More efficient fatigue evaluation of composite structures by leveraging machine learning and surrogate modelling

John-Alan Pascoe (TUD)

EMMC – MatCHMaker Workshop October 24th

Funded by
the European Union

Summary

01

Project background

Motivation

Chapter 1

Project background

Motivation

Situation

- Composite materials crucial for sustainable future
  - Aircraft 50% or more out of FRP
  - Wind energy sector with larger turbines
- Extreme loads and stress cycles during product lifetime
- Damage tolerance needed to extend the lifespan

Challenge

- Lack of fundamental knowledge regarding damage growth process under cyclic loading
- Complex interaction of fibres, fibre orientation, and matrix materials
- Every new design requires multiple tests at various scales
- Imperfect solutions: high-safety factors, 'no growth' criterion

Consequence

Composites products are

- Expensive
- Laborious
- Inefficient to manufacture

Need

A better understanding of the fatigue characterization at a meso-scale, so that we can scale up the gained insights to larger structures

Project background

Problem statement

For composites: each lay-up is a new 'material'

Practical consequence: limitation of design freedom to qualified lay-ups

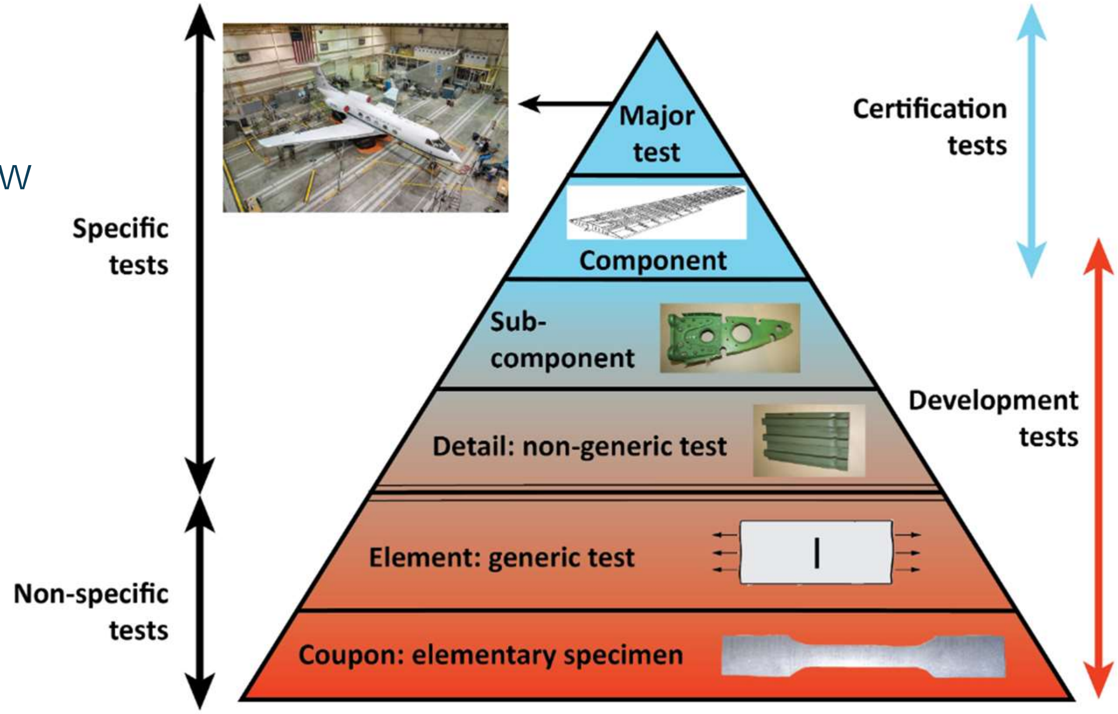


Image: Alderliesten (2018), Introduction to Aerospace Structures and Materials, TU Delft Open, CC-BY-NC-SA 4.0, https://doi.org/10.5074/t.2018.003

02

Project overview

Objective, approach, and impact

Chapter 2

D-STANDART objective

Project intention

What?

To develop **rapid** methods to **characterise fatigue damage** in composites and **sustainability of composite** supply chains; and thereby **model the durability** and sustainability of large-scale composite structures with arbitrary layups **under realistic conditions** (operating loads, application environment, and impact of manufacturing defects)

How?

