

A wireframe model of an airplane, rendered in a glowing cyan color, is positioned diagonally across the upper half of the slide. The model shows the fuselage, wings, and tail section with a grid of lines and dots representing the structure.

Session 3: Effect of Manufacturing Defects

FINAL DISSEMINATION EVENT, NLR Amsterdam (NL), December 17th

Giuliano Allegri (UB), Hanna Beketova (UB), Peter Foster (UB), Stephen Hallett (UB), Alyn James (UB), Anatoly Koptolev (UB), Bing Zhang (UB)



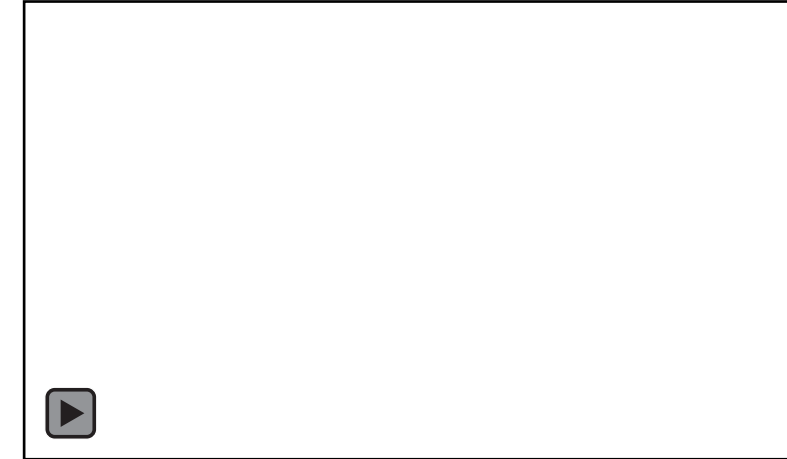
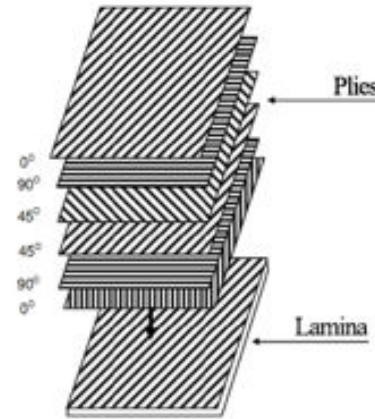
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01

Introduction



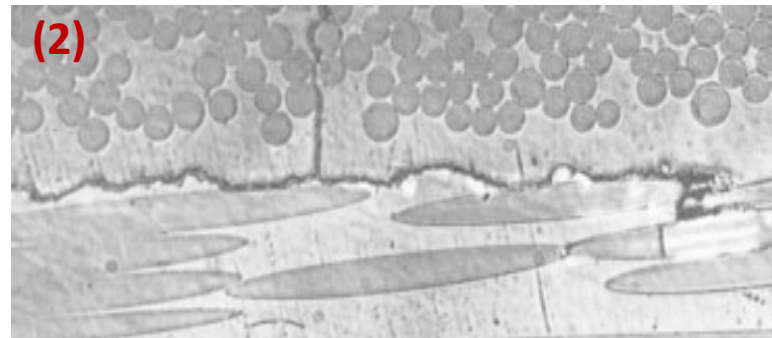
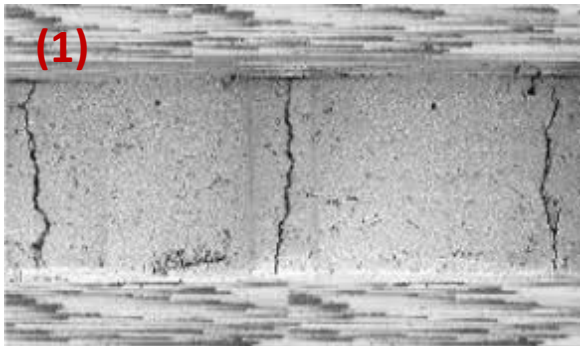
- Three stages of fatigue: 1) matrix cracking; 2) delamination; 3) fibre failure
- Evolution of fatigue governed by the matrix, with potential significant contribution from fibre-bridging
- Fatigue promoted by stress risers (free edges, ply drop-offs) and defects (ply wrinkling/crimping)
- Fatigue strongly dependent on environmental conditions (temperature, moisture, UV radiation) because of the visco-elasto-plastic response of the matrix



(1) Micro-Cracking (intralaminar)

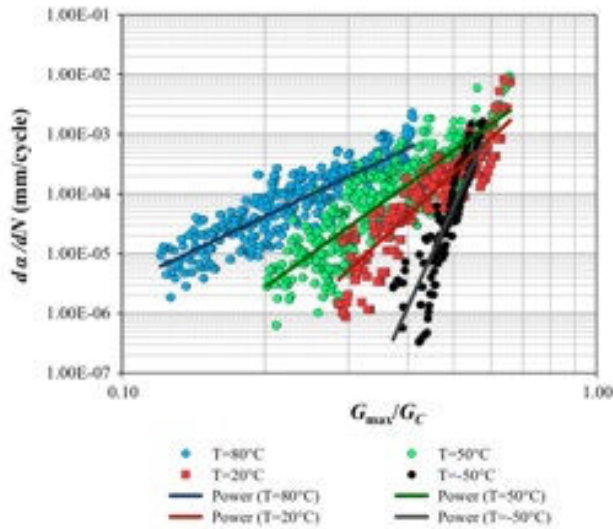
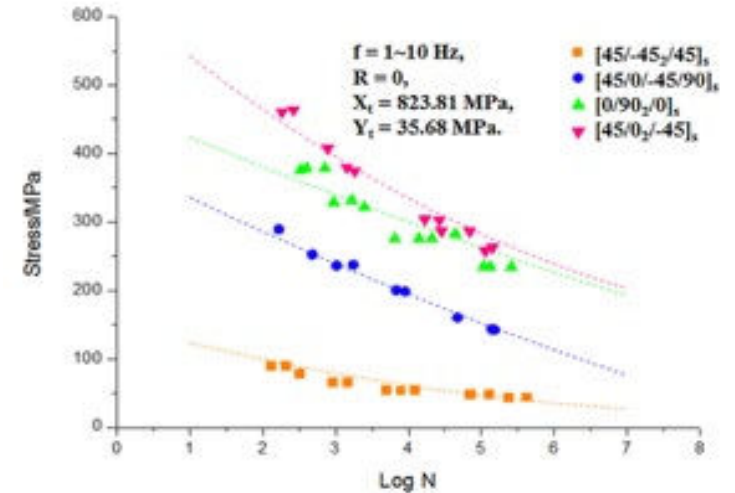
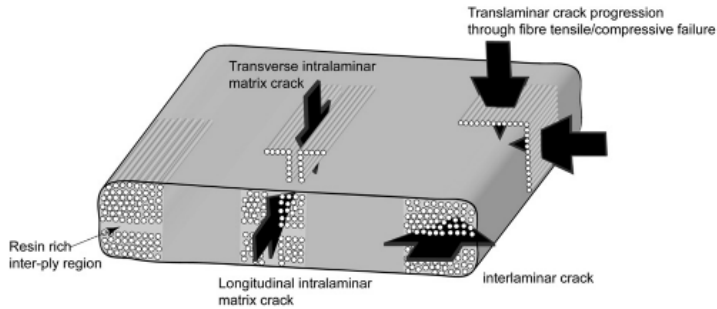
(2) Delamination (interlaminar)

(3) Fibre failure (translaminar)



Challenges

- 1) Failure modes in composites interact in a synergistic fashion
- 2) Temperature and moisture content have a major impact on fatigue behaviour
- 3) Manufacturing defects (e.g. voids, ply wrinkling) act as stress risers

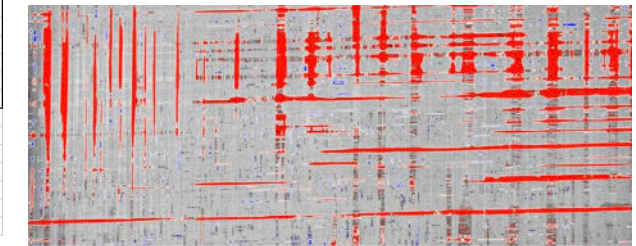
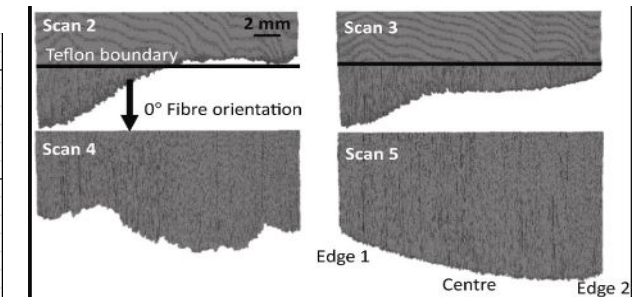


“Fatigue strength justification of composite structures is commonly performed on the basis of **plotting laminate stresses against failure lives**. **This approach is considered fundamentally wrong**, because it implicitly violates the similitude principles that form the basis of engineering prediction.” (Alderliesten, 2013)

Current strategy → “No crack growth” & “Test our way out!”

