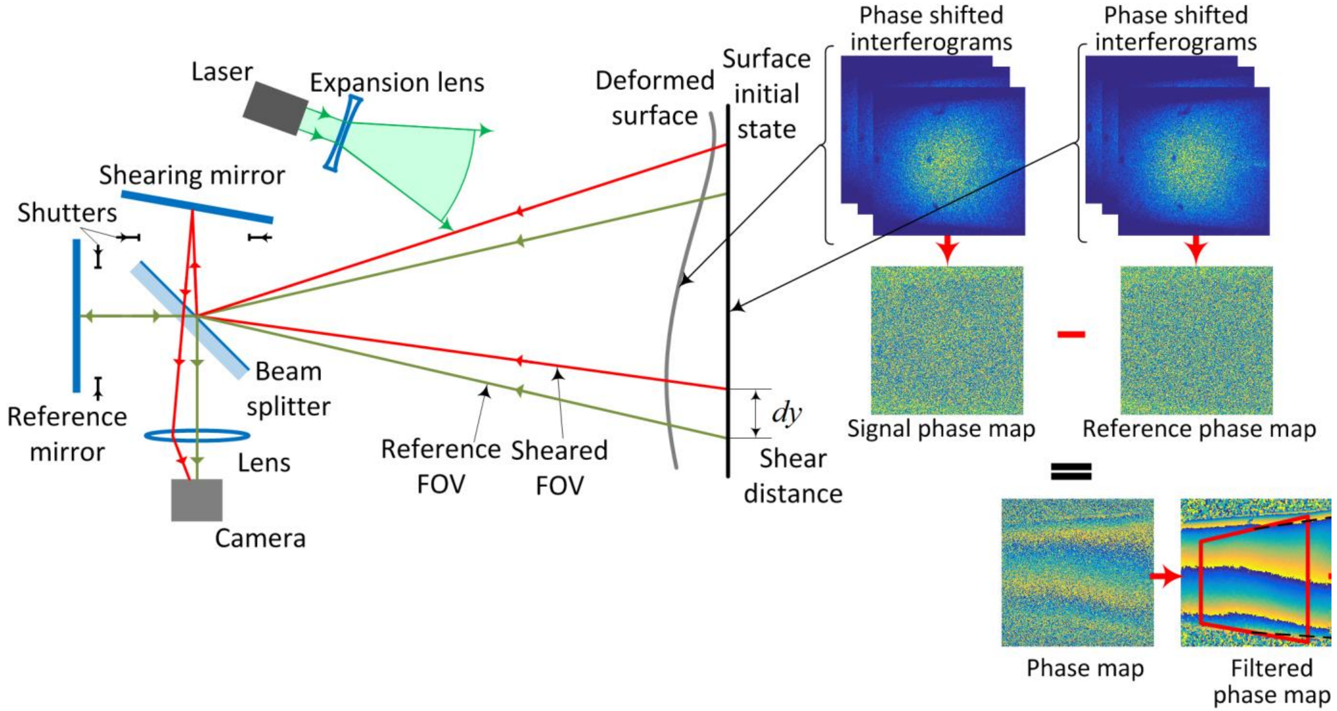
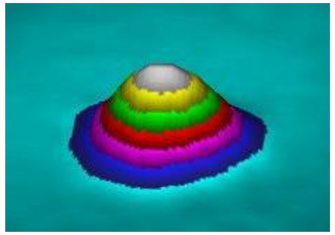
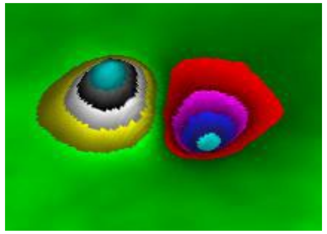
Shearography: speckle pattern shearing interferometry



- Shearography directly measures the surface displacement gradients



- Shape (interferometry)



- Gradient (shearography)

Andrei G. Anisimov, Mariya G. Serikova, and Roger M. Groves, "3D shape shearography technique for surface strain measurement of free-form objects," Appl. Opt. 58, 498-508 (2019)`

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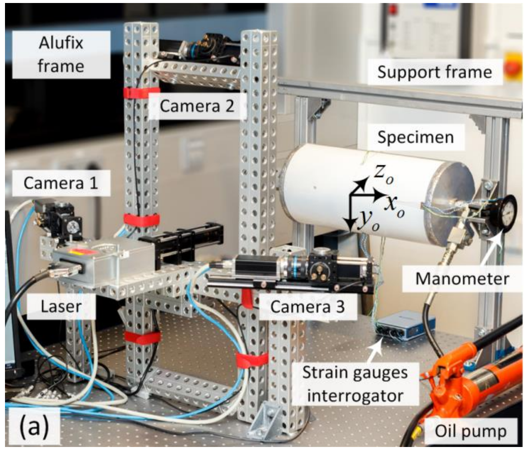
(a) (b) (c) (d)



Francis, D., Tatam, R.P., Groves, R.M., "Shearography technology and applications: a review," Meas. Sci. Technol. 21, 102001, 29 (2010).