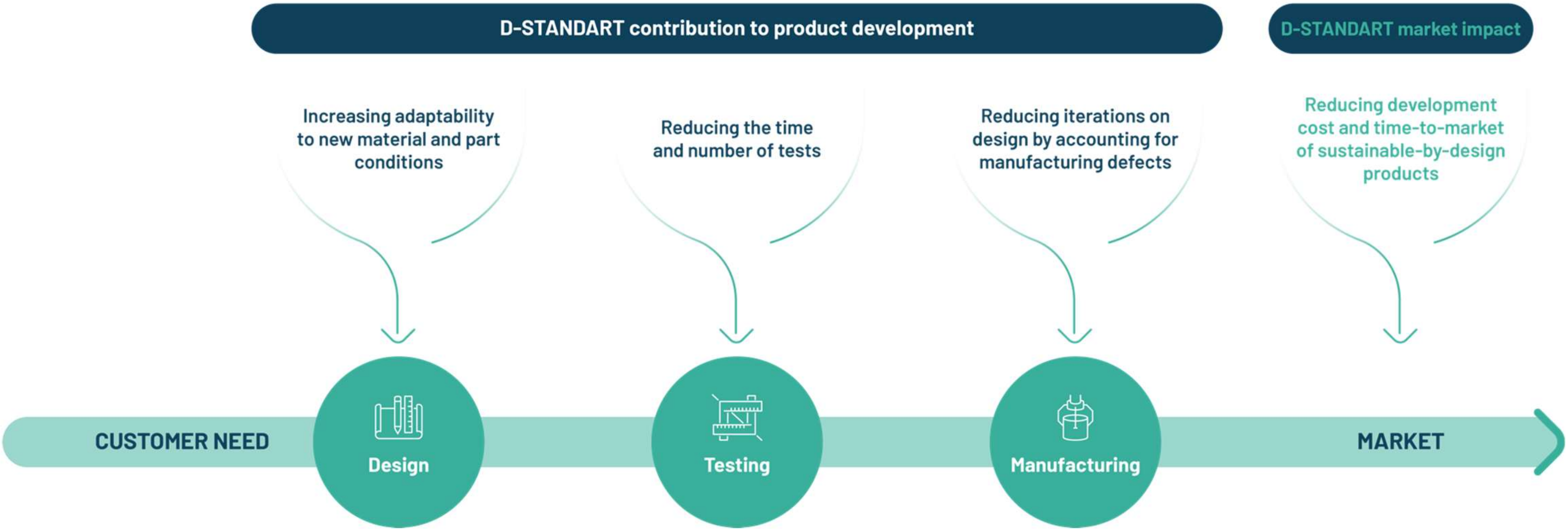
- **Through minimal and accelerated testing** of generic specimens
- Transferring the results of the experiments to large-scale structures using **artificial intelligence and machine learning**

Effect?

Enabling **reduced time-to-market, material waste, and increased lifespan** of composite products in the **aerospace and wind energy** industries

D-STANDART contribution and impact

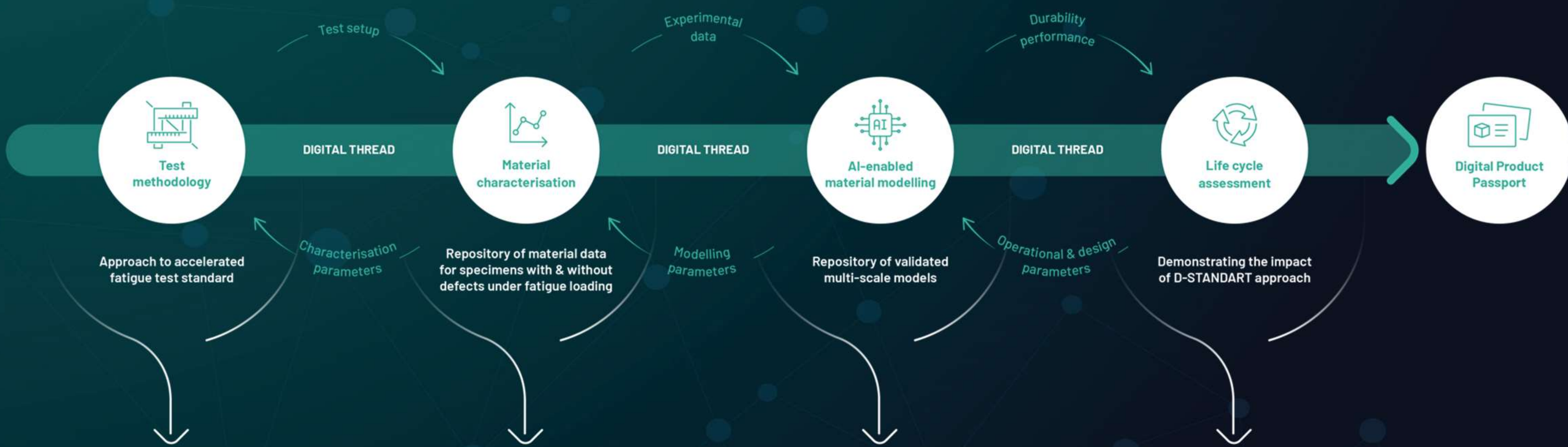
Addressing the “what” and “effect” of the objective



Chapter 2

D-STANDART approach

Addressing the “how” of the objective



IMPACT Reduced design & testing times, more reliable fatigue modelling, higher fatigue performance, reduced time-to-market, sustainable-by-design products

03

Project consortium

Participants and beneficiaries

Chapter 3

D-STANDART in a nutshell

Consortium, Effort in PM, Duration

NLR	UT	TUD	HMI-D and affiliates	LUP	SUZ	UB	NCC	ICO	Total:
71.4 PM	79 PM	97.5 PM	41 PM	25 PM	42 PM	91.2 PM	70,5 PM	30.5 PM	548.1 PM

