MATERA+
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FAILURE AND DAMAGE IN CFRP TORSION TUBES

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- **Initial assessment of CFRP tubes**
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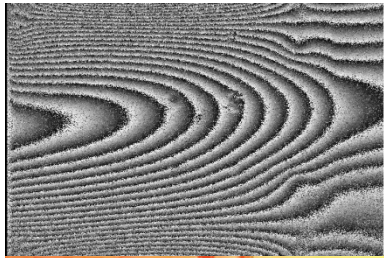
- **Conclusions and Outlook**

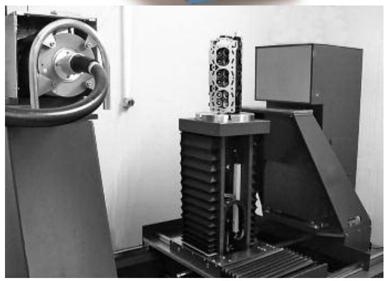
Motivation

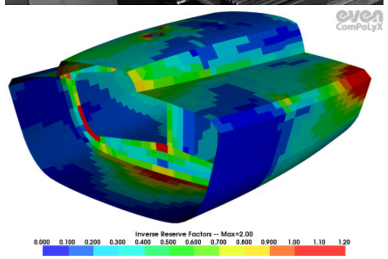
- Defects can cause catastrophic damage in CFRP structural elements.
- Size and type of defects must be known for a realistic FE simulation.
- Simulated debonding using e.g. Teflon insert is not representative of the actual situation.
- How can an actual but well-defined defect be created in a brittle material ?
- A test specimen has been designed with the aim to provoke a defined type of damage that can be grown under controlled conditions.

Methods of assessment

- **DSPI using thermal loading**
  - out-of-plane measurement
  - display of phase gradient
- **TSA using torsional loading**
  - 1 and 5 Hz, $M = M_0 + M_M \cos(\omega t)$
  - display of amplitude images
- **Computed Tomography CT**
  - 0.1 mm resolution
  - Cross-sections
- **FE Analysis**
  - Failure mode prediction
  - Simulation of flawed tube





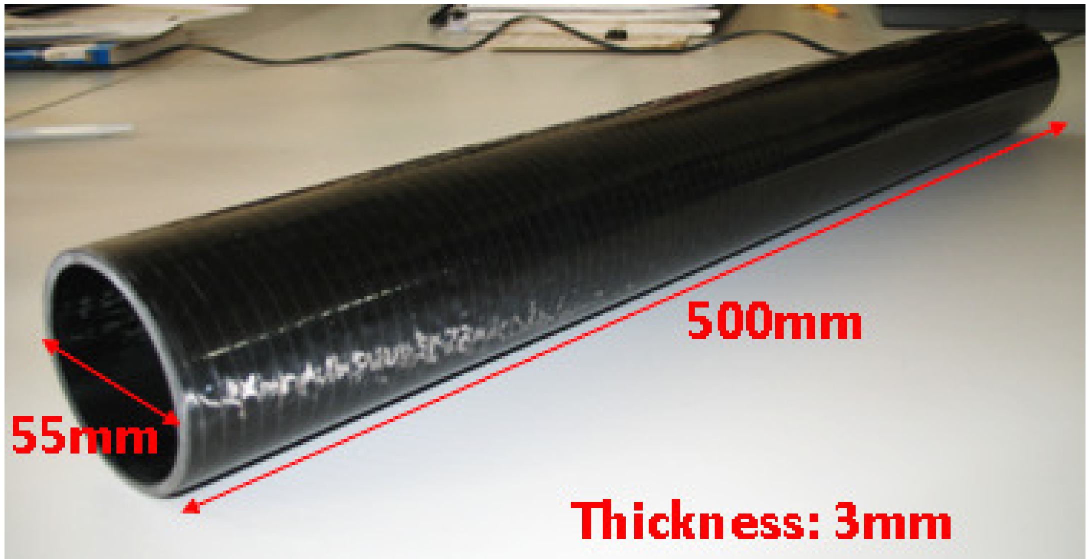


Torsion tube specimen

- **Material: Prepreg UTSXA 150 090**
  - Fibre Toho Tenax UTS50 F24 24k 1600tex, 150 gsm
  - Resin Huntsman XB 3515/Aradur 5021 BD, 37.5 wt%
- **Layup:**
  - 3 x 0°
  - 14 x – 45°
  - 6 x + 45°

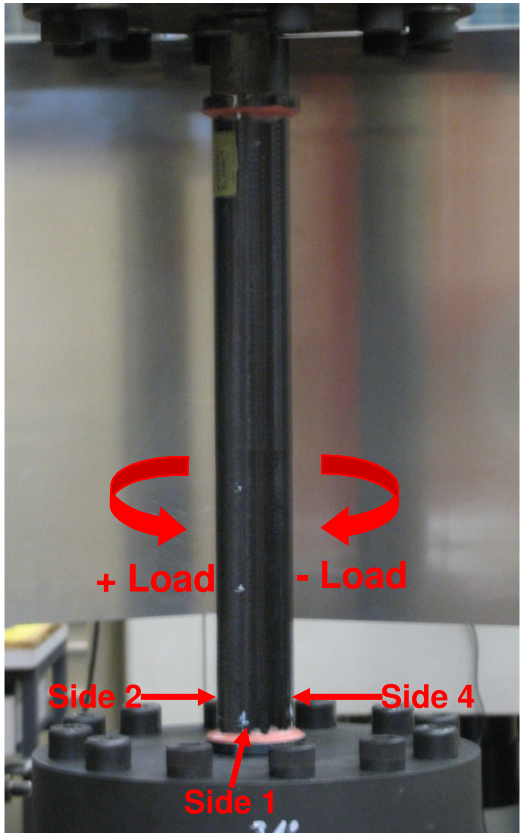
with or without peel-ply finish

- **Dimensions:**

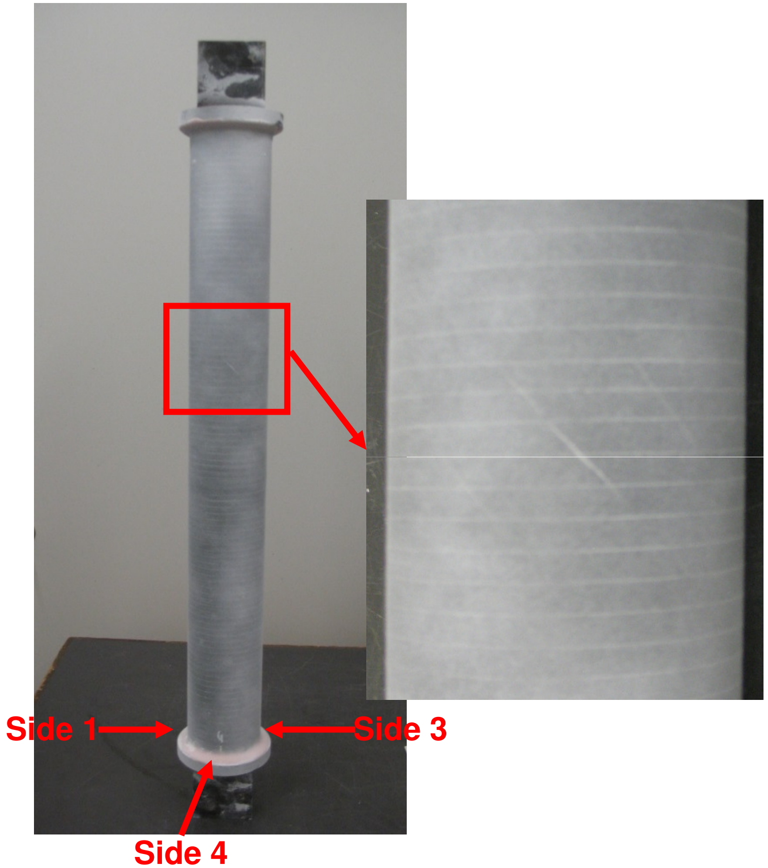


Torsional loading

- Inserts glued in
- Instron machine



Static load	Dynamic load
-350Nm	-250 ± 100 Nm
	-150 ± 100 Nm
	+250 ± 100 Nm
	+150 ± 100 Nm
-450Nm	-350 ± 100 Nm
	-250 ± 100 Nm
	+350 ± 100 Nm
	+250 ± 100 Nm
-550Nm	-450 ± 100 Nm
	-350 ± 100 Nm
	+450 ± 100 Nm
	+350 ± 100 Nm
-650Nm	-550 ± 100 Nm
	-450 ± 100 Nm
	+550 ± 100 Nm
-750Nm	-650 ± 100 Nm
	-550 ± 100 Nm
	+650 ± 100 Nm
	-250 ± 100 Nm
	+250 ± 100 Nm
-850Nm	-750 ± 100 Nm
	-250 ± 100 Nm