The Defect taxonomy consists of a: 1) classification system comprising key discrete/variables for describing the defect; 2) a database of images providing examples of the defects. These information allow the correct representation of defects in FEA models

Defect	Mandatory Parameters			Optional Parameters			Cause Codes	Example Image
	Parameter	Type	Unit	Parameter	Type	Unit		
Wrinkle	Maximum angle deviation	Scalar	degrees	Length	Scalar	mm	Fibre steering	Wrinkle Image/A1
				Maximum ply thickness	Scalar	mm	Preform drape	
				Minimum ply thickness	Scalar	mm	Alignment of gaps/overlaps	
							Additional material	
Delamination	Major axis	scalar	mm	Orientation with respect	scalar	degrees	Ply movement during cure	Delamination Image/A1
	Minor axis	scalar	mm	Orientation with respect	scalar	degrees	Insufficient debulk	
				Location	discrete	edge / embedded	Excess voidage	
							Shrinkage cracking	
Porosity / Voidage	Volume fraction	Scalar	%	Maximum pore size	scalar	um	Preform contamination	Porosity / Voidage Image/A1
	Affected volume	scalar	mm3	Minimum pore size	scalar	um	Accidental inclusion	
				typical morphology	discrete	distributed spheroidal / intraply / interply / dendritic network	Deliberate inclusion (seeded delam)	
							Handling damage	
Notes	1. User selects which defect is being applied to the specimen 2. User is presented with information about how that defect is parameterised (incl the images) 3. Mandatory parameters are filled in 4. Optional parameters are filled in or skipped 5. A single cause code is selected from the list							



(a) IM7/8552, $V_v = 7.26\%$

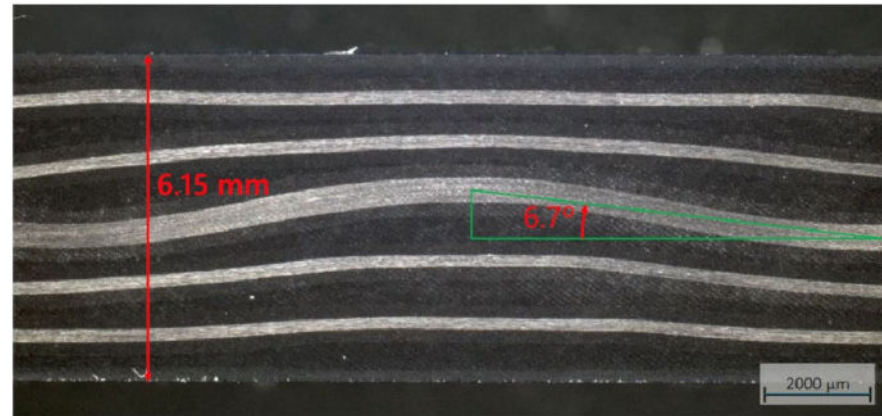
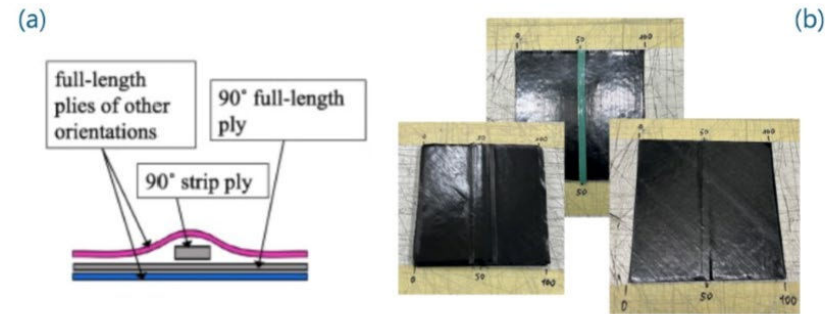
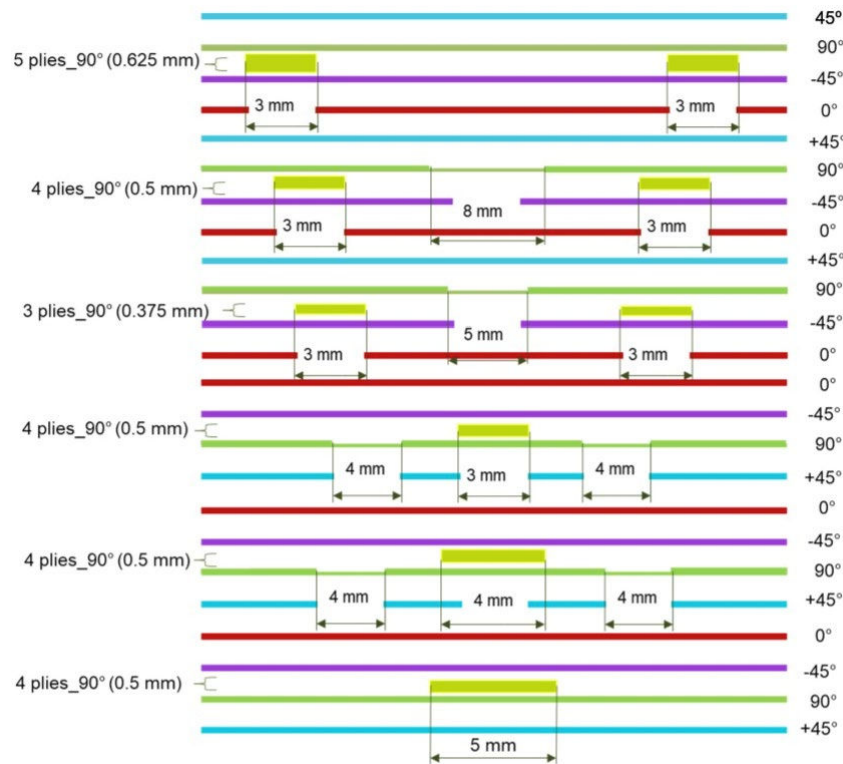
Note: the defect taxonomy is a “live” document – the image database can be further populated with examples of defects from real components

02

Manufacturing and Process Modelling

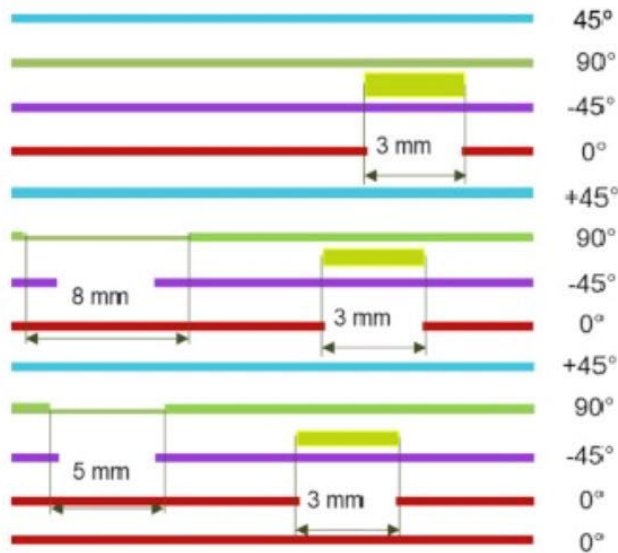


A robust method to manufacture coupons with embedded wrinkles has been developed. It entails inserting transverse strips of materials and terminating plies to achieve a controlled amount of out-of-plane waviness in a baseline quasi-isotropic laminate

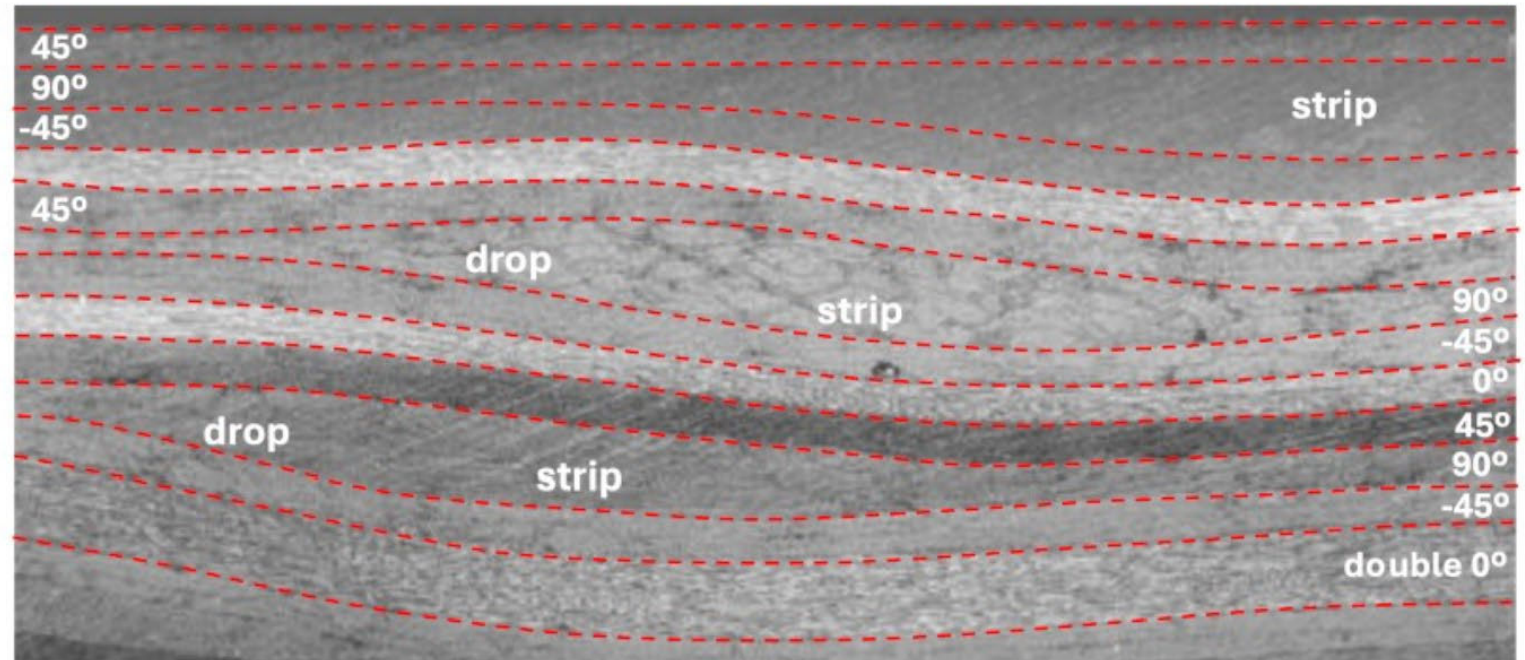


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(a)