GA: 101091409
Start: 1 January 2023
Duration: 36 months

6 Beneficiaries, **4** Affiliates
3 Associated Partners
7 European countries

5 RTOs
1 IND
2 SMEs

Chapter 3

Advisory Board Members

Initial list

Rolls Royce	Fokker Aerostructures	Siemens Gamesa	Embraer	Coexpair (SME)

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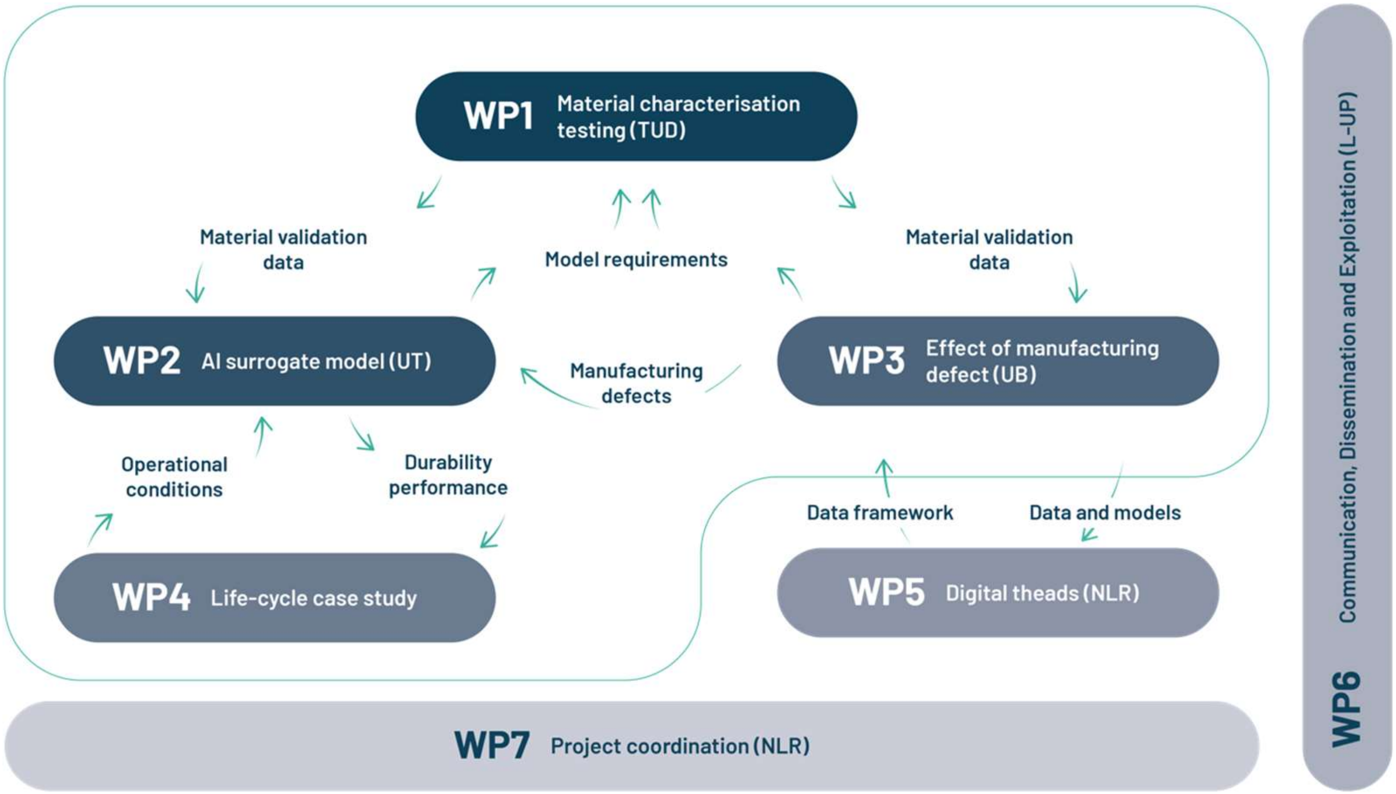
Work Breakdown Structure, interrelations and timeline