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Panel 7C: laminate with Teflon inserts

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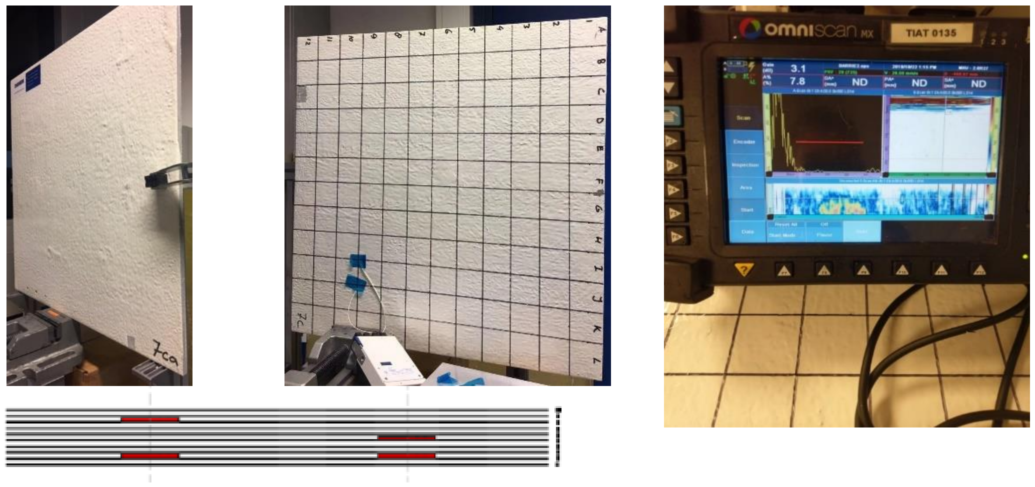
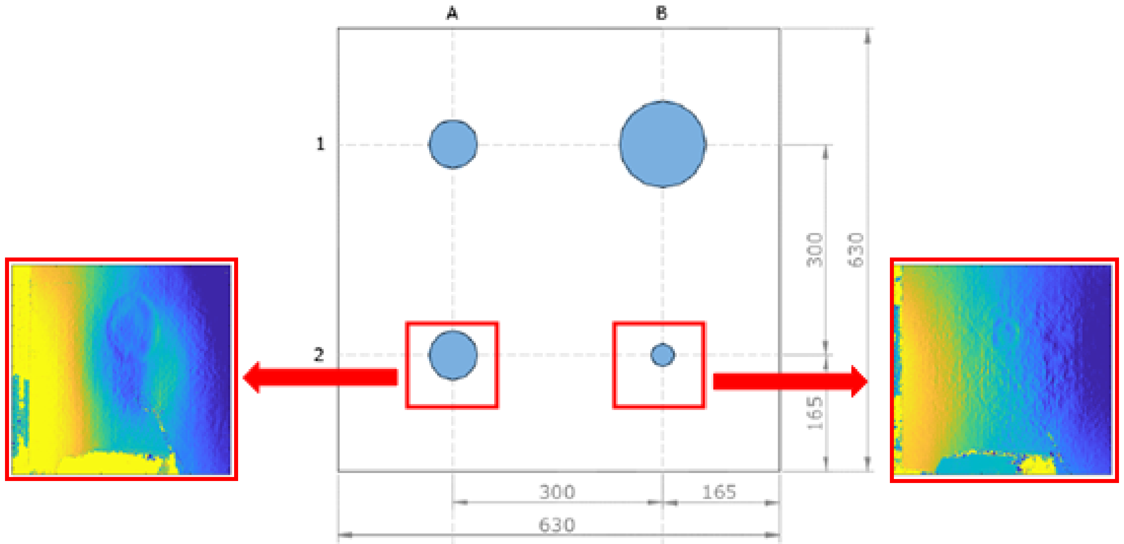
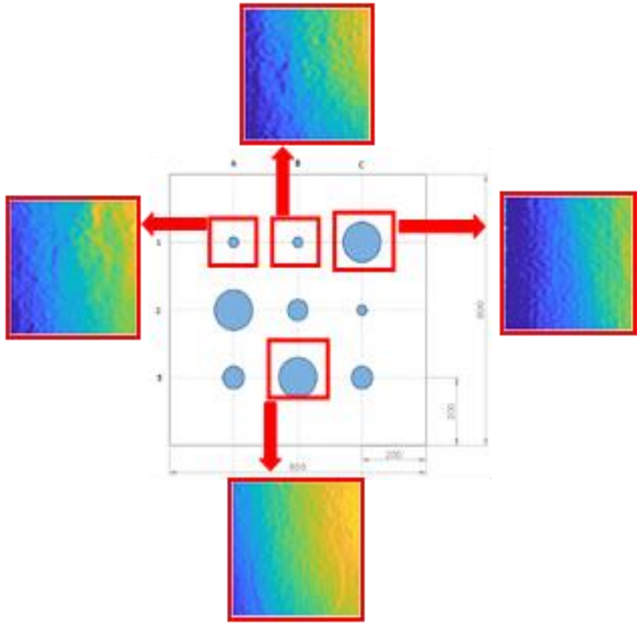