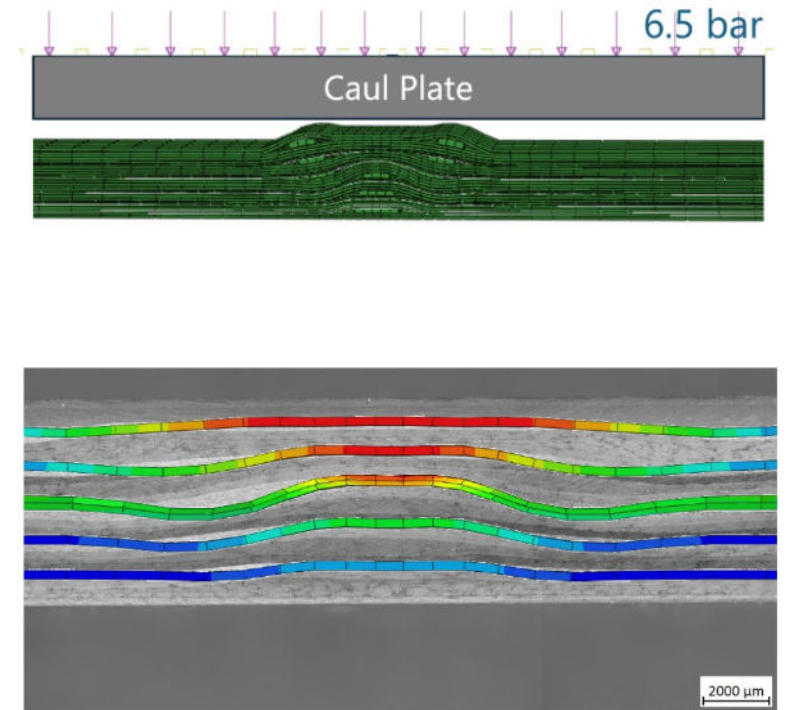
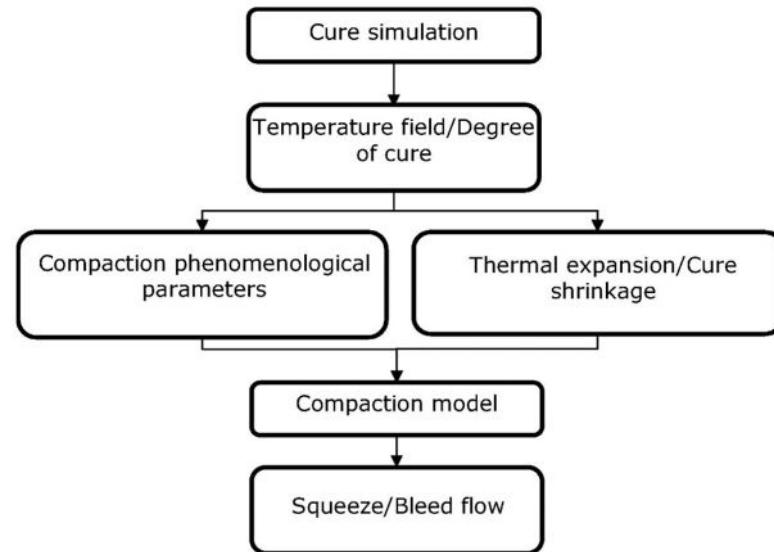
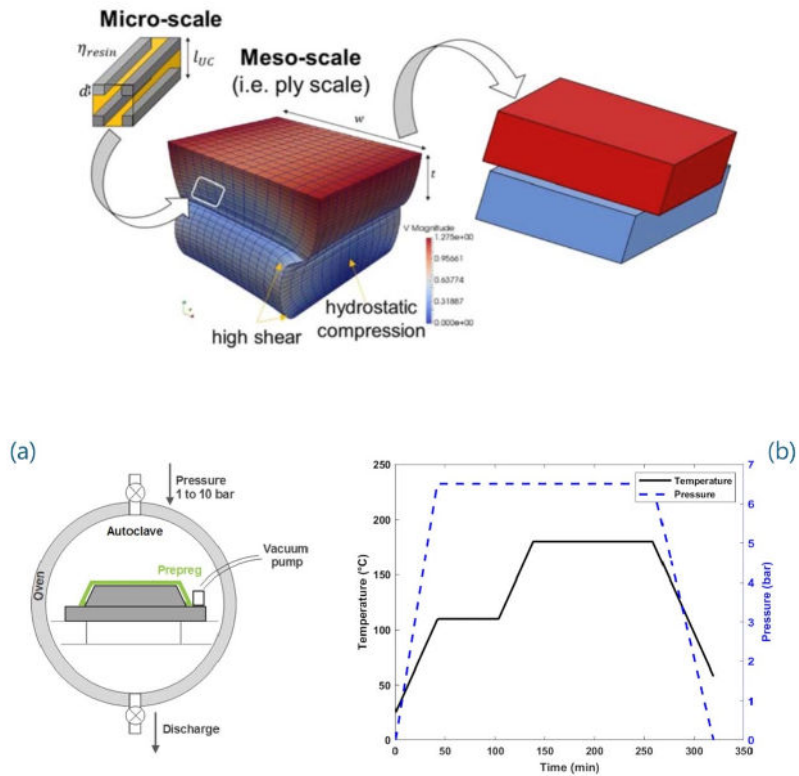


(b)



Chapter 2 Process Modelling of Defect Formation

A multi-scale modelling framework has been developed and validated to predict defect formation (Abaqus/Standard Implementation)



03

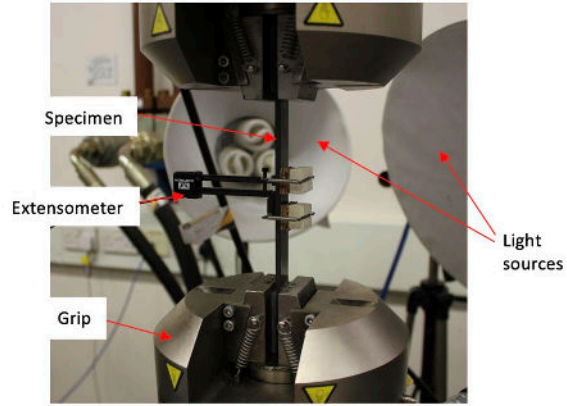
Fatigue Testing And Modelling



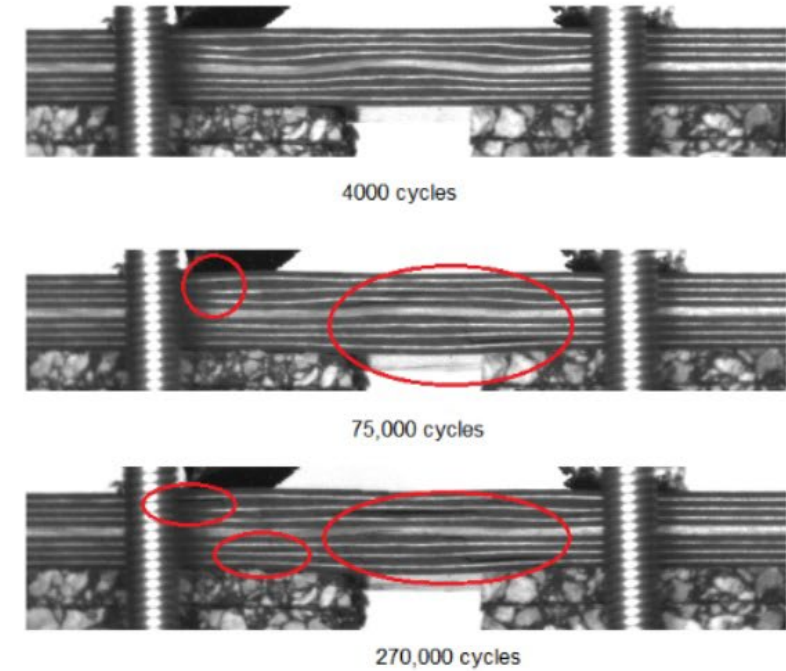
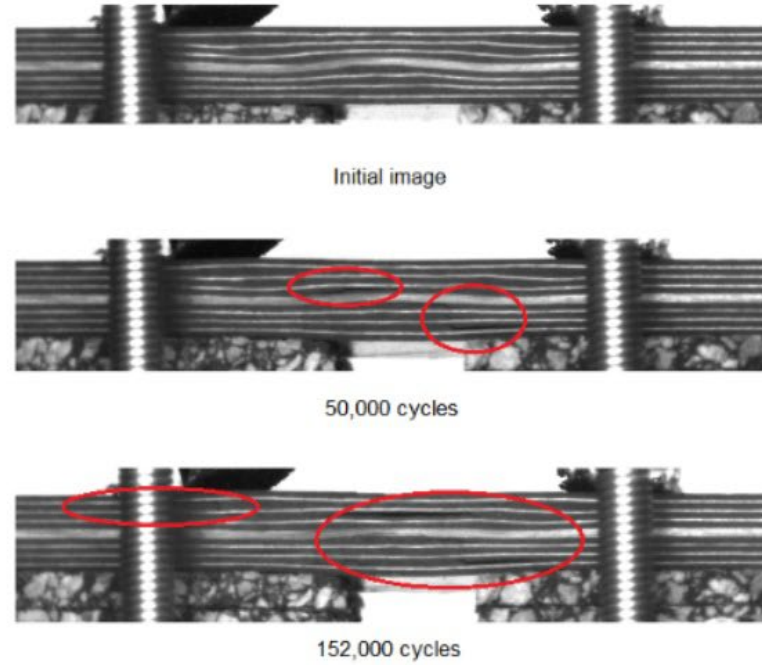
Chapter 3