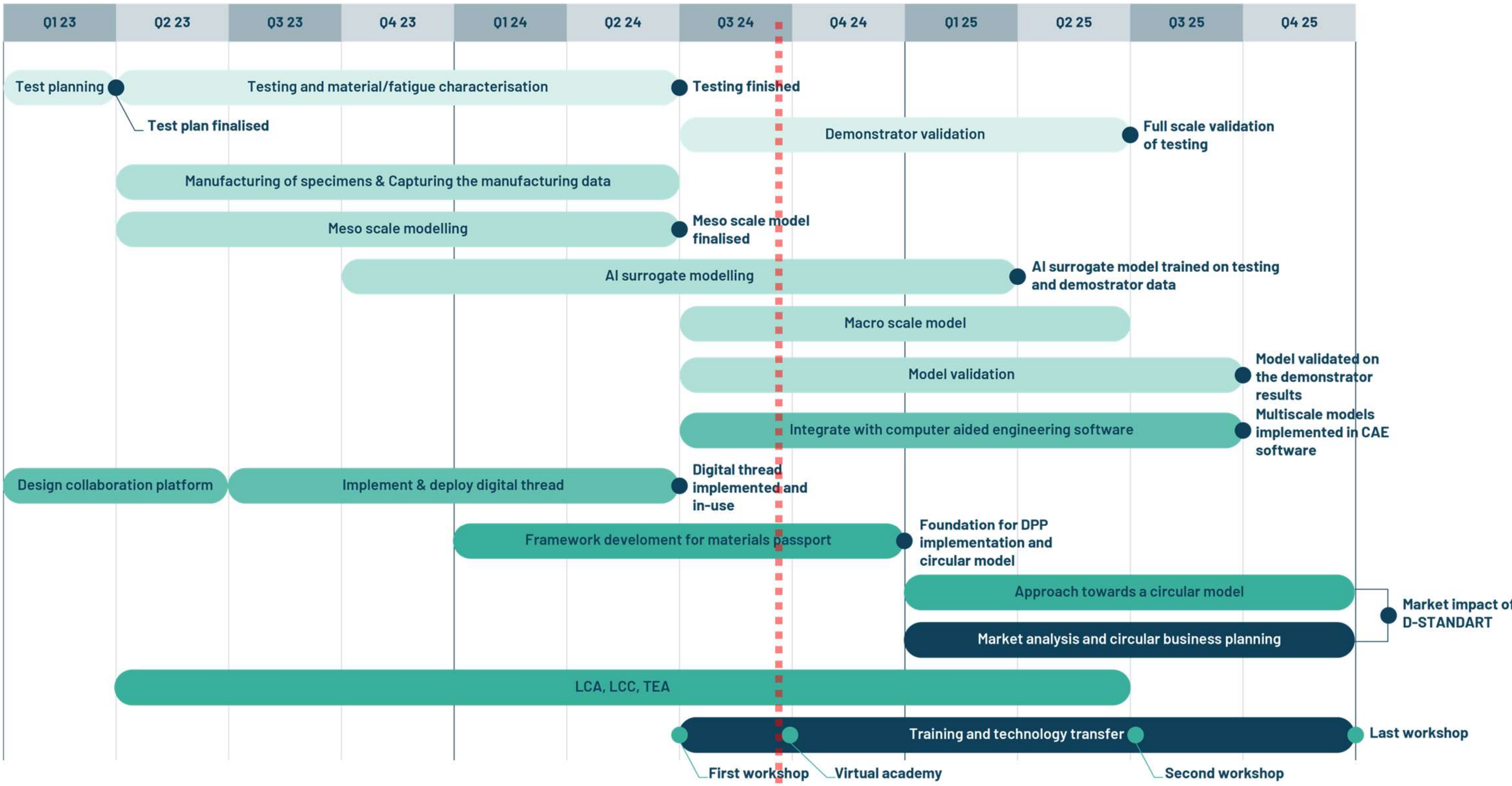
Breakdown of activities

Chapter 4

D-STANDART WBS

And interrelations




Q1 23
Q2 23
Q3 23
Q4 23
Q1 24
Q2 24
Q3 24
Q4 24
Q1 25
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Q3 25
Q4 25
Test planning
Testing and material/fatigue characterisation
Testing finished
Test plan finalised
Demonstrator validation
Full scale validation of testing
Manufacturing of specimens & Capturing the manufacturing data
Meso scale modelling
Meso scale model finalised
AI surrogate modelling
AI surrogate model trained on testing and demostrator data
Macro scale model
Model validation
Model validated on the demonstrator results
Integrate with computer aided engineering software
Multiscale models implemented in CAE software
Design collaboration platform
Implement & deploy digital thread
Digital thread implemented and in-use
Framework develoment for materials passport
Foundation for DPP implementation and circular model
Approach towards a circular model
Market analysis and circular business planning
Market impact of D-STANDART
LCA, LCC, TEA
Training and technology transfer
Last workshop
First workshop
Virtual academy
Second workshop