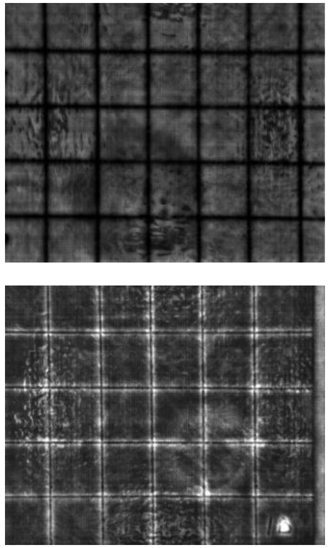


Shearography: top layers

Panel 1B: foam core with Teflon inserts



Shearography: top skin-core



Lock-in thermography: top skin-core

FEM-assisted shearography

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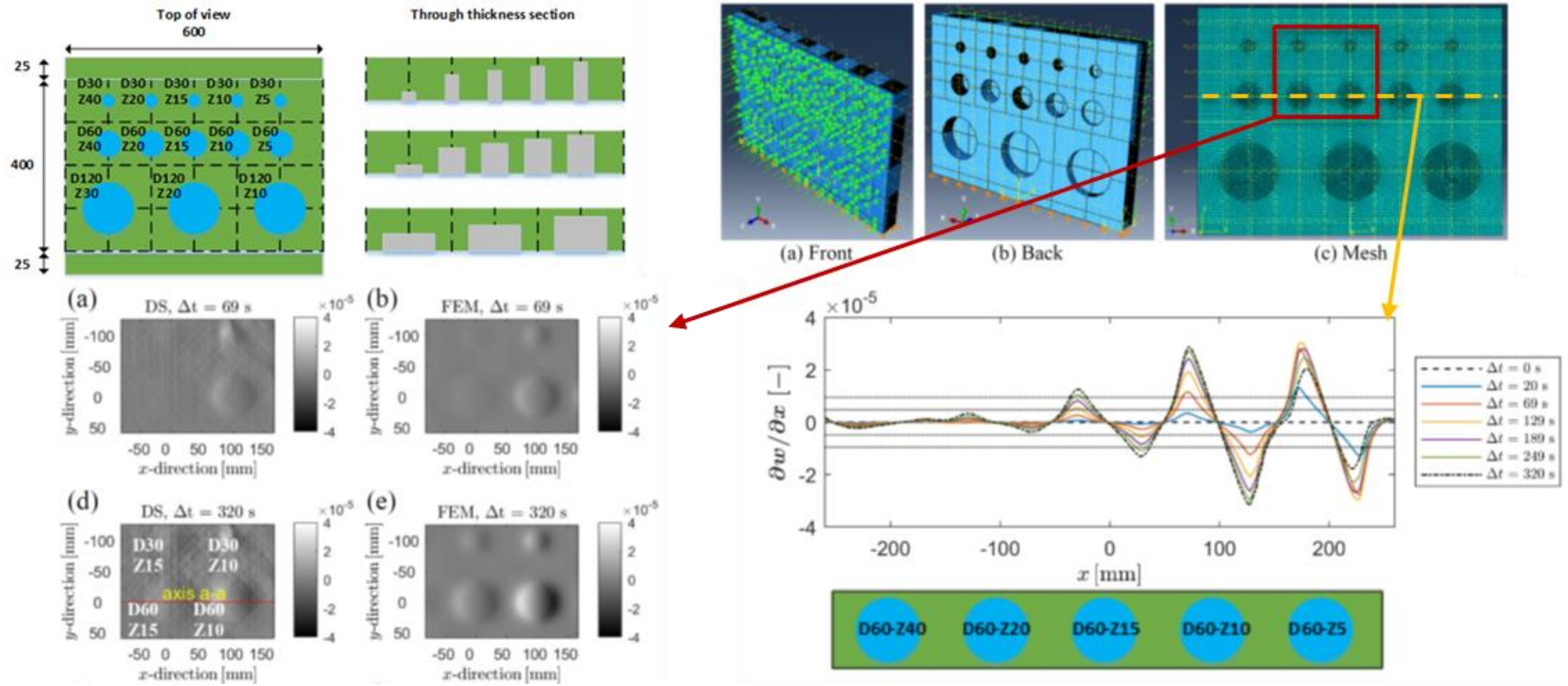
- To detect at depth of 20-25 mm