Testing Coupons with Embedded Wrinkles

Different severities (as % of static failure load); multiple environmental conditions



(a)



Load cycles

Specimen video

Fatigue parameters

Calibration & control buttons

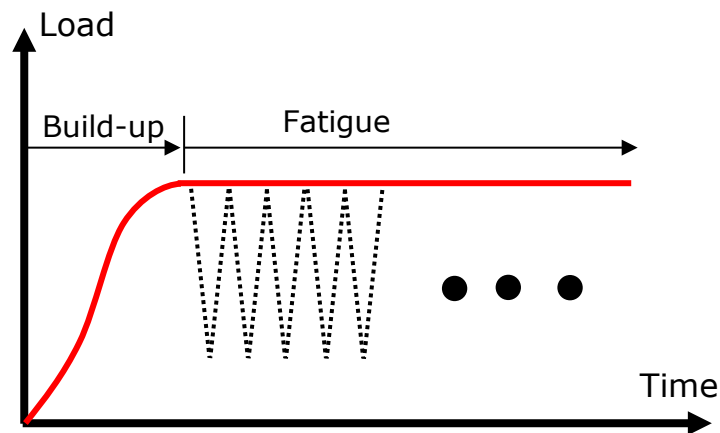
In-time fatigue variables

Set these parameters prior to running program		Pause frequency (number of cycles between pauses)	No. of cycles completed	Pause? (0/1)	Pause length (min)
Amplitude (MPa)	1.1	1000000	0	0	5
Load level (%)	4	100			
Frequency (Hz)	10				

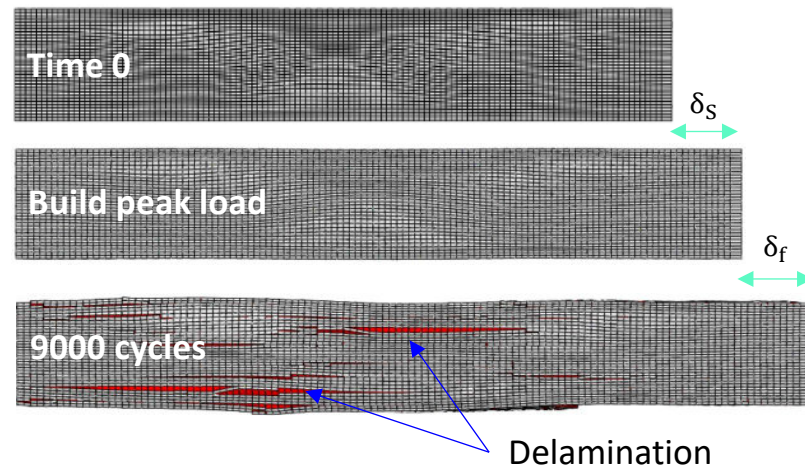
Calculated	Calculated	Data Acquisition	Load max	Load min
Amplitude (MPa)	1.12141	Ready to start test	0.00797	0.00511
Amplitude (MPa) (Load level)	4.4722			
Amplitude (MPa) (Load level) (90)	22.2222			

Full scale (V)	Calibration (mV/mV)	Calibration complete	Load max	Load min
10	10	Completed	0.0079721429	0.0051121429
			Load Measurement	Load Measurement
			0.00444801	0.00292

- In the UB fatigue CZM, a virtual composite structure is loaded to the peak load of the first cycle, then held under the peak load envelope. Inserted cohesive elements follow a fatigue cohesive law to predict delamination in Abaqus/Explicit.
- The model can be significantly accelerated by using a fatigue frequency that is orders of magnitude higher than the one used in actual tests, e.g. 105 Hz in the model vs. 5 Hz in experiment.

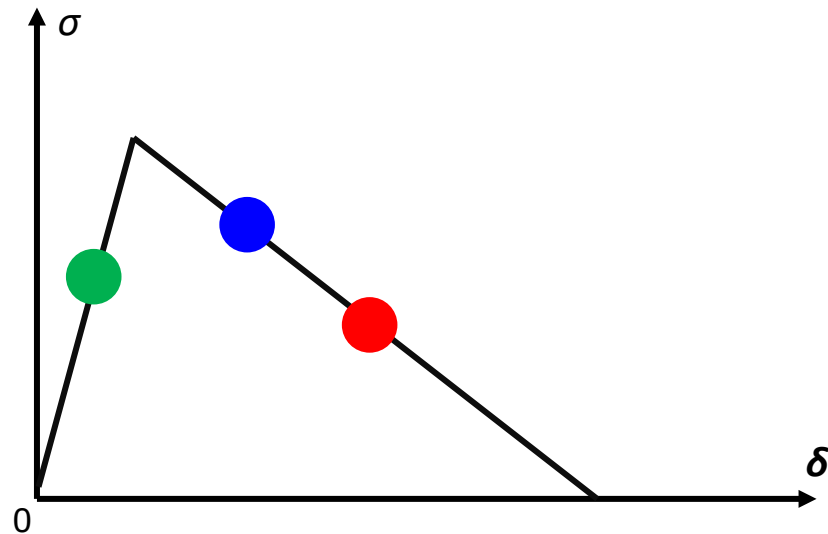


Peak load envelope



A tensile fatigue model at different stages

- The fatigue cohesive law was developed based on Bristol's bilinear static cohesive law.
- The fatigue CZM covers fatigue initiation and fatigue propagation

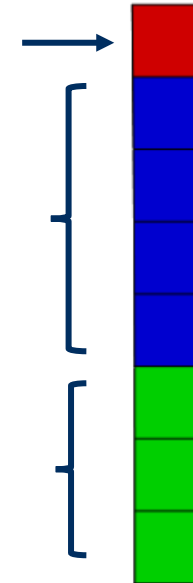


Static bilinear cohesive law

Cohesive zone crack tip
(Fatigue propagation law)

Cohesive zone elements
(Static cohesive law)

Elastic element
(Fatigue initiation law)



Map of cohesive laws in a portion of cohesive interface

Jiang W-G, Hallett SR, Green BG, Wisnom MR. A concise interface constitutive law for analysis of delamination and splitting in composite materials and its application to scaled notched tensile specimens. *Int J Numer Methods Eng* 2007;69:1982–95.

Kawashita LF, Hallett SR. A crack tip tracking algorithm for cohesive interface element analysis of fatigue delamination propagation in composite materials. *Int J Solids Struct* 2012;49:2898–913.

May M, Hallett SR. A combined model for initiation and propagation of damage under fatigue loading for cohesive interface elements. *Compos Part A Appl Sci Manuf* 2010;41:1787–96.

- Fatigue initiation criterion is based on S-N curve and Linear Cumulative Damage (LCD) rule. At damage initiation, cohesive strengths are reduced.

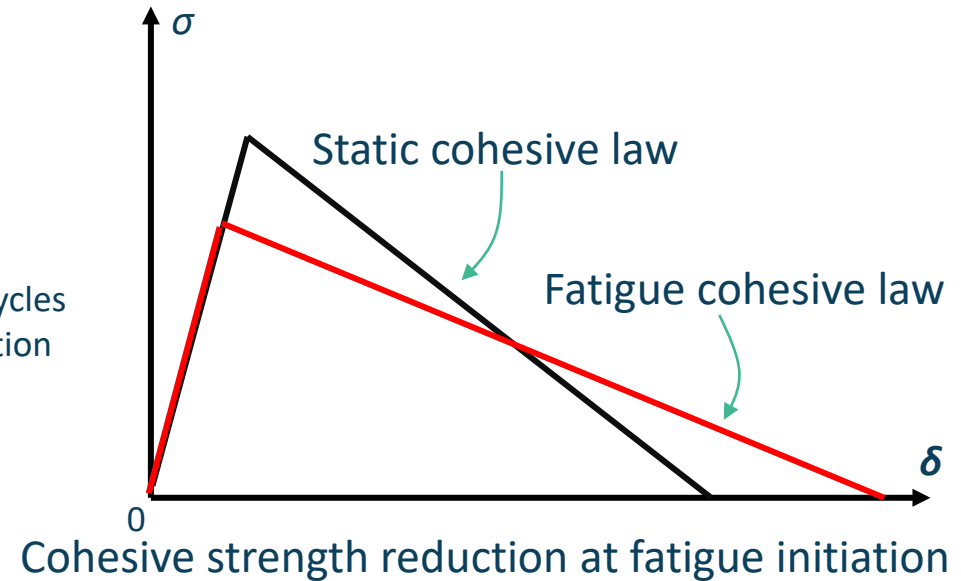
Mixed-mode S-N formula – **parameters can be randomised!**

$$\sqrt{\left(\frac{\sigma_I}{\sigma_{I\max}}\right)^2 + \left(\frac{\sigma_{II}}{\sigma_{II\max}}\right)^2} = 1 - \left[b_I \left(\frac{\delta_I}{\delta_m}\right)^2 + b_{II} \left(\frac{\delta_{II}}{\delta_m}\right)^2 \right] \cdot \log_{10} N_i$$

load severity S-N constant No. of cycles to initiation

Update initiation variable by LCD rule:

$$D_i^t = D_i^{t-dt} + \frac{f_N \cdot dt}{N_i^t}$$



May M, Hallett SR. A combined model for initiation and propagation of damage under fatigue loading for cohesive interface elements. Compos Part A Appl Sci Manuf 2010;41:1787–96.
doi:10.1016/j.compositesa.2010.08.015

Tao C, Mukhopadhyay S, Zhang B, Kawashita LF, Qiu J, Hallett SR. An improved delamination fatigue cohesive interface model for complex three-dimensional multi-interface cases. Compos Part A Appl Sci Manuf 2018;107:633–46.