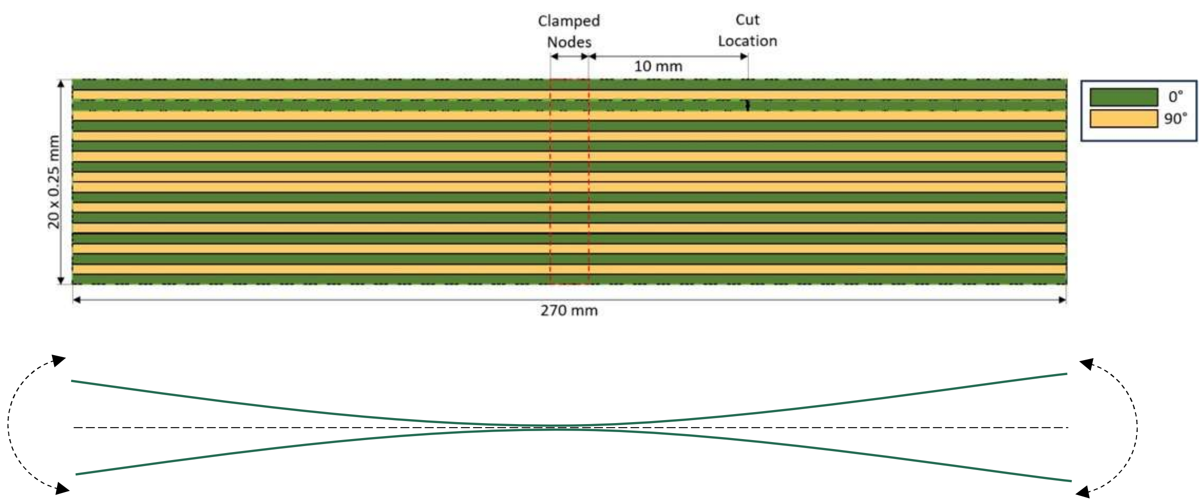
05

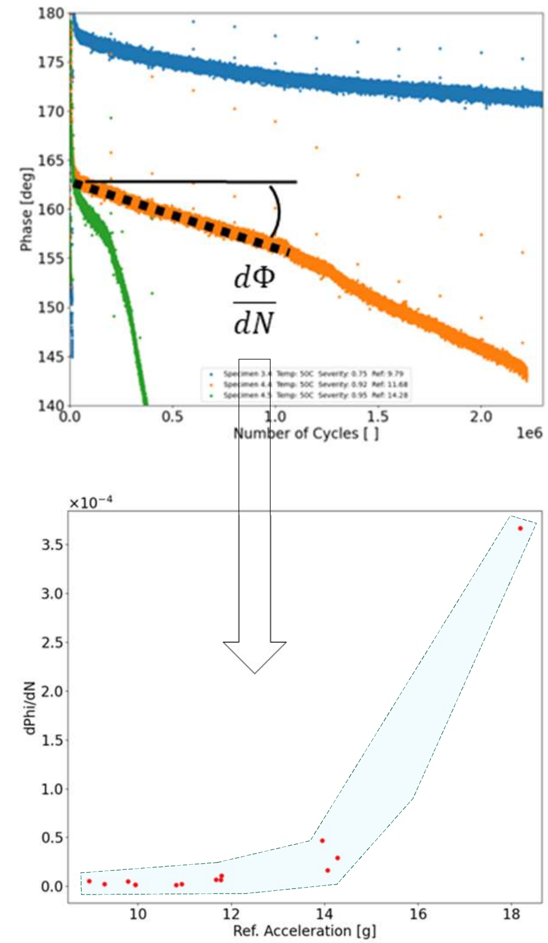
Method Development

Approach & first results

Accelerated testing

High frequency testing



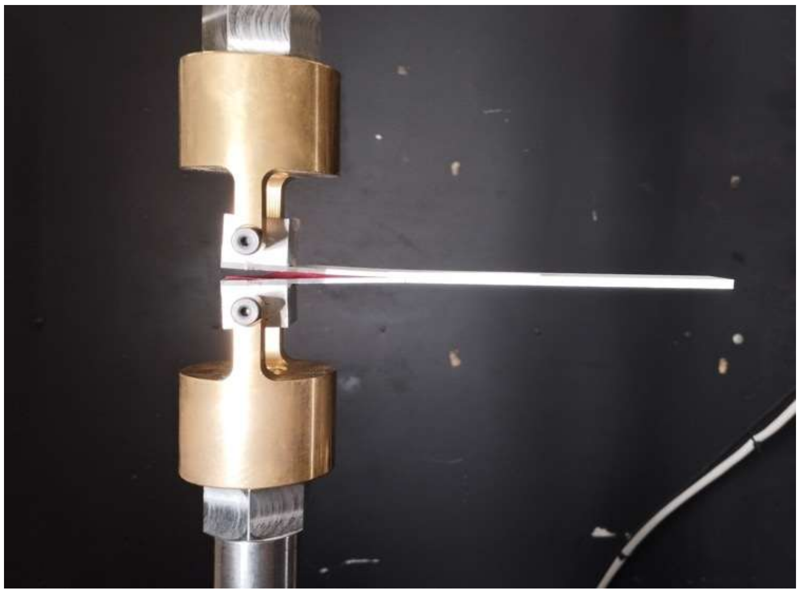


Strong correlation response phase drop, damage propagation, and temperature increase.

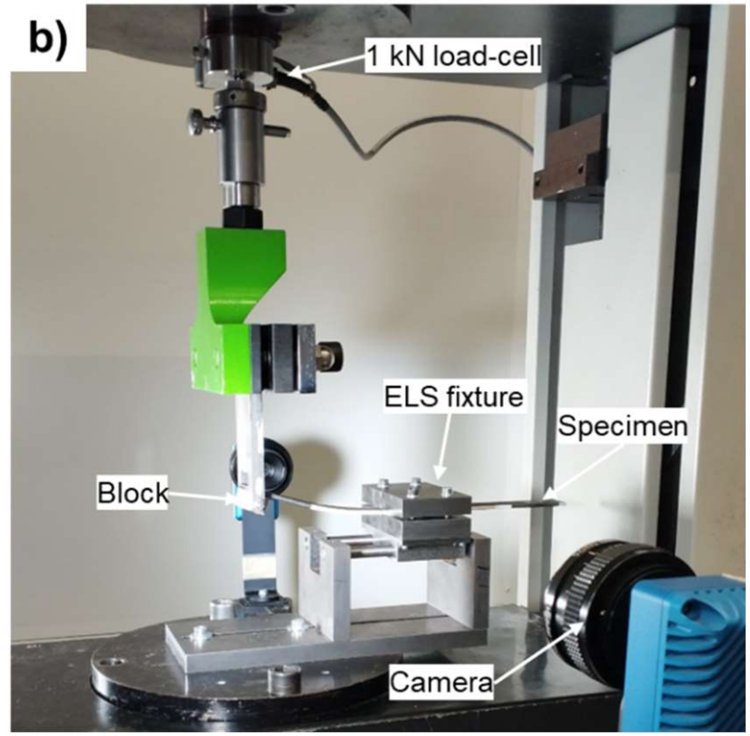
Challenge: correlate to traditional fatigue metrics & design tools