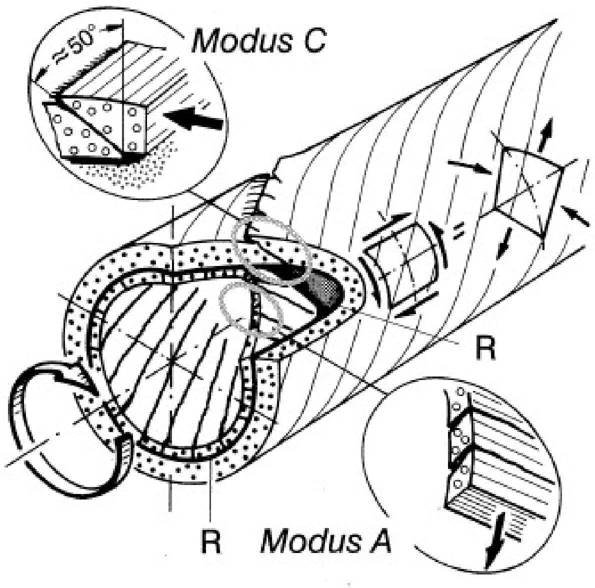


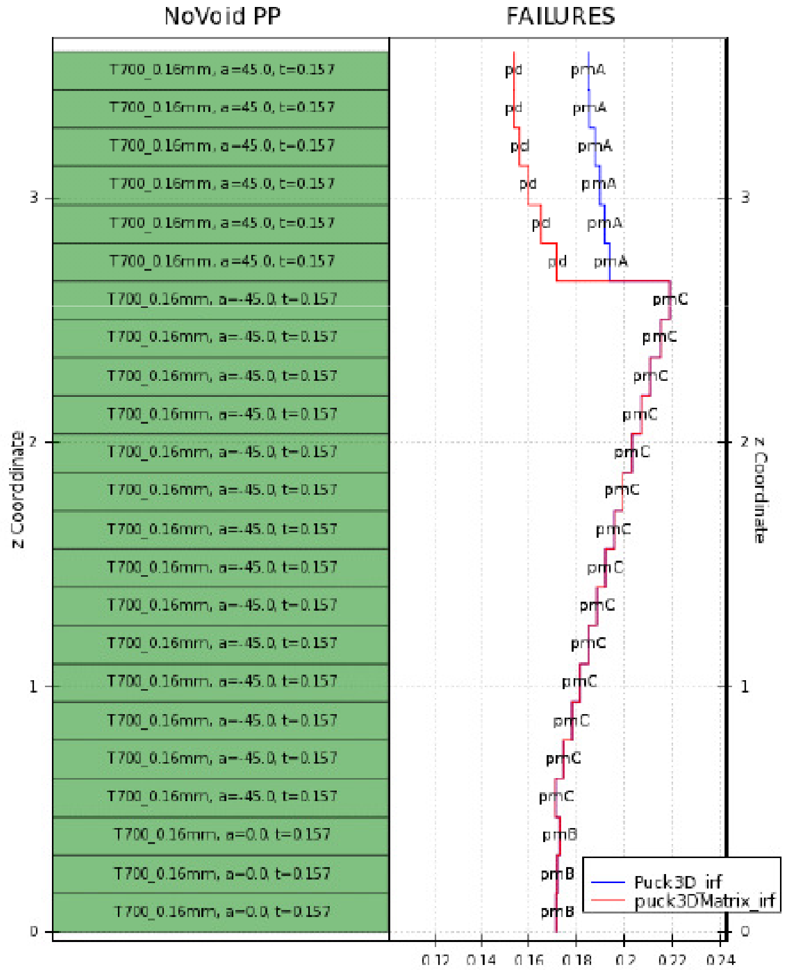
Crack Initiation

Failure modes

Perfect Tube

- Initial predicted failure/strength without voids:
  - Critical failure mode: Matrix failure due to compression (pmC)
  - Critical interface: -45/45
  - Limit load (first ply failure): 3'700 Nm



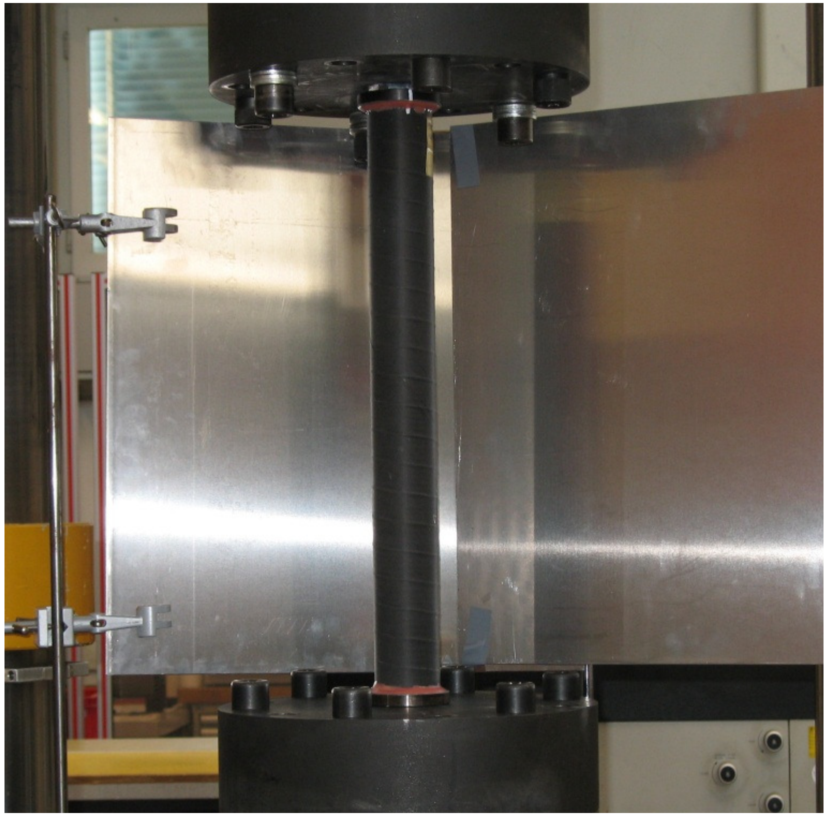


Overview of tests

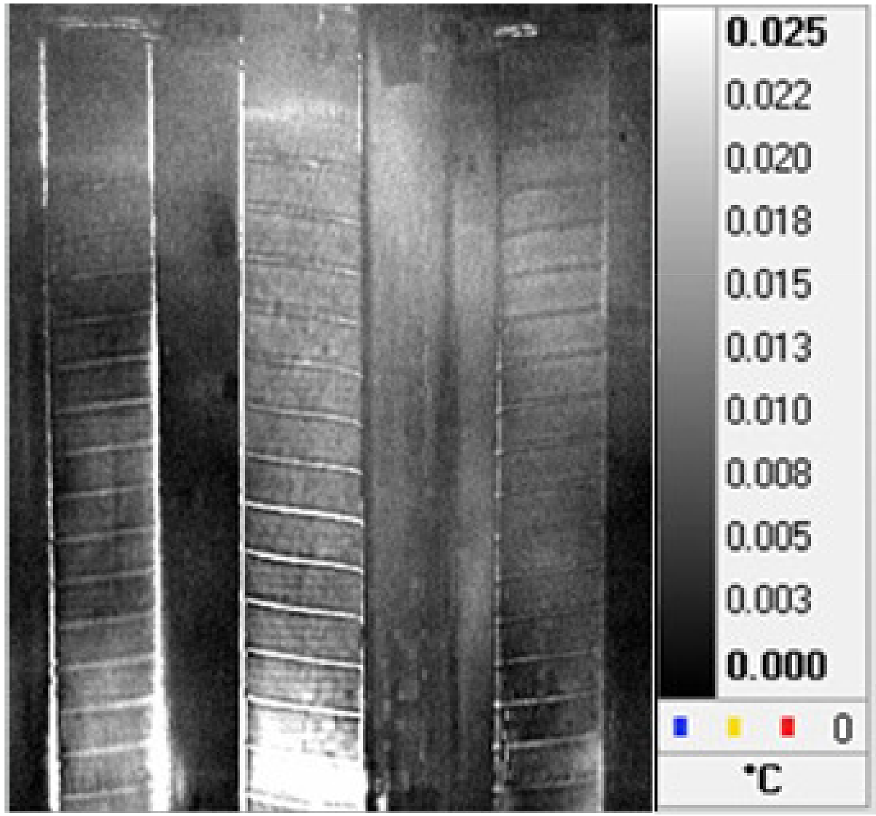
- **Specimen without peel-ply: B1**
- **Specimens with peel-ply: B2 – B6**
  - Specimen B3: taken to failure
  - Specimen B2: TSA and DSPI.
    Fatigued over approx. 80 000 cycles and taken to failure
  - Specimen B4 & B5: TSA and DSPI. Then taken to failure.
  - Specimen B1 & B6: X-ray CT scan
  - Specimen B1: damage growth monitored by TSA during torsion test.
    Measurement by DSPI pre/post damage growth.