- Fatigue damage propagation is considered in the CZM by a stiffness-based fatigue damage variable, which is derived from the crack propagation rate da/dN

Modified Paris law – **parameters can be randomised!**

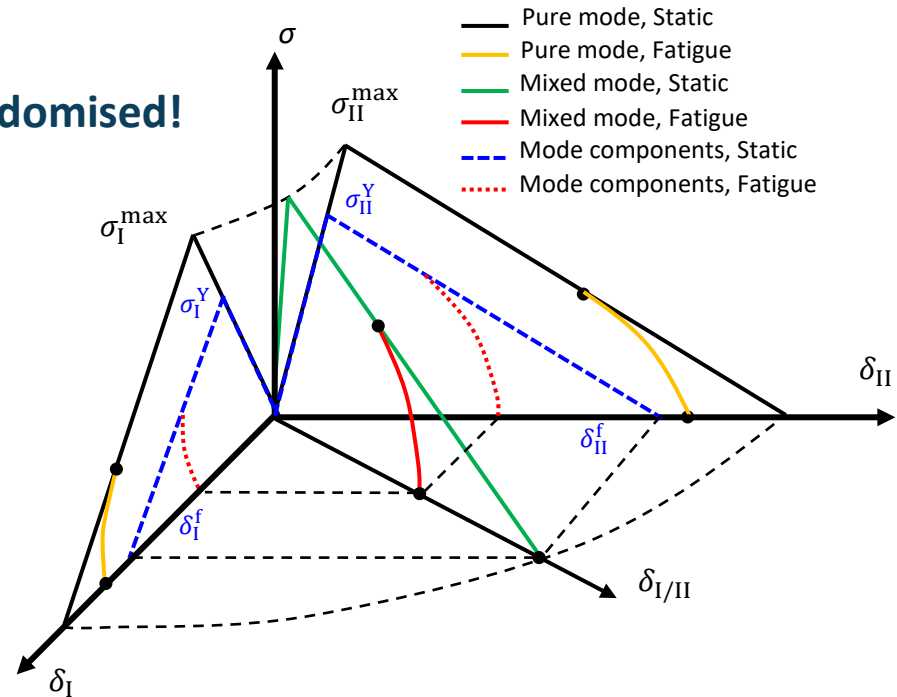
$$\frac{da}{dN} = C \left(\frac{G}{G_C} \right)^{\frac{m}{(1-R)^{1+\alpha}} e^{-h\phi}}$$

Fatigue damage rate:

$$\frac{dD_f}{dN} = \frac{1 - D_s}{\frac{dN}{da} l_f}$$

Fatigue damage variable update:

$$D_f^{t+dt} = D_f^t + \frac{dD_f}{dN} \cdot f_N \cdot dt$$



Bilinear cohesive fatigue damage propagation law

Allegri G, Jones MI, Wisnom MR, Hallett SR. A new semi-empirical model for stress ratio effect on mode II fatigue delamination growth. Compos Part A Appl Sci Manuf 2011;42:733–40. doi:10.1016/j.compositesa.2011.02.013.

A crack tip tracking algorithm for cohesive interface element analysis of fatigue delamination propagation in composite materials. Int J Solids Struct 2012;49:2898–913. doi:10.1016/j.ijsolstr.2012.03.034

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Modified Paris law – parameters can be randomised!

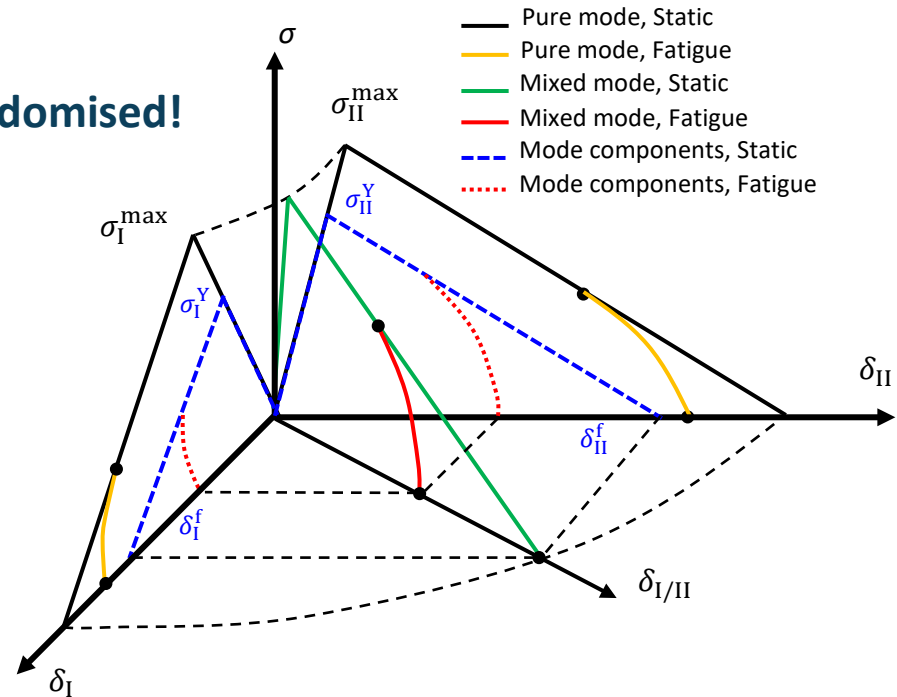
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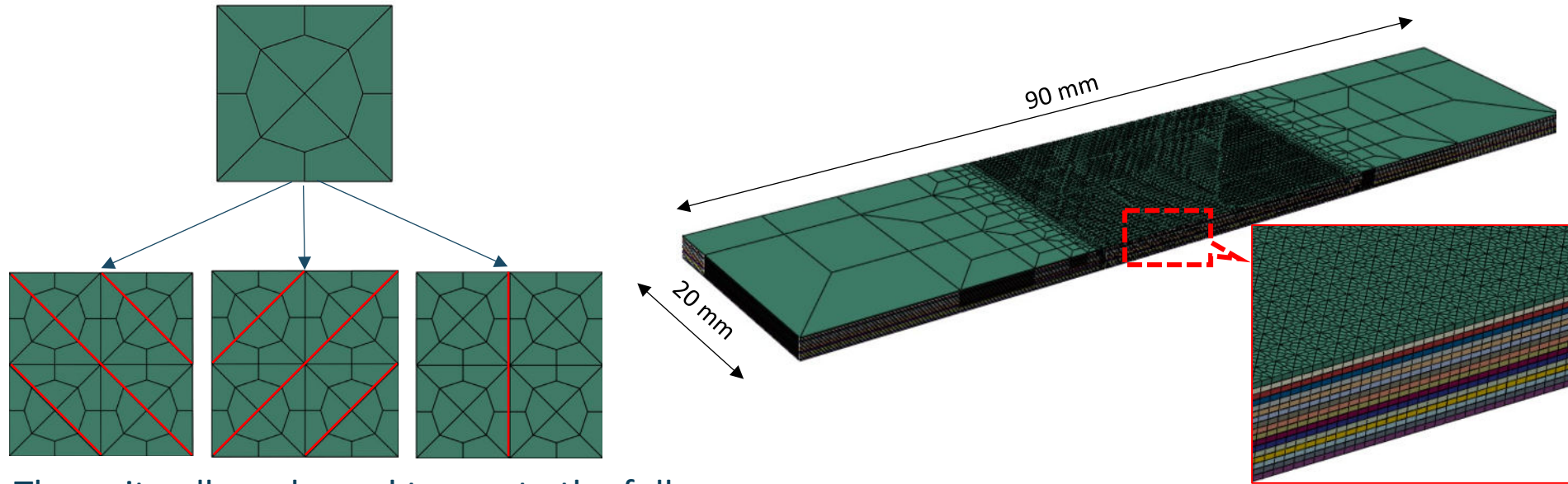