Fibre orientation effect

Based on existing ASTM / ISO standards



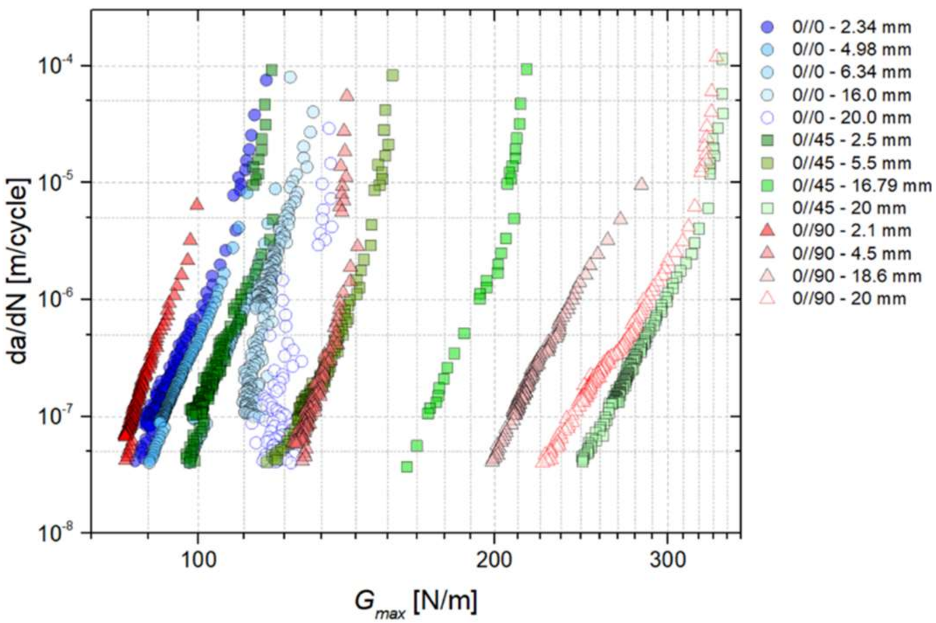
Mode I



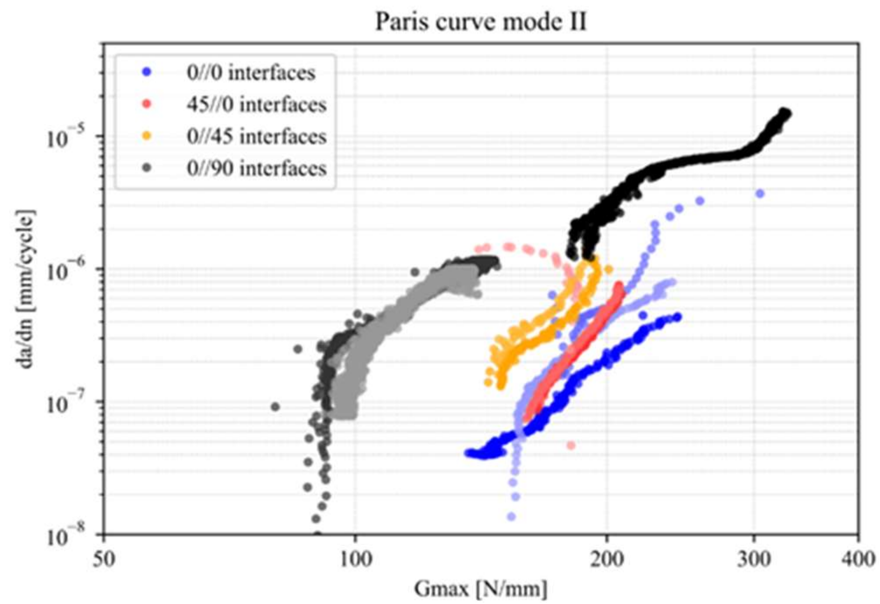
Mode II

Fibre orientation effect

Based on existing ASTM / ISO standards



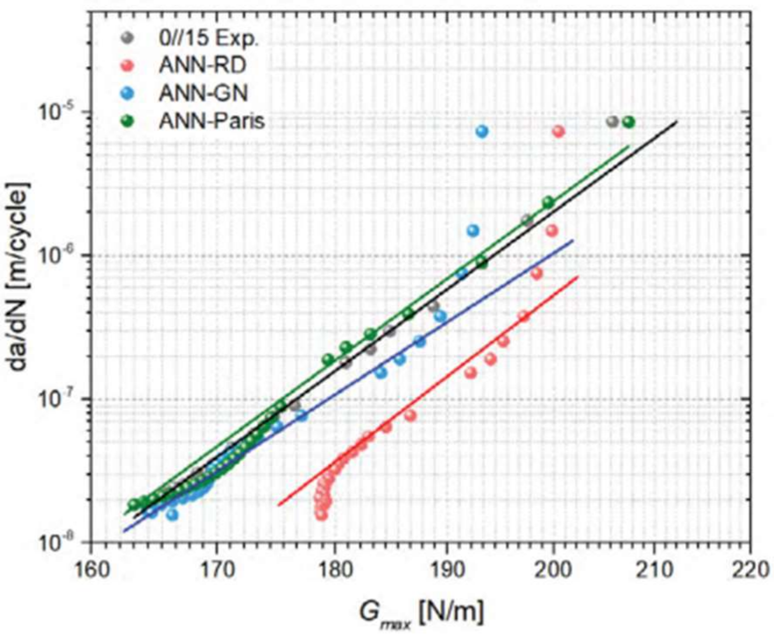
Mode I: Mainly effect at longer pre-cracks -> more fibre bridging



Mode II: Strong effect also for short pre-cracks

ANN to capture fibre orientation effect

Ongoing trials

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1420

Identifying the Most Effective Data Processing for Fatigue Delamination Growth in FRPs: Insights on Artificial Data Simulation

Francisco Maciel Monticeli[1*], Yasmine Mosleh[2], John-Alan Pascoe[1]