Thermal Measurements

- Thermal Stress Analysis: Sinusoidal load of ± 125Nm
- High-speed video for detecting crack initiation



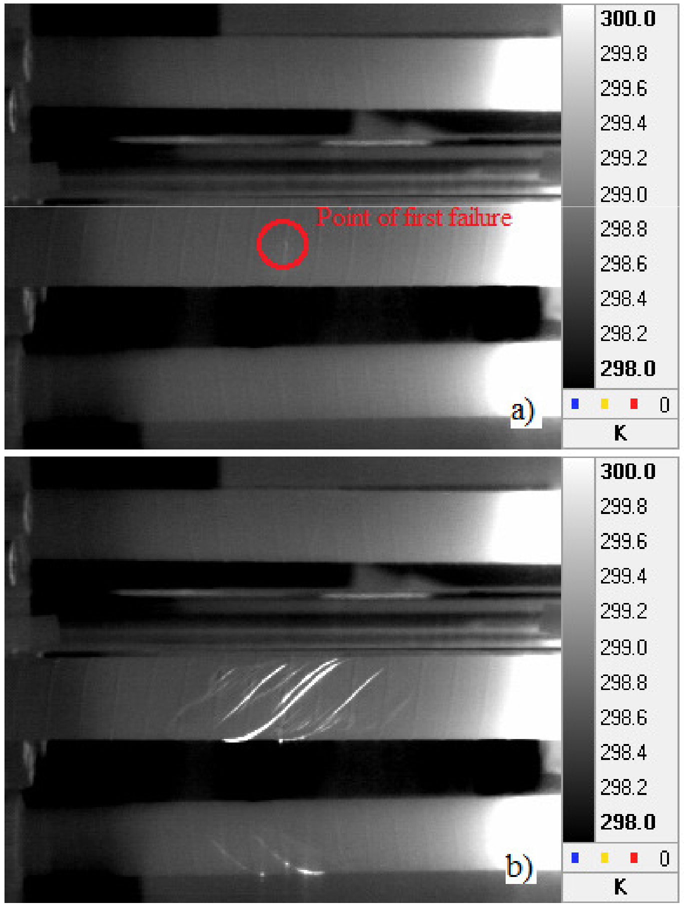
Set-up with mirrors for 360° monitoring

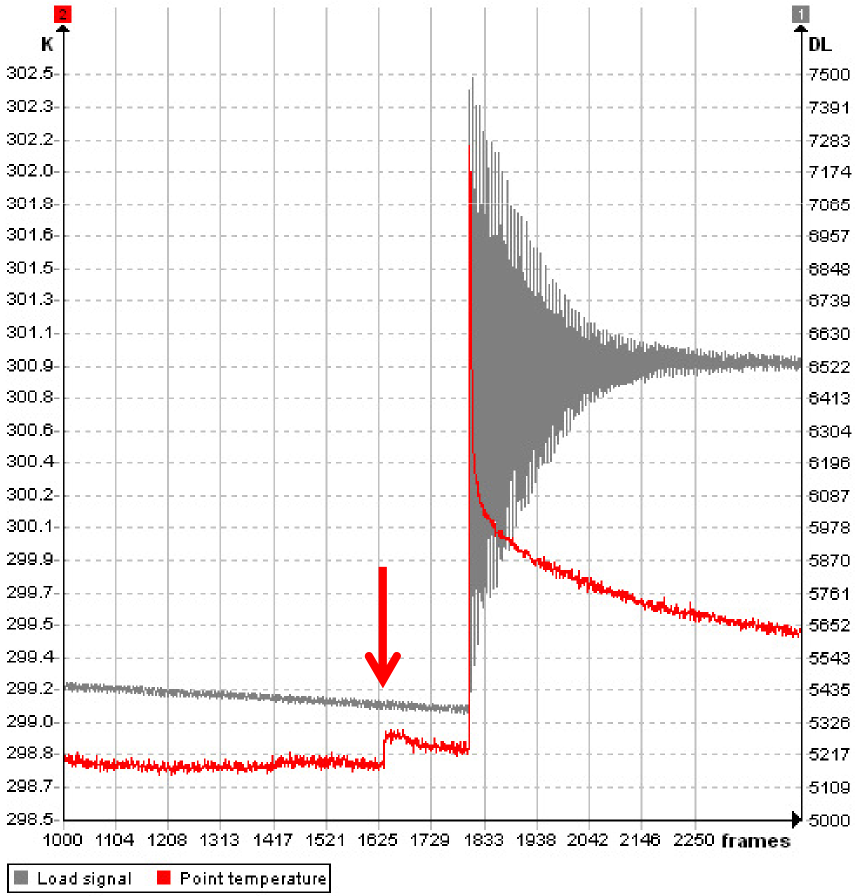


TSA amplitude image *ΔT*

Quasi-static failure on B3

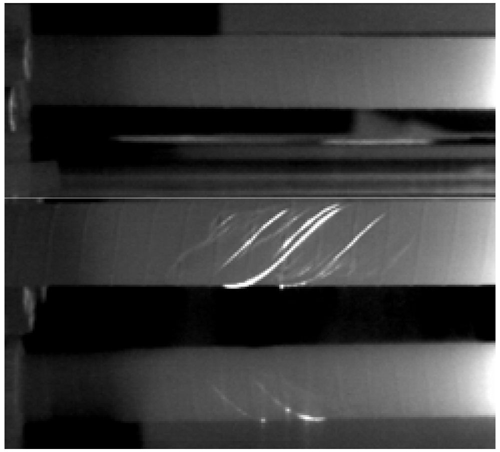
- Failure test applying a quasi static load of –2°/min
- IRT revealed failure initiation site at -1200 Nm
- Specimen failed at -1300 Nm (FEA prediction -3700 Nm)

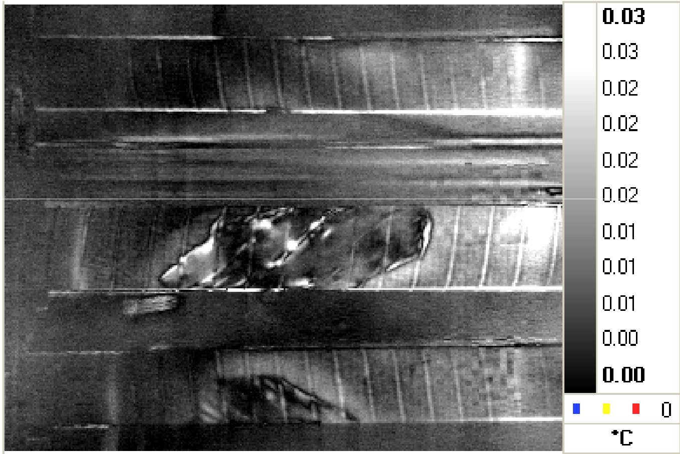




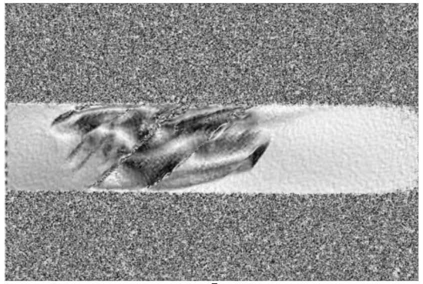
B3: post-failure comparison of TSA and DSPI

- TSA post failure at –150 ± 125 Nm at 1 Hz
- DSPI using thermal loading
- TSA and DSPI both show the extent of the delamination