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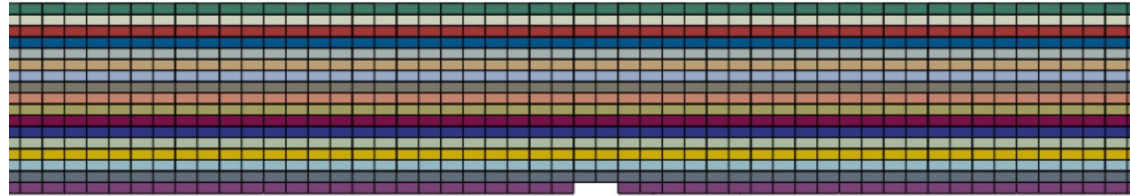
The standard fatigue CZM was first calibrated through single interface DCB/ELS/MMB tests on IM7/8552. It was then applied to multi-interface fatigue defect cases on coupons with embedded wrinkles and/or ply-terminations



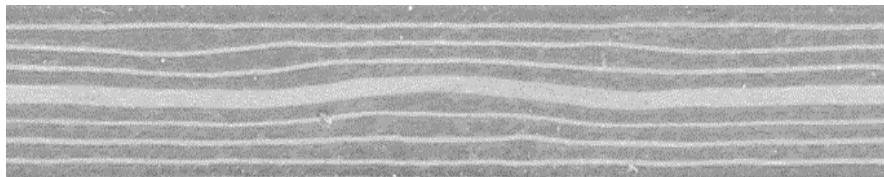
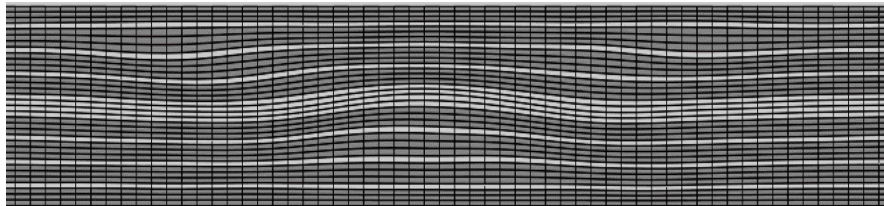
The unit-cell mesh used to create the full model and insertion of cohesive elements for predicting matrix crack within all angle plies.

Fatigue model without defects (pristine)

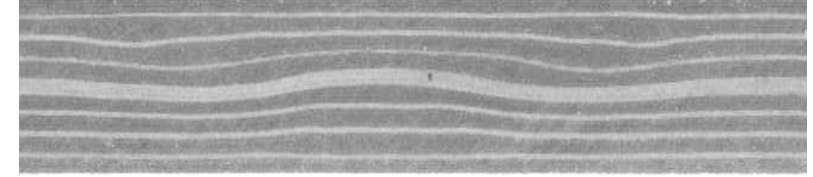
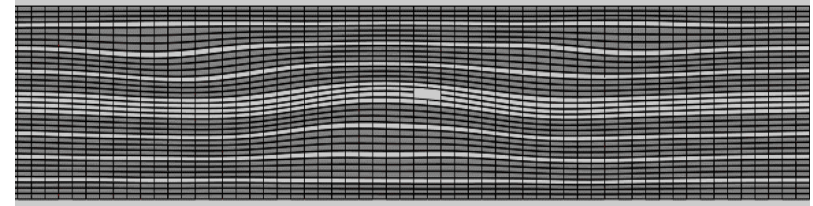
Defect description – Image-based meshing for each coupon!



Numerical description of **cut-ply**.

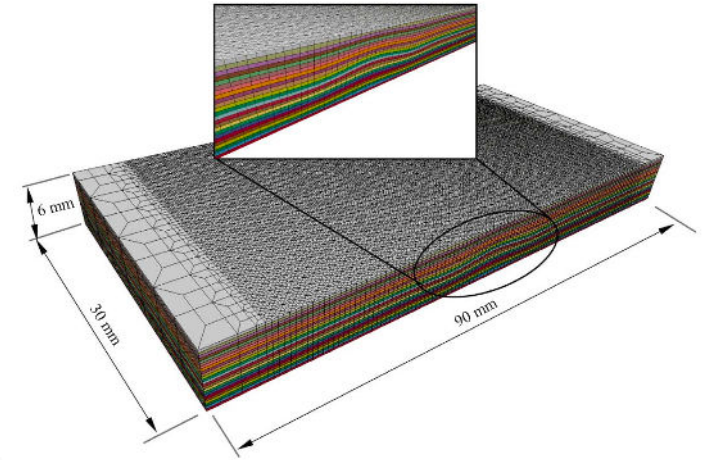
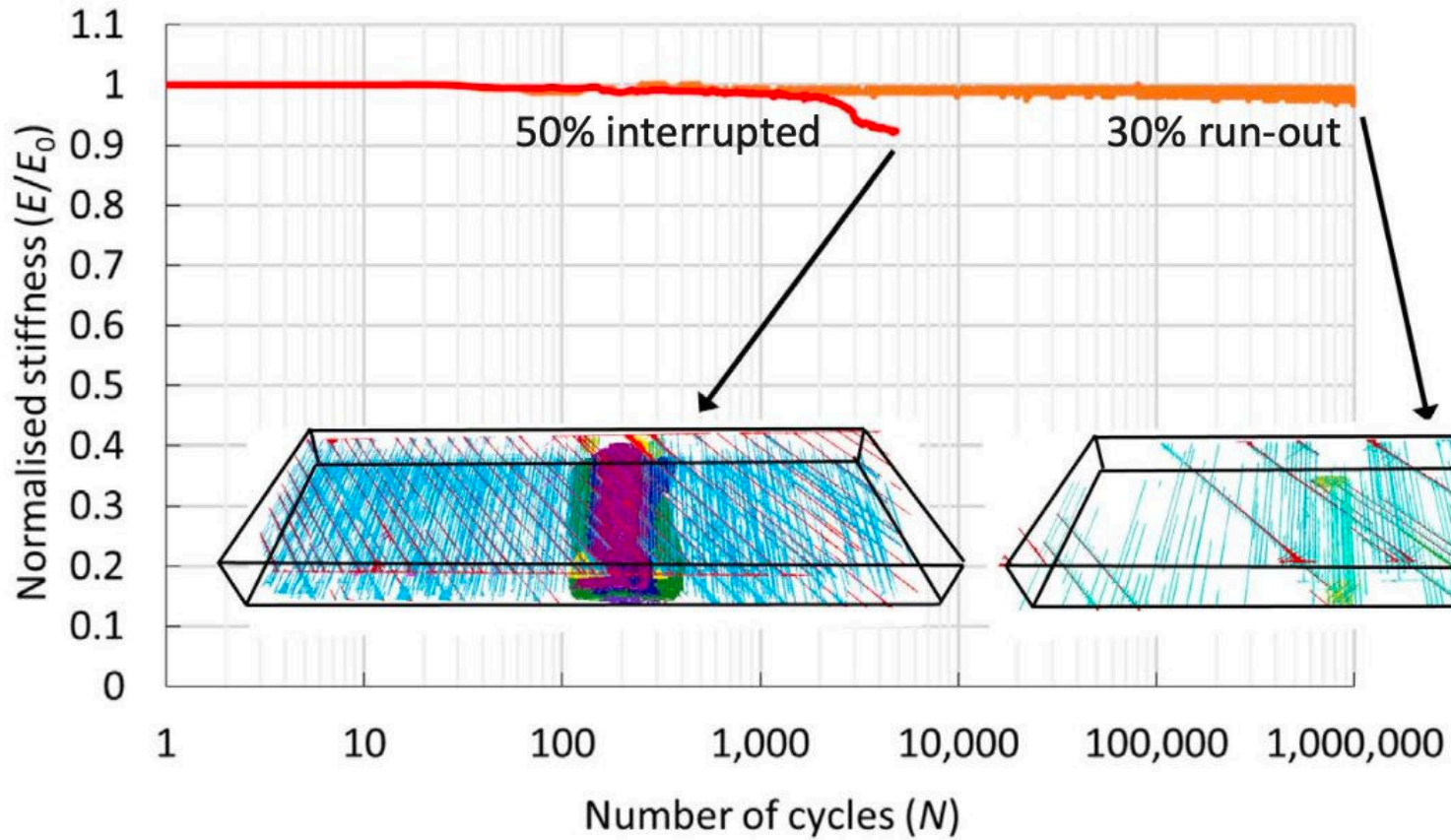


Numerical description (top) and microscopic observation (bottom) of the **wrinkle** defect.