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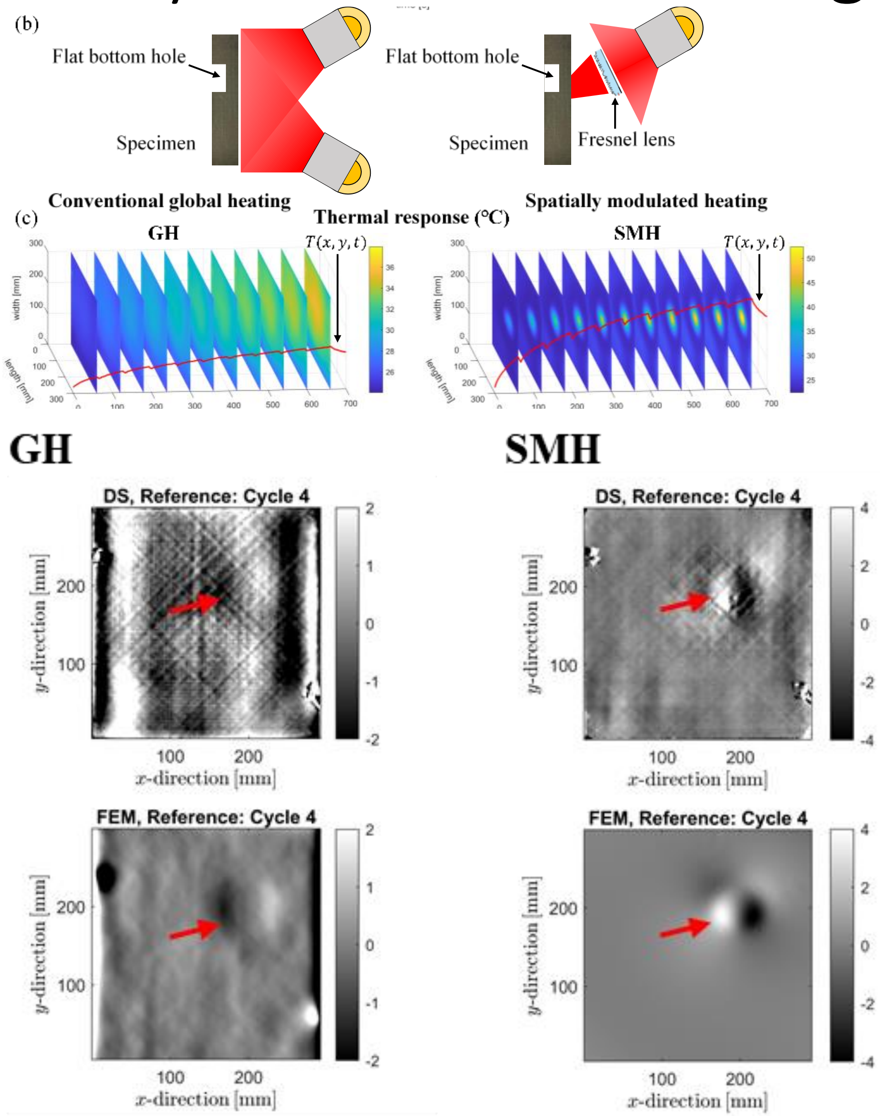
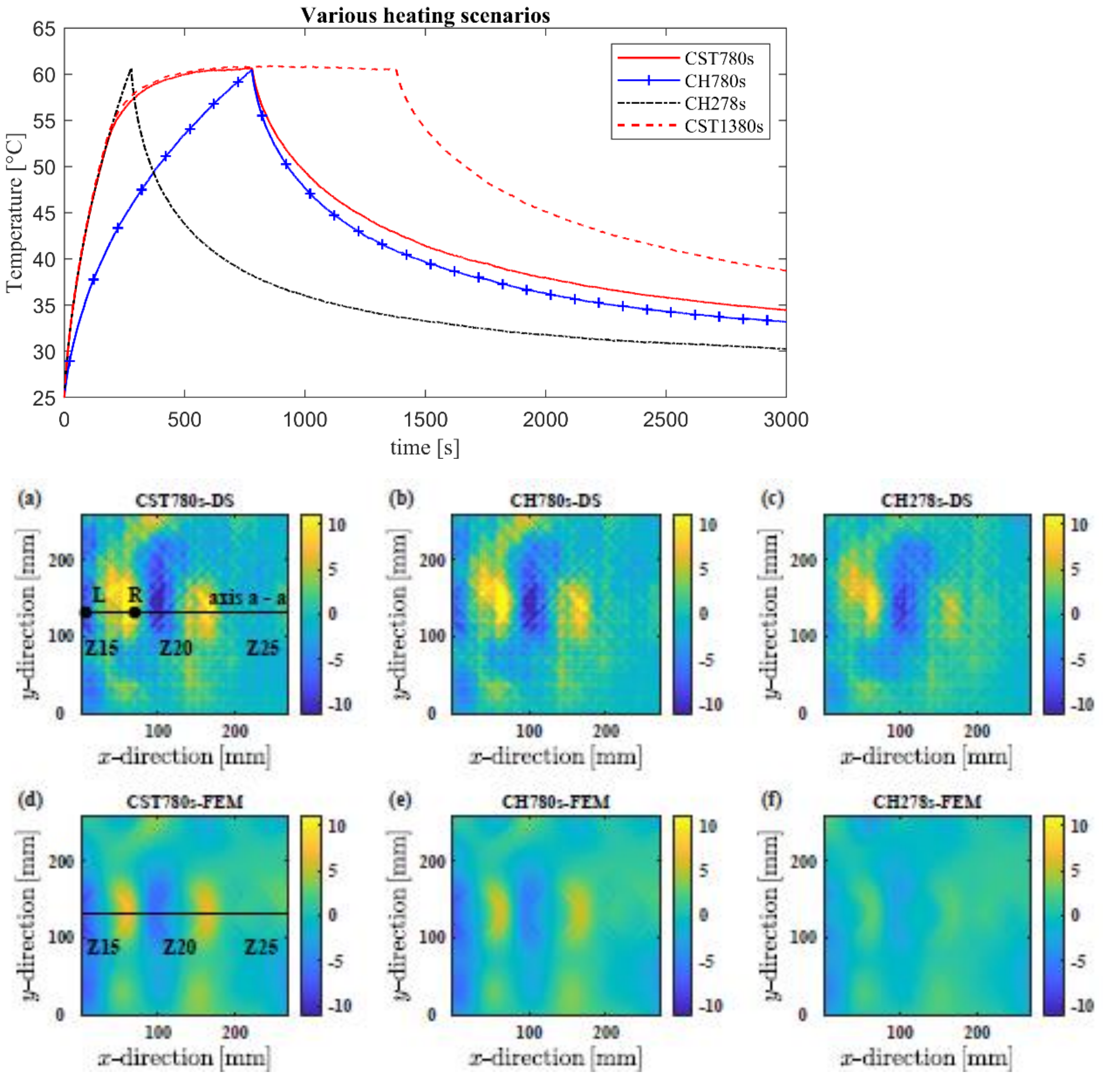
Tao, Nan, Andrei G. Anisimov, and Roger M. Groves. "Shearography non-destructive testing of thick GFRP laminates: Numerical and experimental study on defect detection with thermal loading." *Composite Structures* 282 (2022): 115008.