NTENTS

Model trained on 0//0, 0//45, 0//90 data; validated against 0//15 data

Modeling of manufacturing features

High fidelity FEA

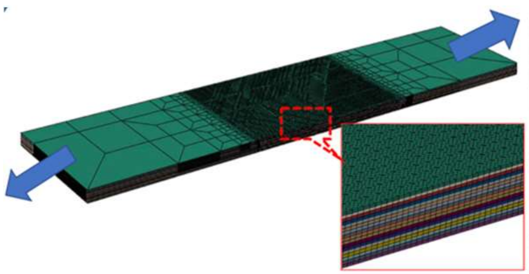


Fig. 5. Snapshot of pristine model.

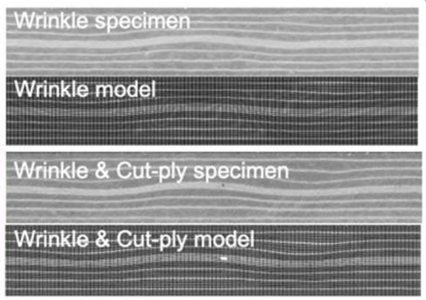


Fig. 6. Cross sections of defect specimens and models.

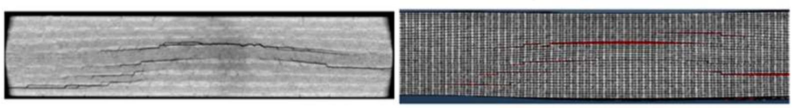


Fig. 7. CT observed and model predicted damage in the “wrinkle” case.

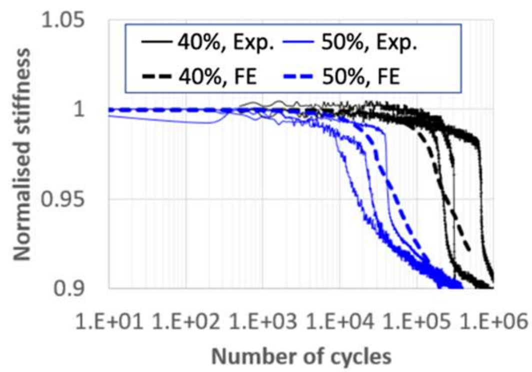


Fig. 8. Comparison between experiment and “wrinkle” model.

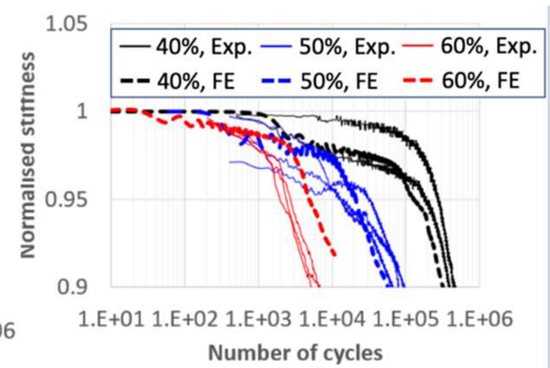


Fig. 9. Comparison between experiment and “wrinkle & cut-ply” model.