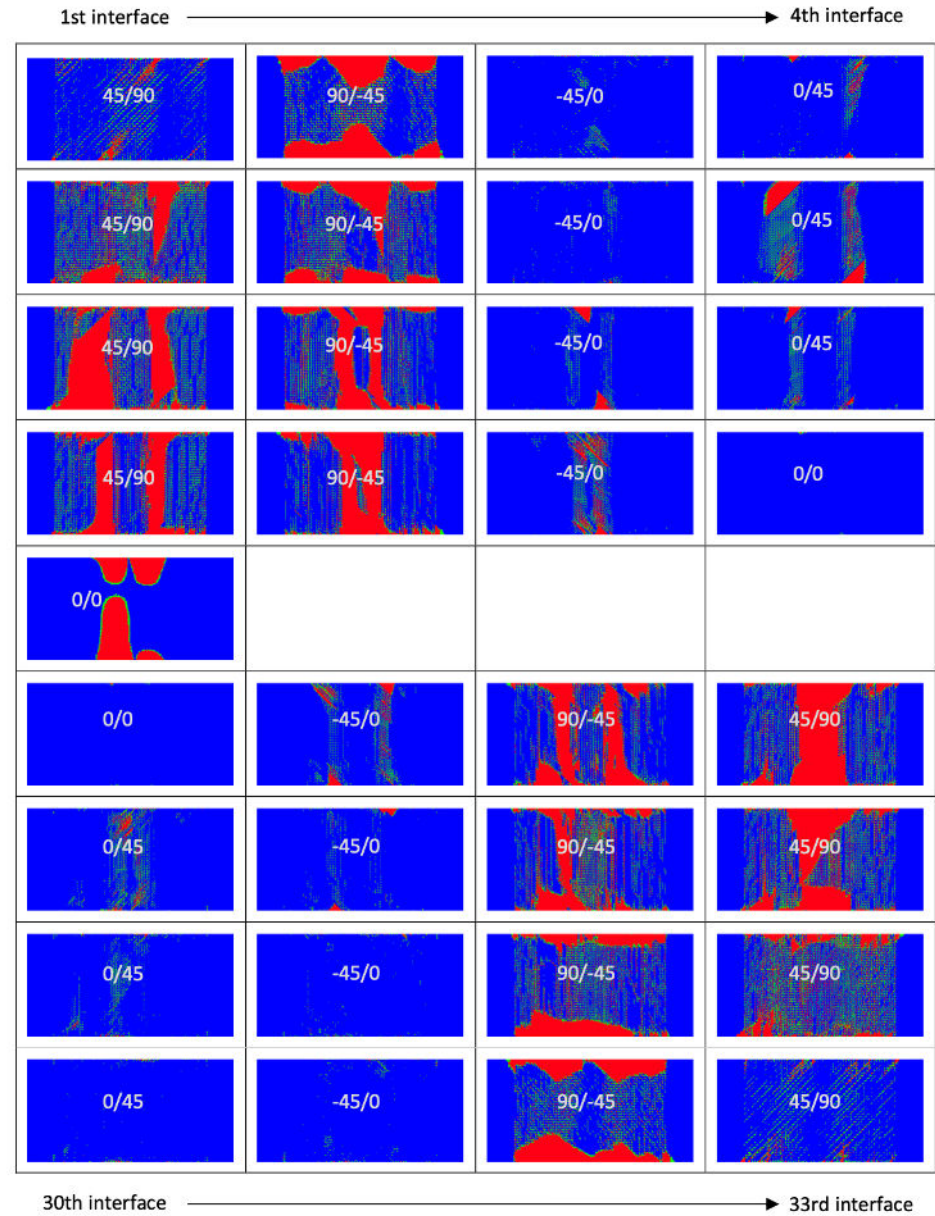
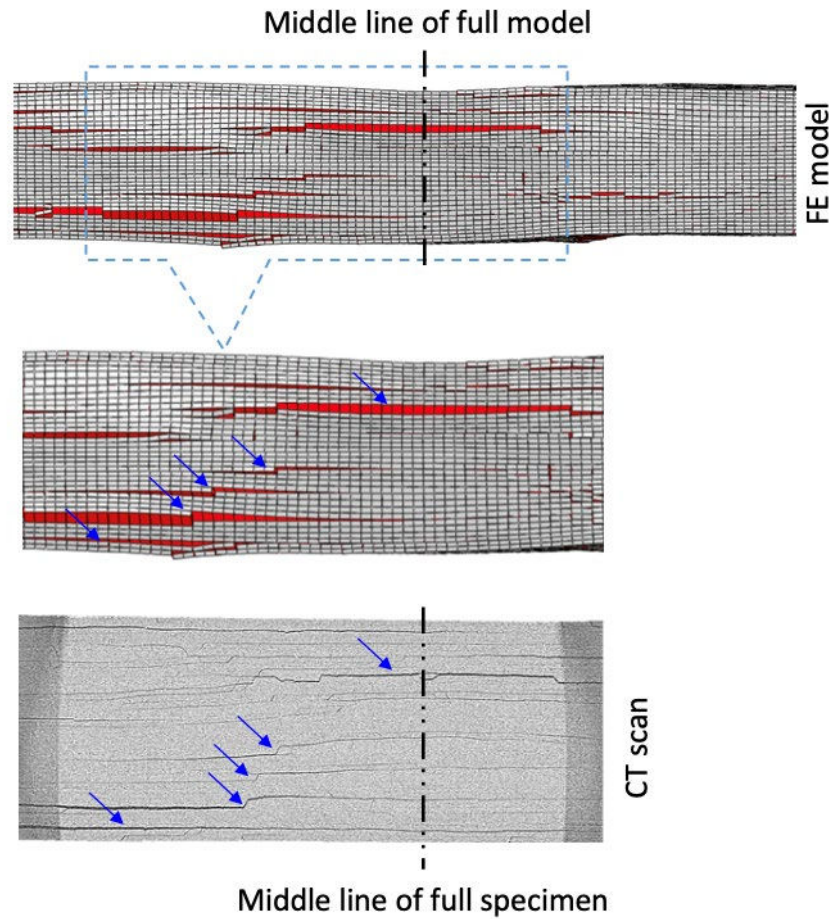


Numerical description (top) and microscopic observation (bottom) of combined **W&C defect**.

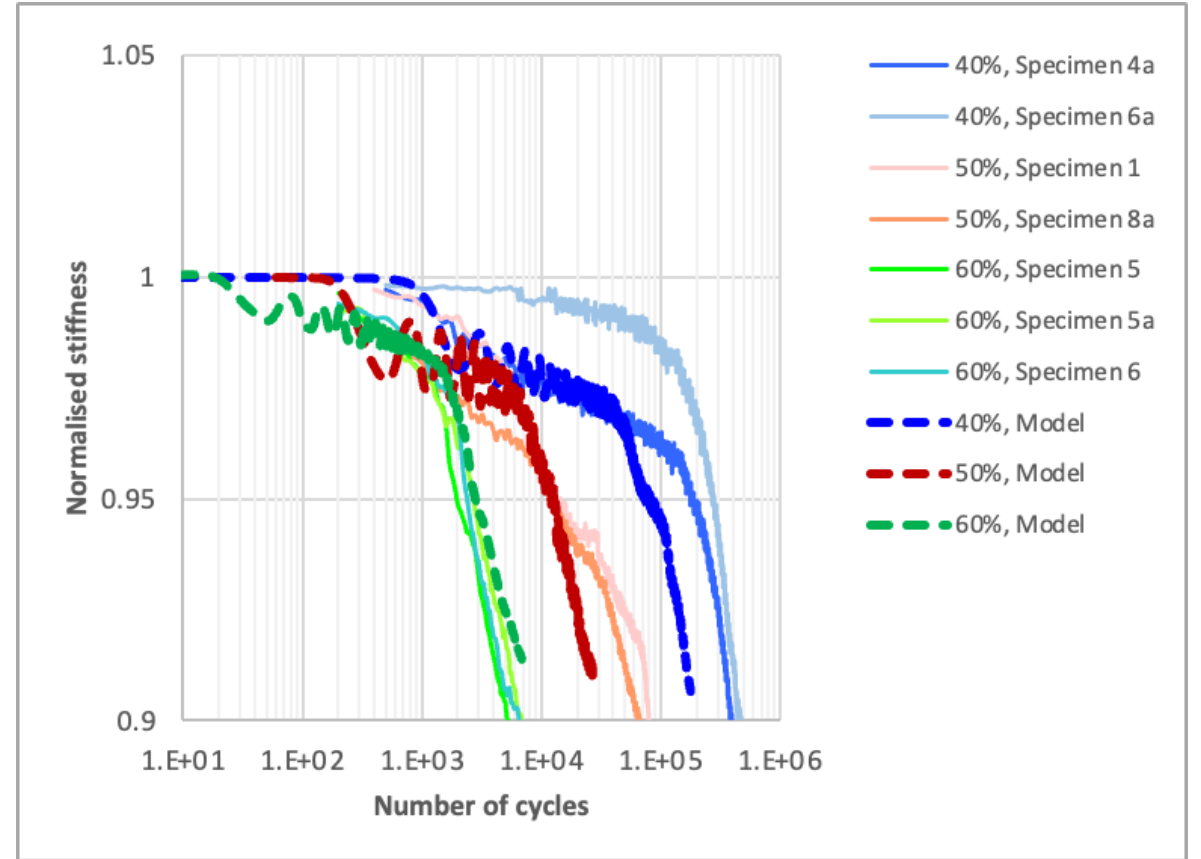
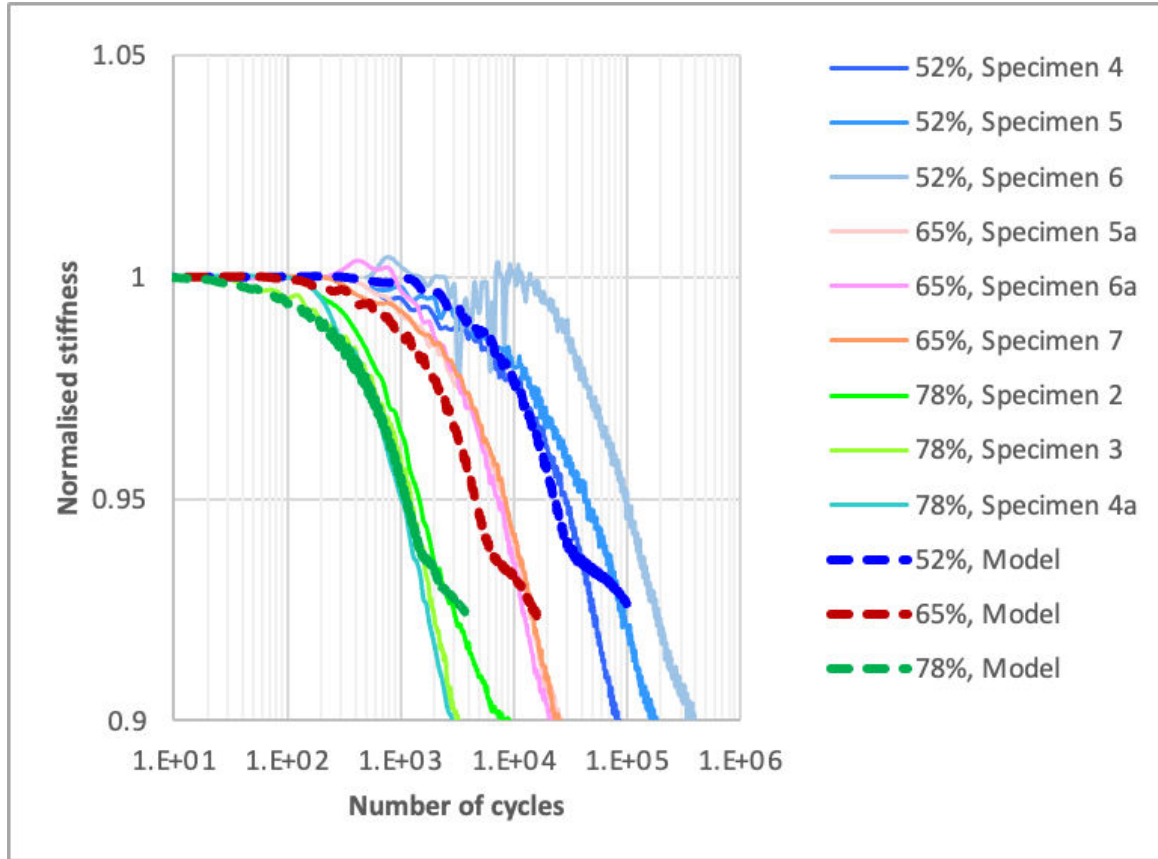
Data-rich approach, e.g. X-Ray CT of “Wrinkle” coupons