Spatially modulated heating



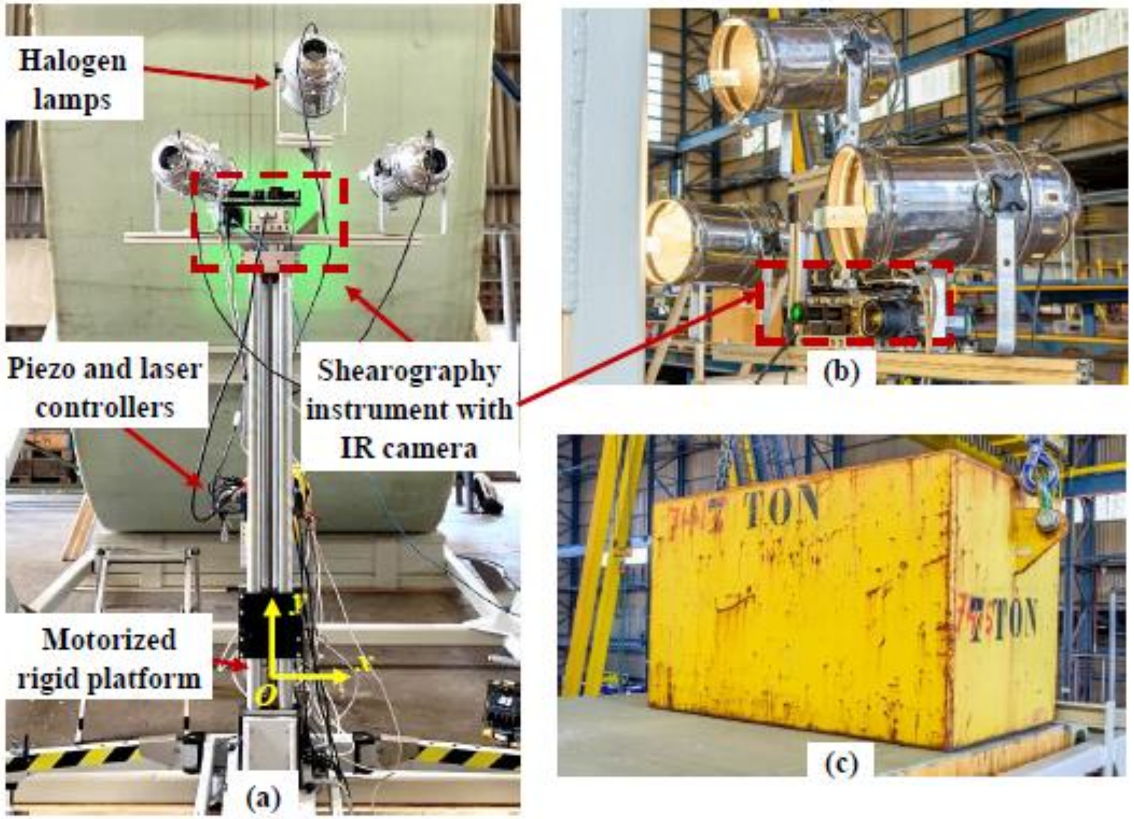
Temporally modulated heating



Tao, Nan, Andrei G. Anisimov, and Roger M. Groves. "FEM-assisted shearography with spatially modulated heating for non-destructive testing of thick composites with deep defects." Composite Structures 297 (2022): 115980.

Tao, Nan, Andrei G. Anisimov, and Roger M. Groves. "Towards safe shearography inspection of thick composites with controlled surface temperature heating." *NDT & E International* 139 (2023): 102907.

RAMSSES inspection at Damen



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Tao, Nan, Andrei G. Anisimov, and Roger M. Groves. "Shearography non-destructive testing of a composite ship hull section subjected to multiple impacts." Proceedings of the 20th European Conference on Composite Materials, 2022