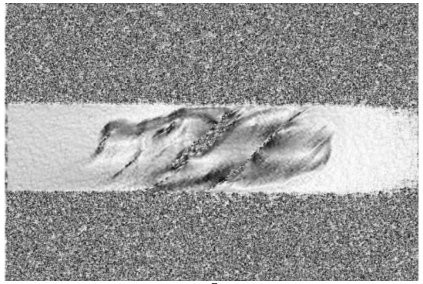




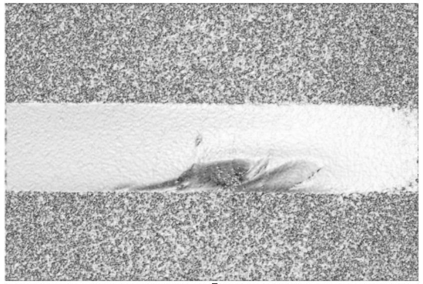
TSA amplitude image ΔT



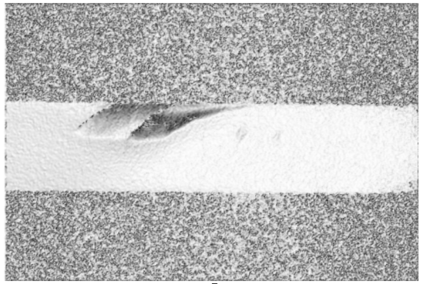
Side1



Side2



Side3

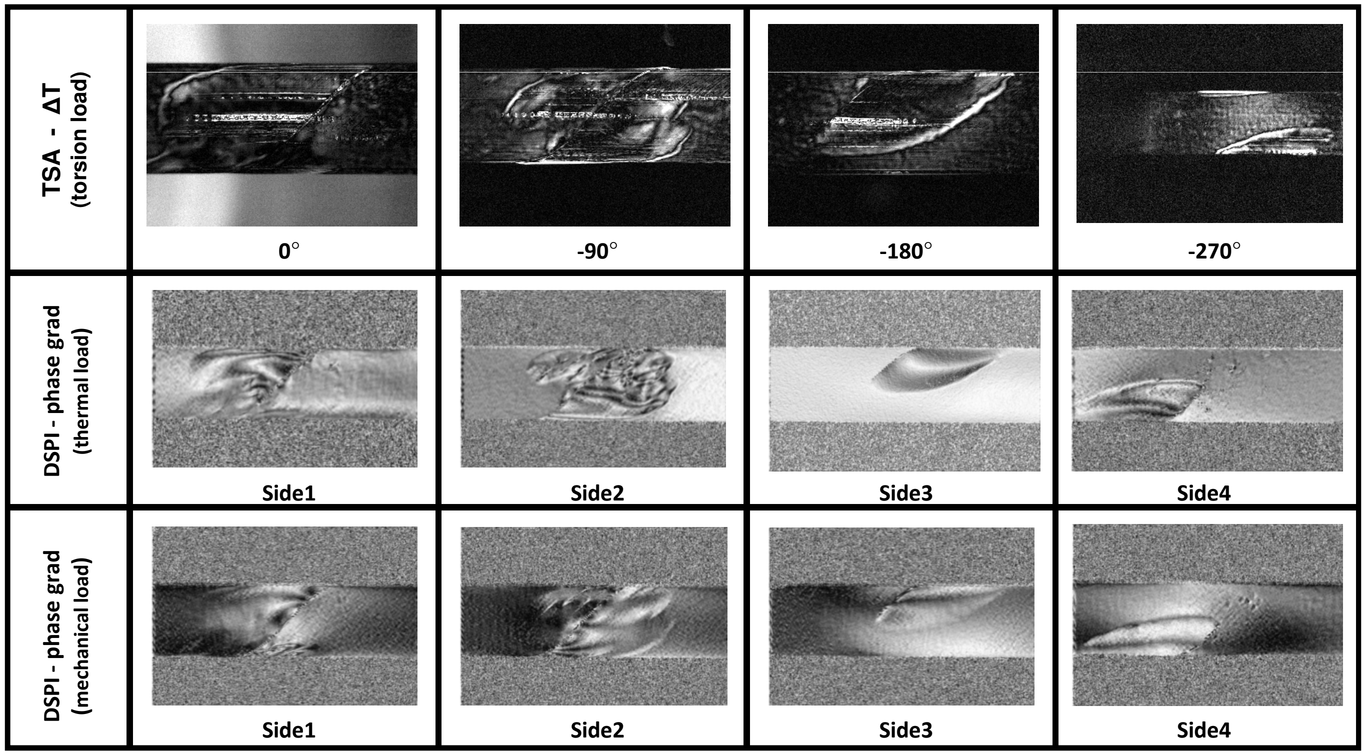


Side4

DSPI - phase gradient

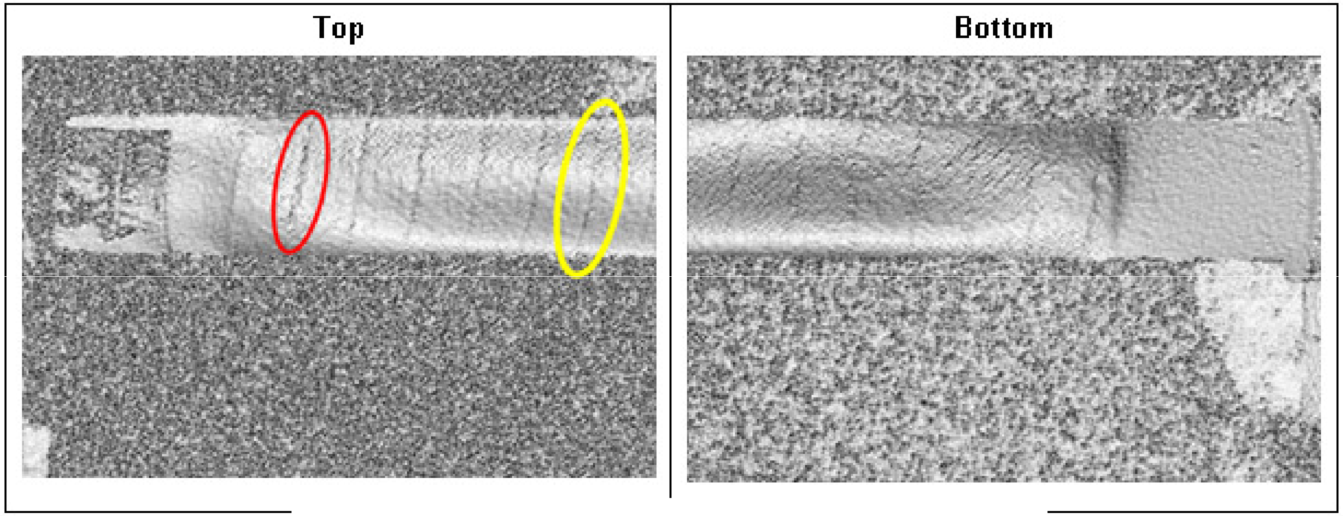
Results from TSA and DSPI

- TSA and DSPI correlate well identifying the extent of flaws
- TT and TSA can be used as a monitoring tool
- Failure load similar for all peel-ply specimens
- **Can the failure initiation site be predicted?**

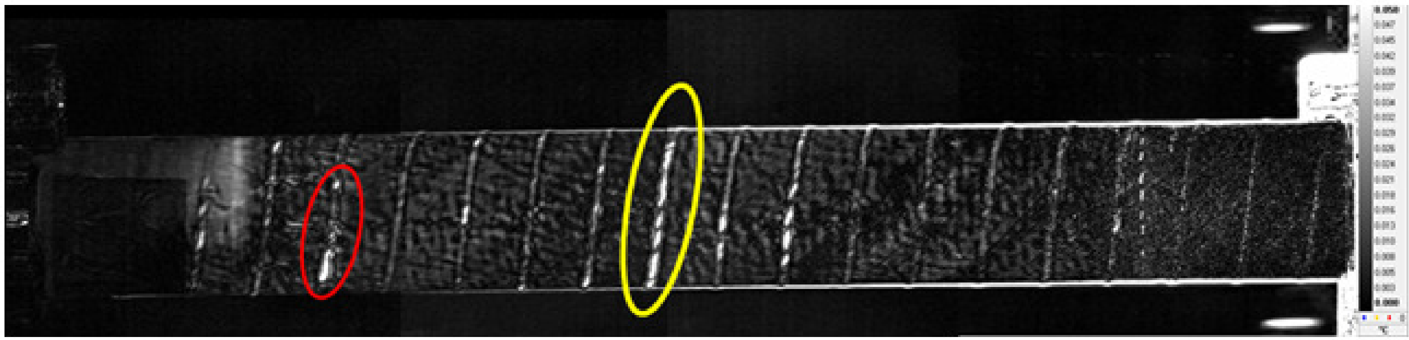


Damage initiation

- Several sites are potential failure initiators (B4 and B5)
- Only retrospective correlation, but not prospective identification