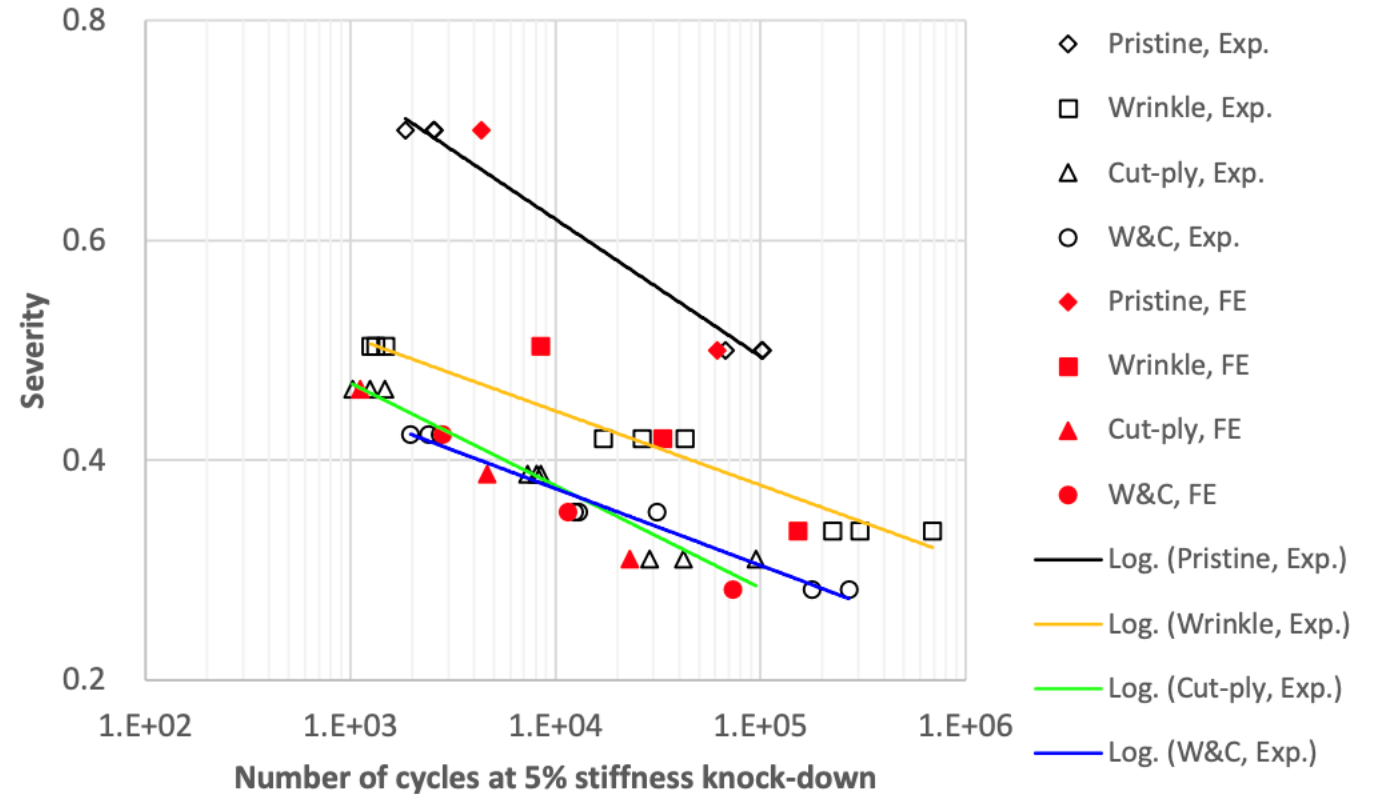
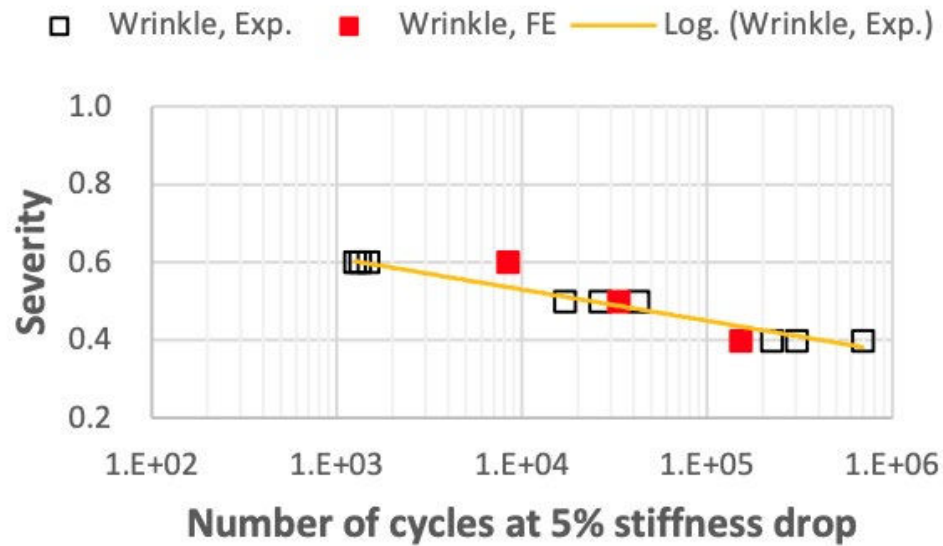
Example of FEA model output versus CT data



Excellent correlation achieved between experimental results and FE model



Excellent correlation achieved between experimental results and FE model



04

Conclusions



- I. A methodology to manufacture coupons with controlled and reproducible defects has been developed
- II. The manufacturing methodology has been tailored with the help of advanced process modelling tools, which have been further extended in scope and validated
- III. A comprehensive dataset of fatigue behaviour for quasi-isotropic laminates with embedded wrinkles has been generated, also including the influence of environmental effects (all the experimental results are available on the D-STANDART Zenodo repository)
- IV. A meso-scale fatigue modelling framework based on a novel cohesive zone implementation has been developed and validated. Our approach captures the complex interplay of matrix cracking, delamination and fibre-failure in a fatigue setting coupled with environmental effects

Chapter 4

Want to know more?

Read our results and use our data!

› www.d-standart.eu/publications

› <https://doi.org/10.5281/zenodo.15049769>

PUBLICATIONS

D-STANDART PUBLICATIONS

Partners will disseminate results through publications and active participation to conferences and standardization working groups. Please note that a specific Zenodo community has been created to share open access publications.

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D-STANDART - for Durability Modelling of Composites (HEU)
Part of EU Open Research Repository

Published March 19, 2025 | Version v1

D-STANDART - Experimental mechanical test data set

Monticeli, Francisco (Researcher)¹; Biagini, Davide (Researcher)¹; Pascoe, John-Alan (Work package leader)¹; Mosleh, Yasmine (Project member)¹; Di Maio, Dario (Work package leader)²; Ren, Yunxia (Researcher)³; Beketova, Hanna (Researcher)⁴; Allegri, Giuliano (Work package leader)^{5,6}; Amsterdam, Emiel (Researcher)⁷; van den Brink, Robbert-Jan (Researcher)⁷

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DCB (Fibre Orientation effect) - Quasi-static Mode I.rar	4.1 MB	Download
DCB (Fibre orientation effect)_NLR_final.7z	481.3 MB	Download
ELS (Fiber Orientation effect)- Fatigue Mode II.rar	569.3 MB	Download
ELS (Fibre Orientation effect) - Quasi-static Mode II.rar	3.1 MB	Download
ELS.zip	11.1 MB	Preview Download

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