RAMSSES inspection at Damen

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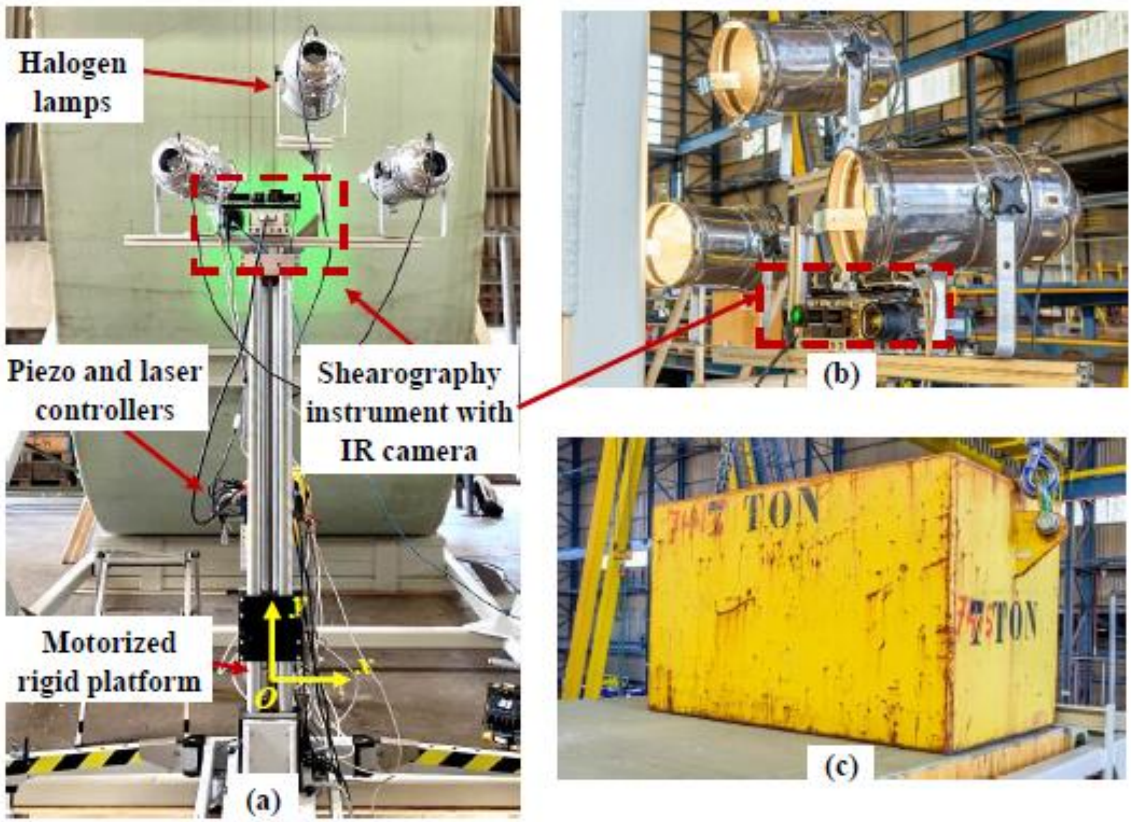
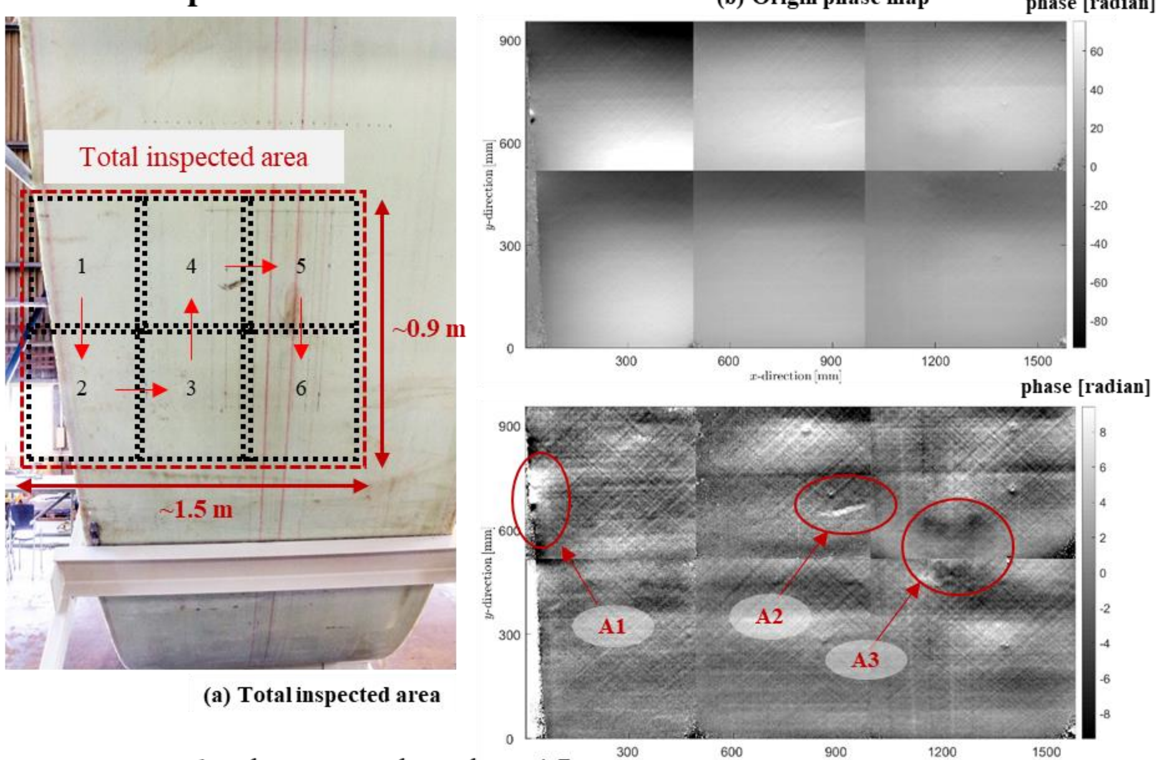
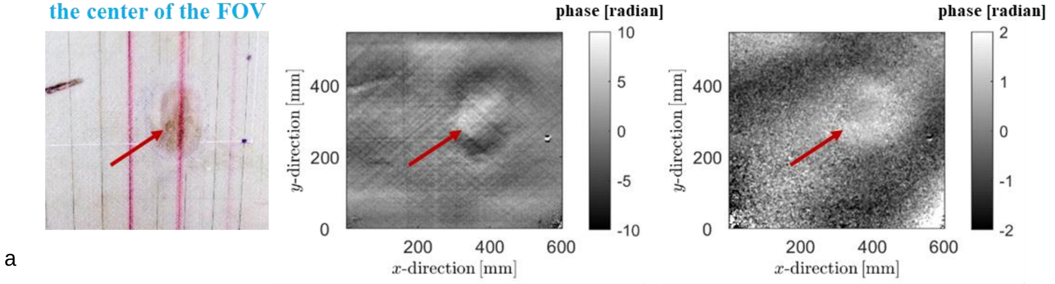