DSPI phase gradient

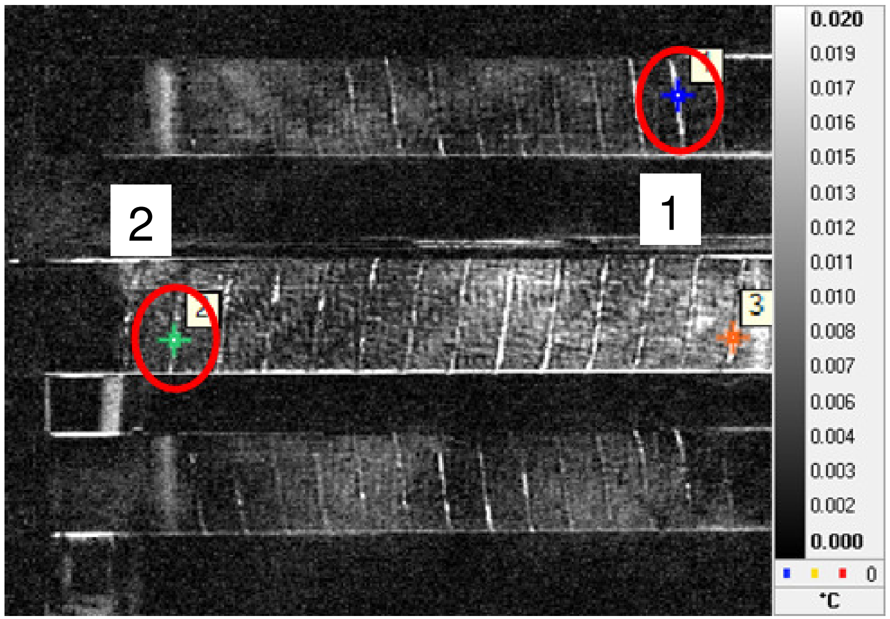


TSA ΔT stitched from 4 images

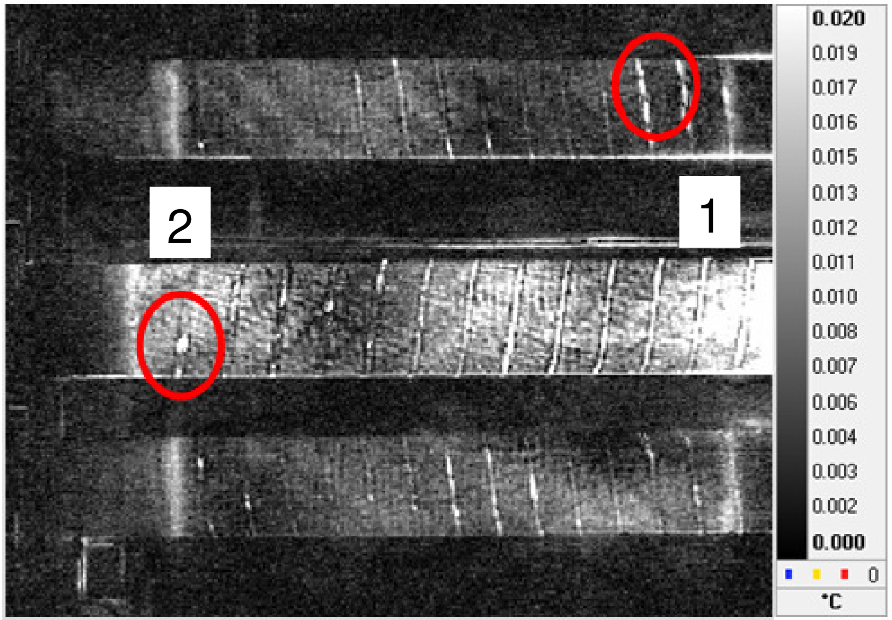
Damage growth

- No controlled growth of manufacturing defects with fatigue loading (peel-ply specimen B2)
- Further work to predict failure initiation with confidence: X-Ray CT on specimens B1 and B6 to identify presence, size and depth of voids/defects.

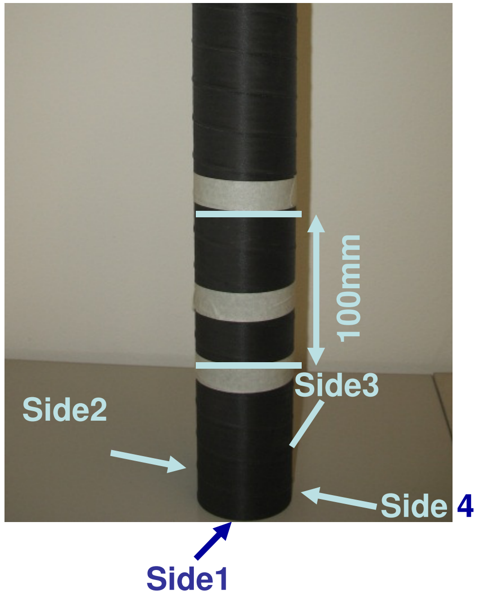
ΔT at 2000 cycles

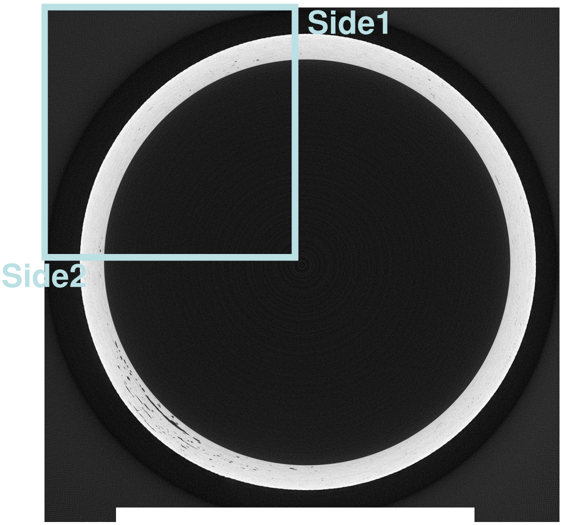


ΔT at 76000 cycles

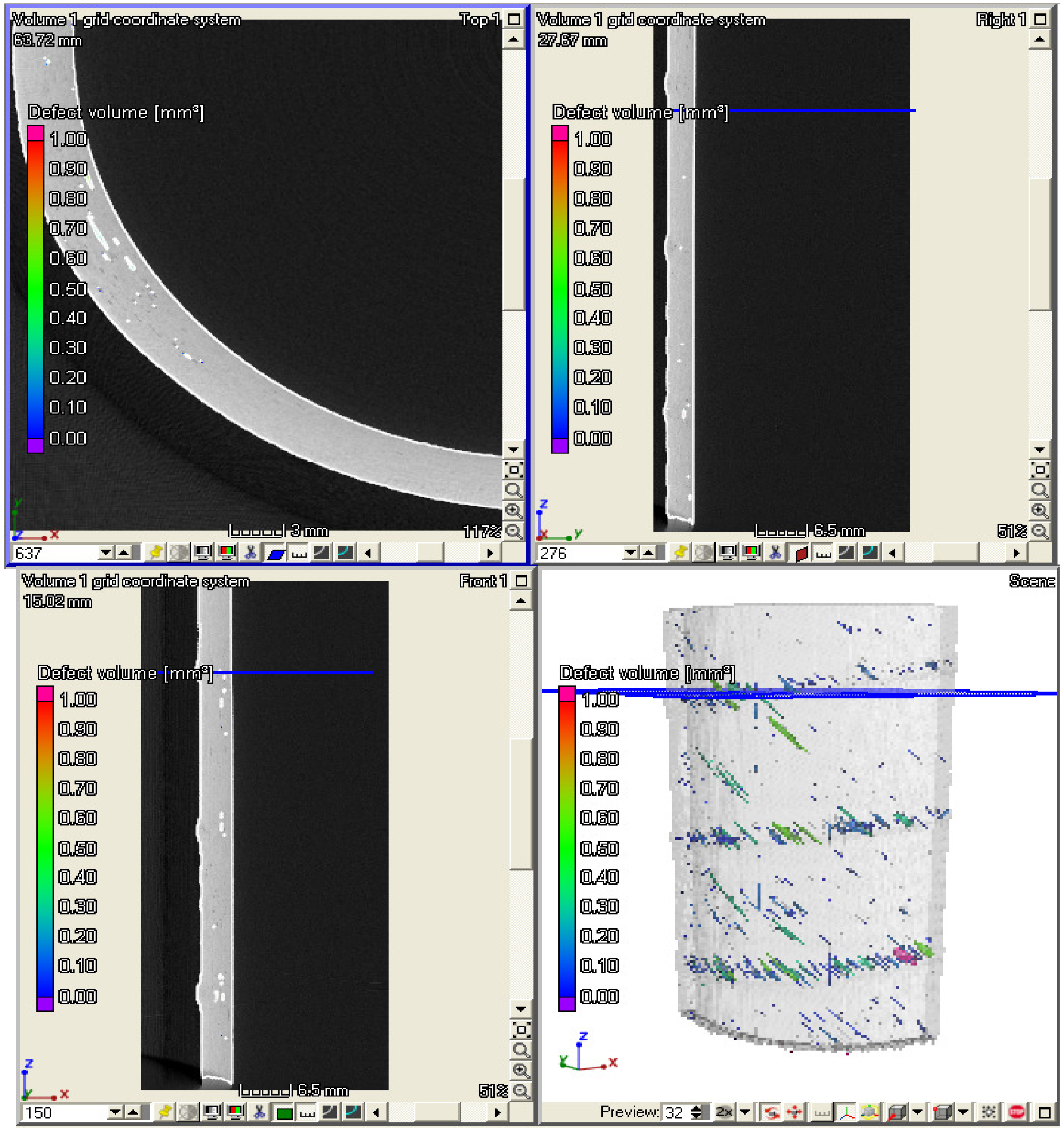


CT results for peel-ply specimen B6

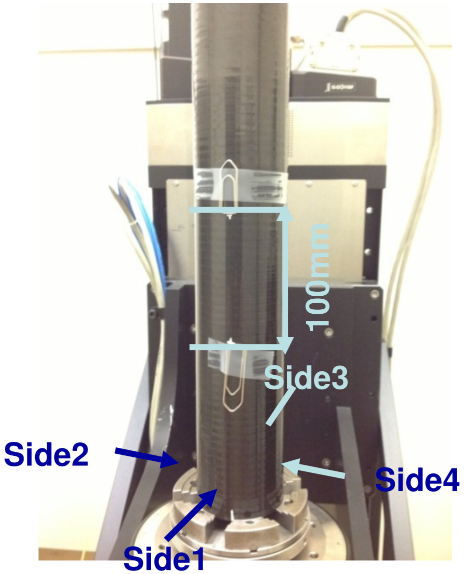


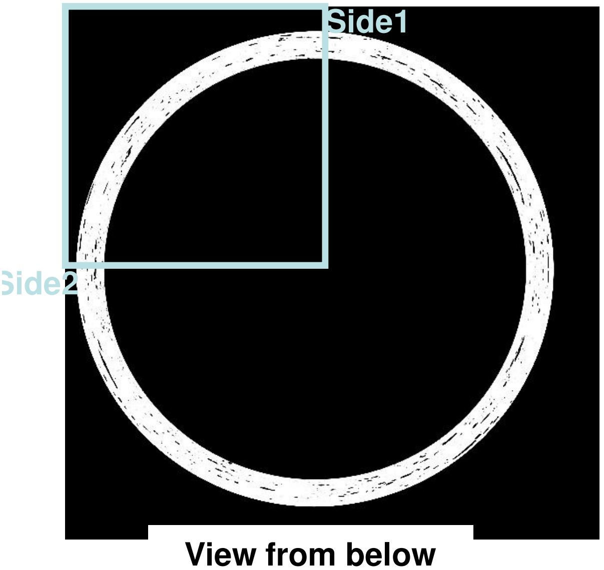


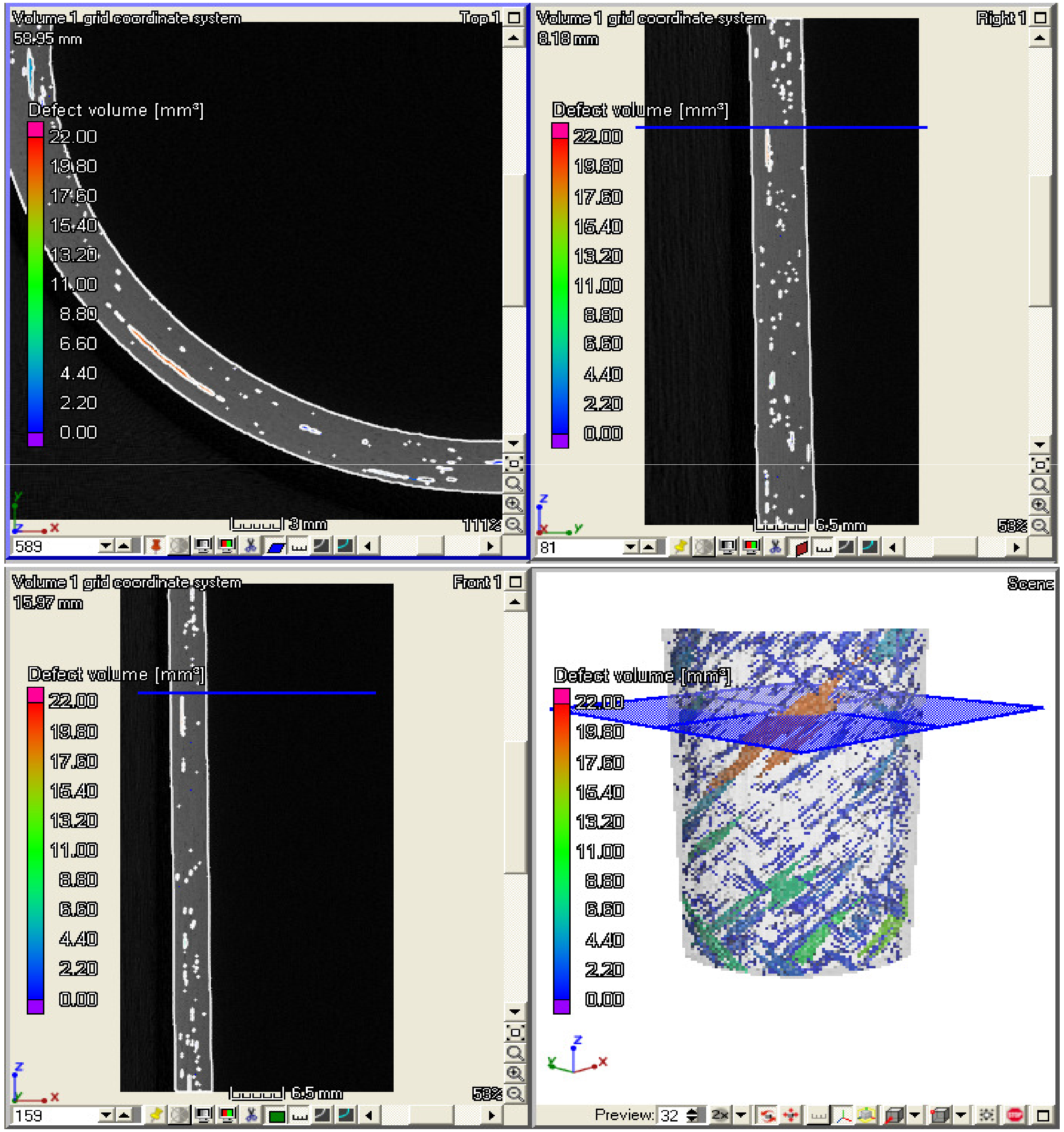
View from below



CT results for smooth specimen B1