1 rad corresponds to about 4.7 $\mu\varepsilon$



(a) Inspection area (with multiple impacts)
(b) Compensated phase map (with thermal loading)
(c) Compensated phase map (with mechanical loading)

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WP4 NDI of Thick-Walled Composites

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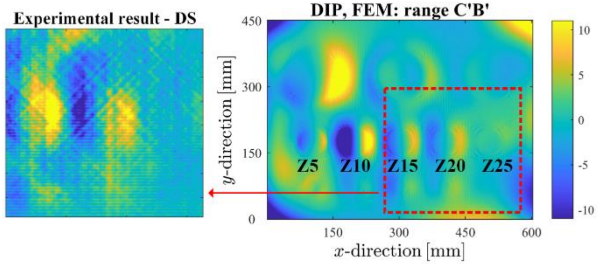
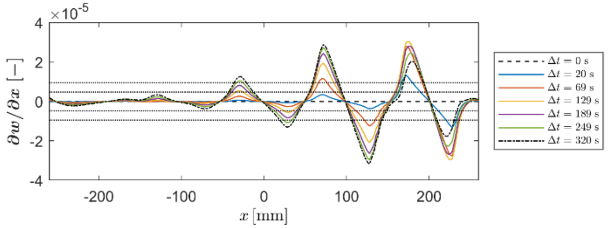
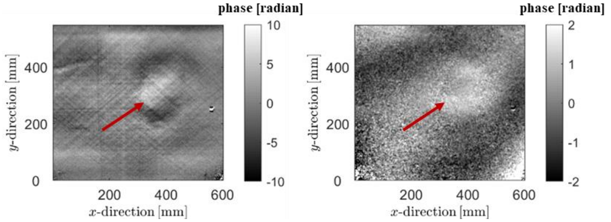
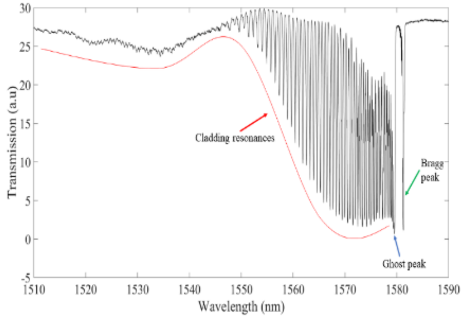
- Benchmarking of NDT techniques on real samples/structures
- Optical fibre sensors (FBG) for simultaneous strain, temperature and refractive index monitoring
  - New sensor concept
    - Picked up by ESA and 2 Horizon projects
- Shearography
  - FEM-assisted inspection for deep defects at 20-25 mm depths
- Joint inspection of RAMSSES demonstrator
- Joint work and collaboration with Damen, TiaT
  - HISTRATE COST Action on high strain rate and impact
- 2 PhDs, 10+ papers published









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