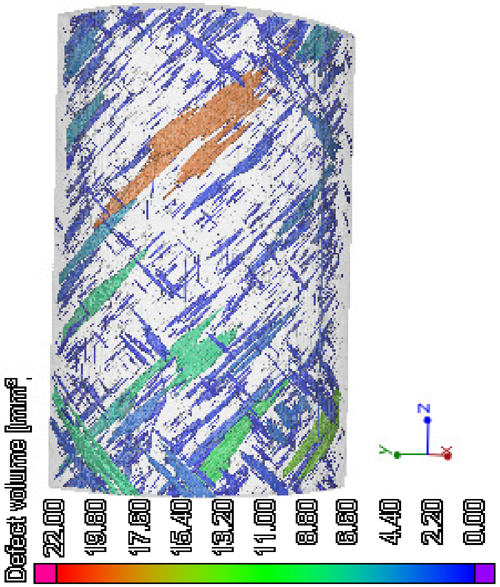


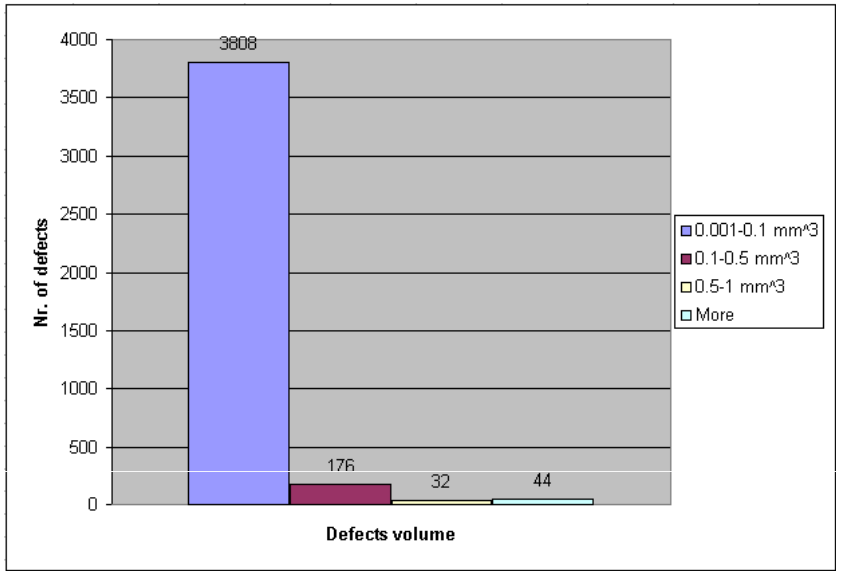


Comparison of defect volumes

Specimen B1

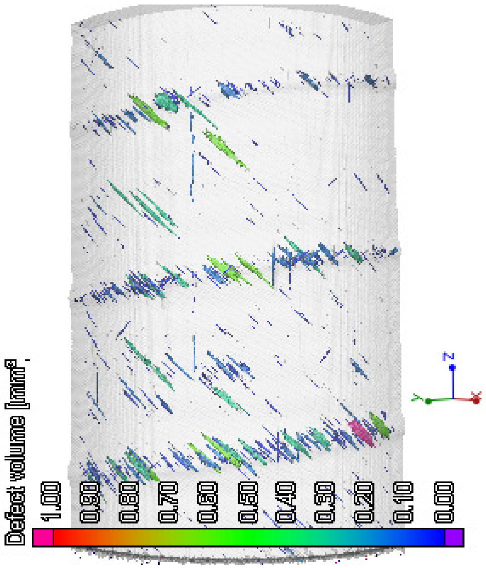
No peel-ply

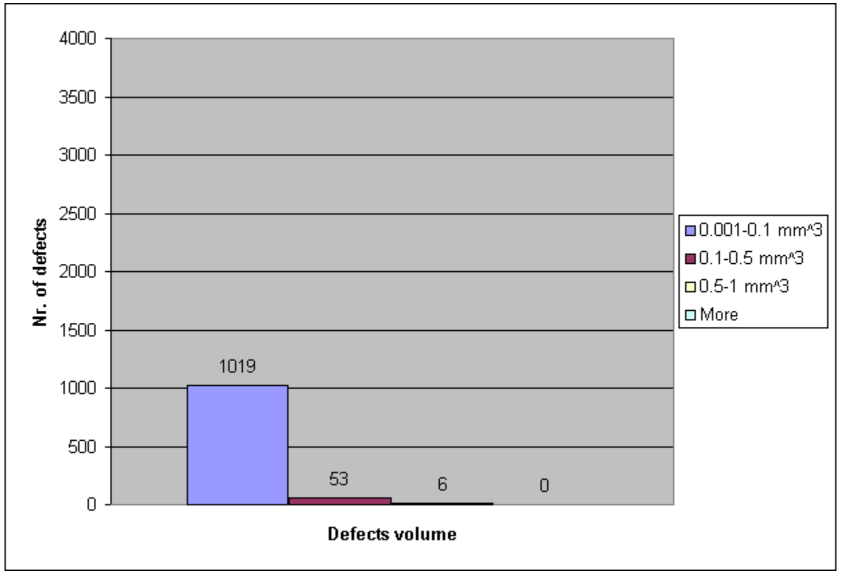




Specimen B6

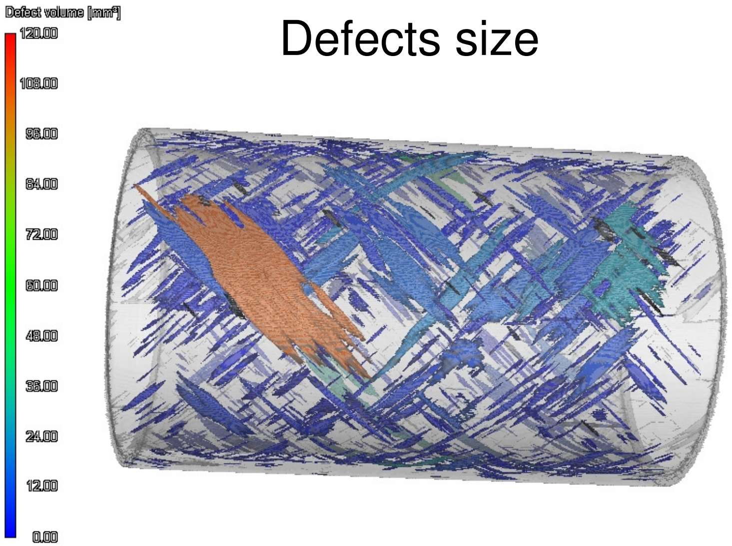
Peel-ply finish



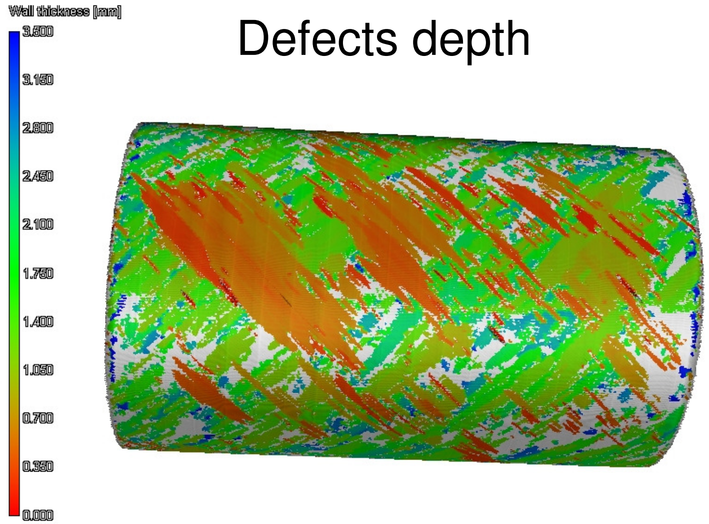


Comparison of CT and DSPI (B1 pre-test)

Defects size

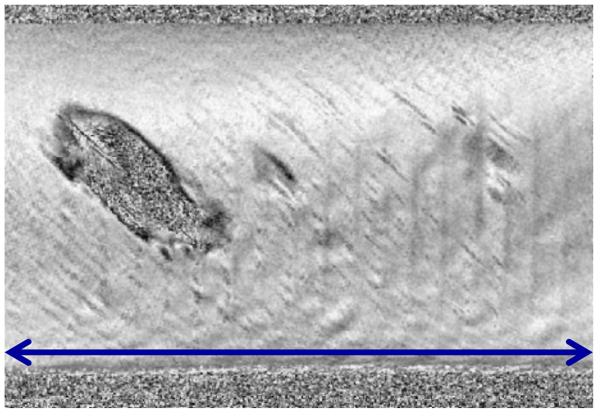


Defects depth



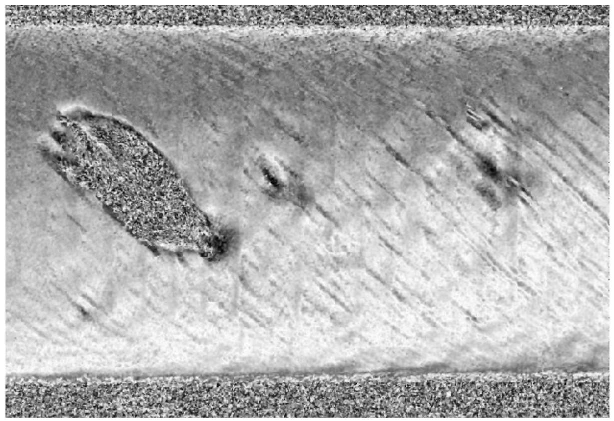
DSPI: halogen lamp from outside

Side 4

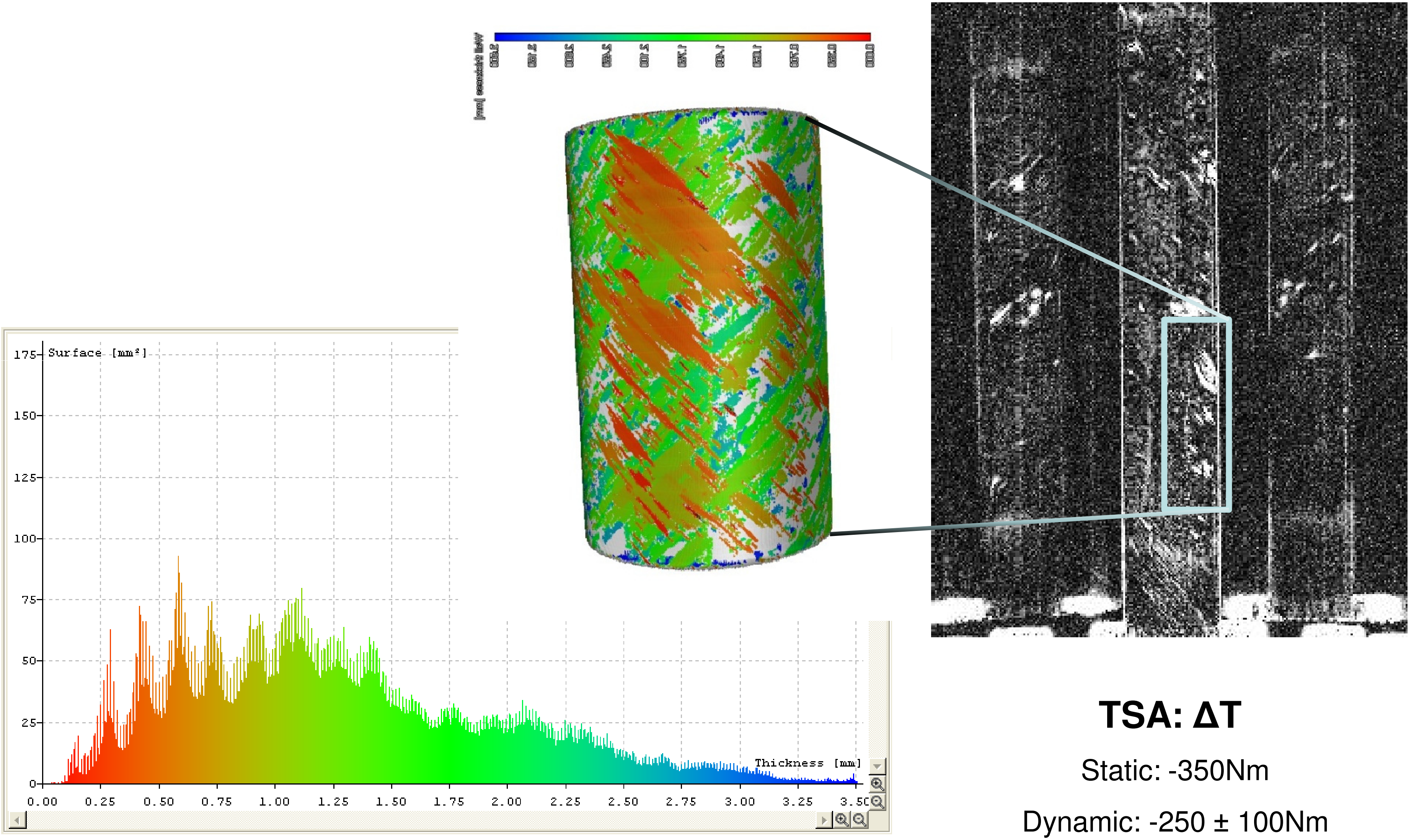


100 mm

Load: hot air from inside



Confirmation of flaws with TSA



TSA: ΔT

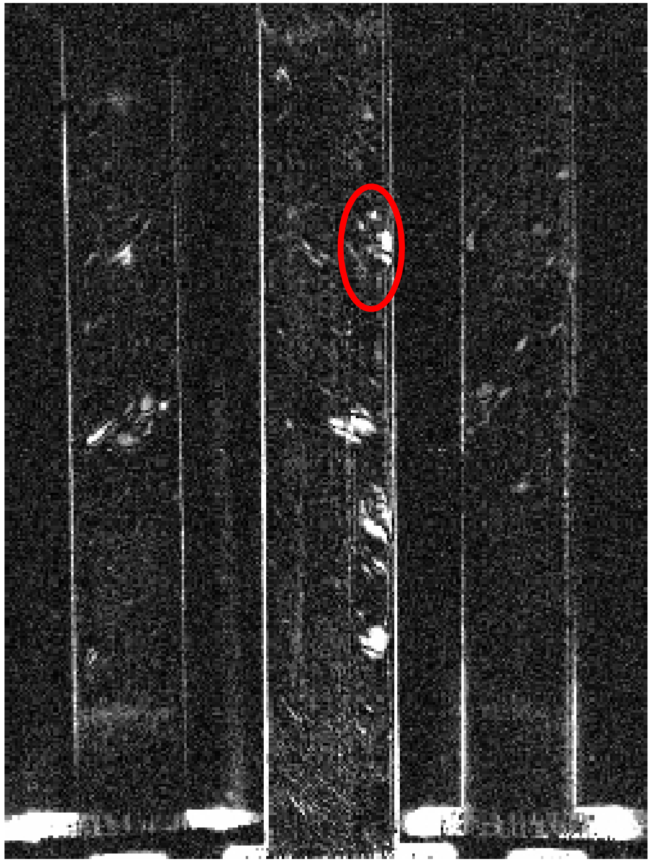
Static: -350Nm

Dynamic: -250 ± 100Nm

Damage growth

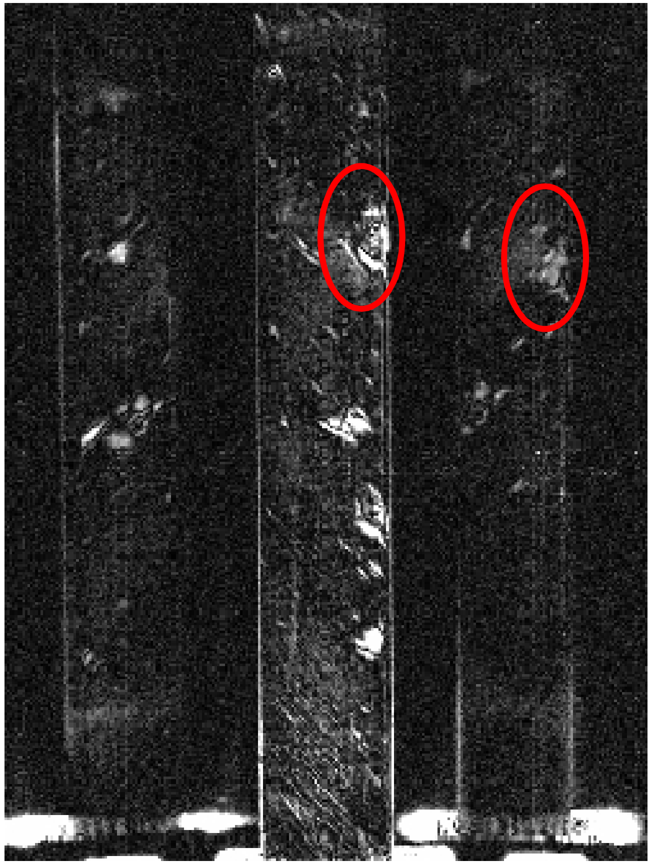
- Crack initiation at -850 Nm

State before cracking



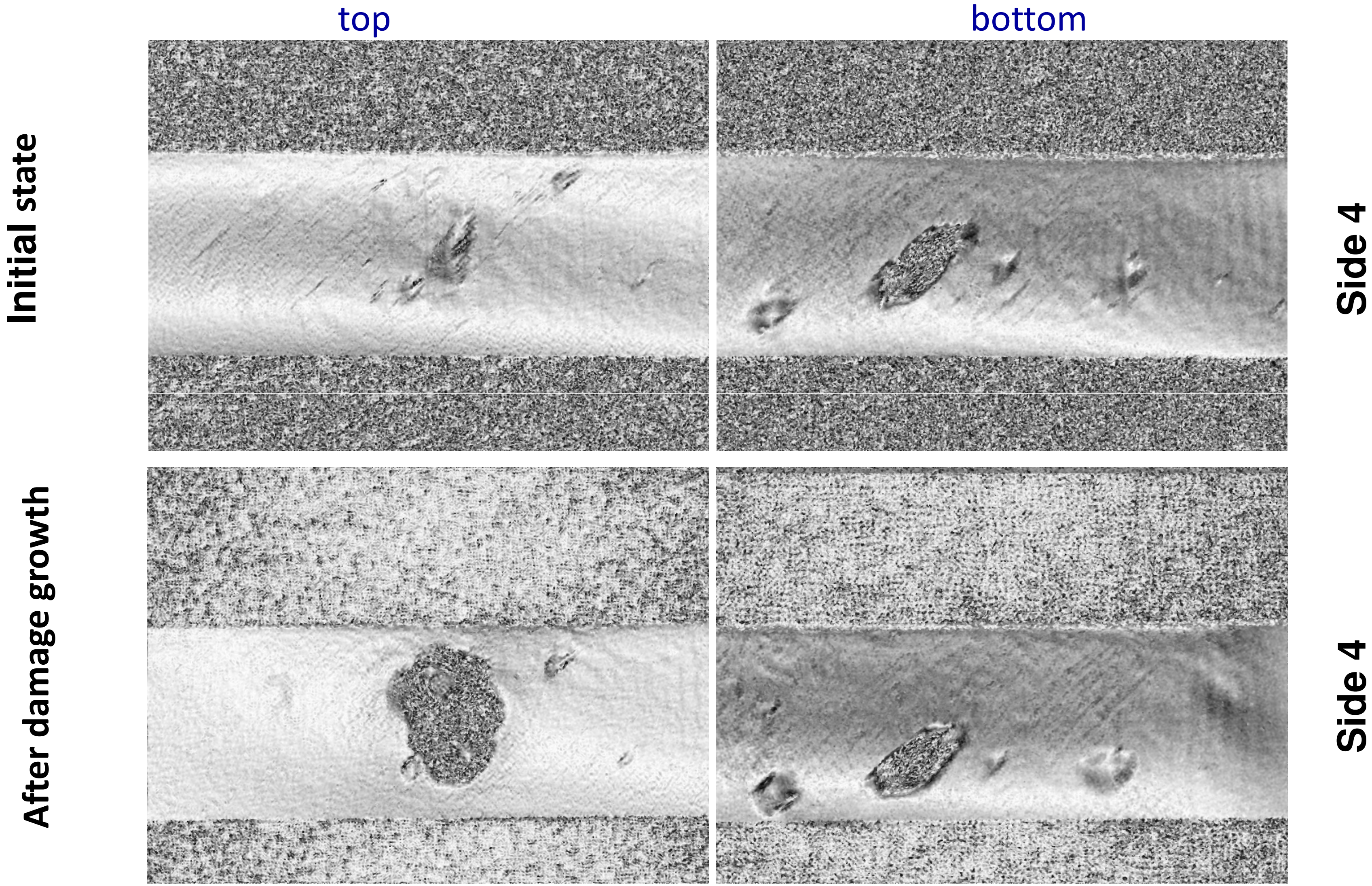
TSA at: -650 ± 100Nm

State after cracking



TSA at: -250 ± 100Nm

Damage growth confirmed with DSPI



DSPI phase gradient

Conclusions

- **TSA and DSPI confirmed the presence of major manufacturing defects identified with X-ray CT scan.**
- **Defect was grown without complete failure of the specimen.**
- **Small defects in peel-ply specimens cannot be grown.**
- **FE simulations confirm that the presence of voids reduces ultimate strength while torsional stiffness is hardly affected.**
- **Prediction of the first ply failure site is only possible when a clear hierarchy of defect sizes and locations is present.**

MATERA+ Acknowledgements

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- Funding from the Swiss *Commission for Technology and Innovation* and the British *Technology Strategy Board* is acknowledged
- We thank
  - CarboLink for manufacturing the torsion tubes
  - Even AG for performing FE analyses
  - FLIR Systems ATS for providing a thermal camera
  - Empa Laboratory Mechanical Systems Engineering for operating the torsion test machine

- The AMUSED consortium consisted of

EMPA	**CH**	**AWE plc**	**UK**
Airbus UK Ltd	**UK**	**LaVision UK Ltd**	**UK**
University of Southampton	**UK**	**GE Aviation**	**UK**
Enabling Process Technologies Ltd (UK)		**Carbo Link**	**CH**
FLIR Systems Ltd	**UK**	**EVEN AG**	**CH**

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