Bridging the scales

AI-based surrogate modelling

Experimental data
- Capturing fibre orientation effect
- Capturing manufacturing features

High fidelity mesoscale models
- Validated with experimental data
- Including manufacturing features

Synthetic data
- Database of material fatigue responses at mesoscale

AI model
- Gaussian processes to interpolate material behaviour

Surrogate model
- Material constitutive behaviour

Macroscale FE analysis
- Large structure, coarse mesh
- Surrogate model provides material response

Digital thread

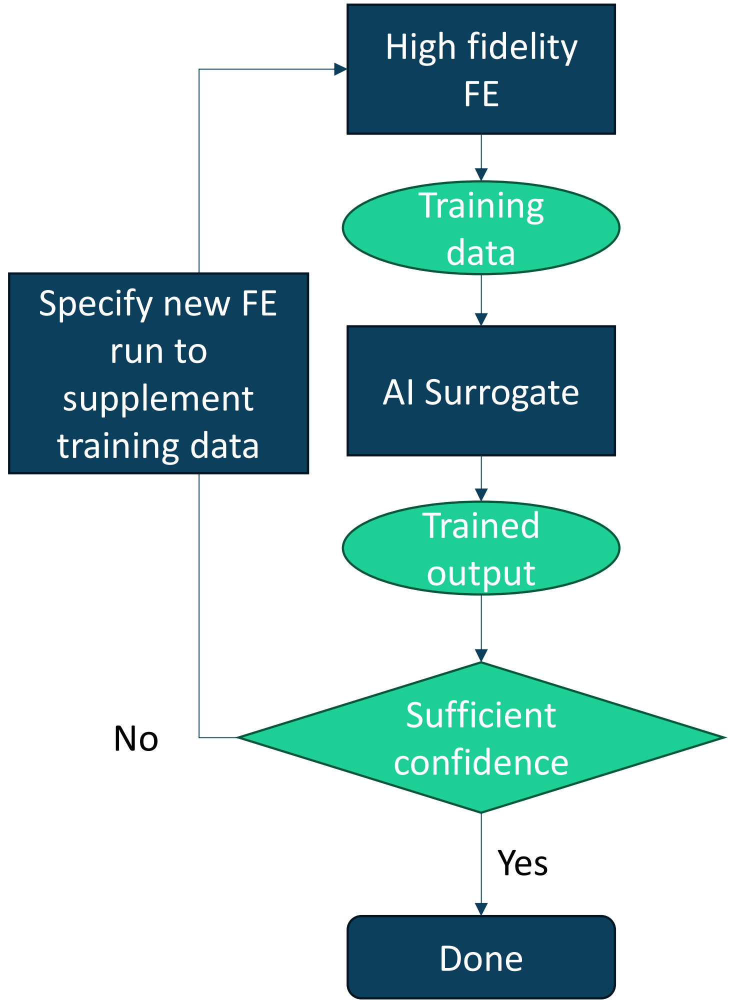
- Facilitate data exchange
- Maintain traceability from macroscale FE back to raw material

AI-based surrogate model

- Gaussian process with adaptive sampling
- Current status: training of quasi-static loading and fracture

- **Inputs**: Load vector (3 normal components, 3 shear components). **Output**: Stress and strain tensors

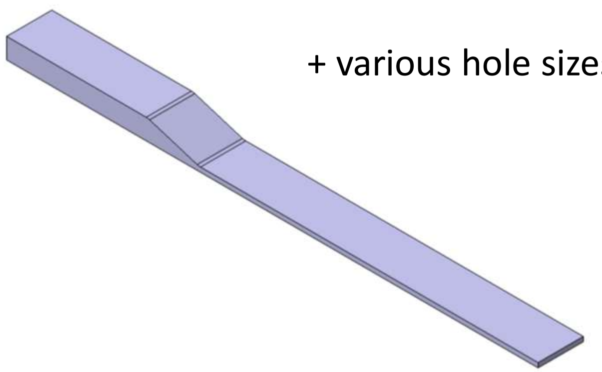
- Advantage of Gaussian process: information on certainty of model outcome, can 'order' new high-fidelity model runs to improve data.



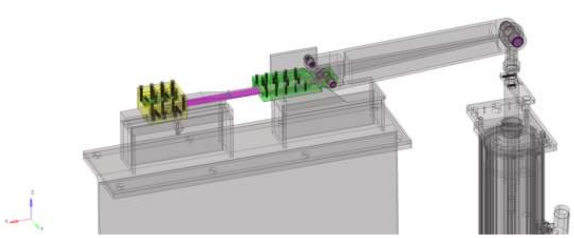
Validation cases

2 demonstrators

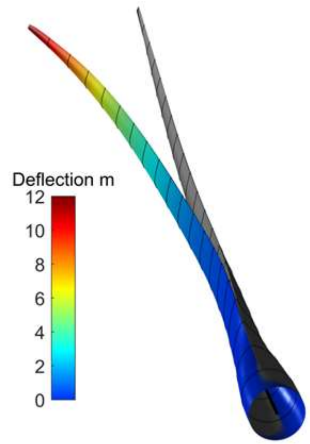
Aero demonstrator

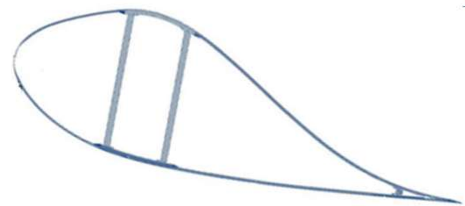


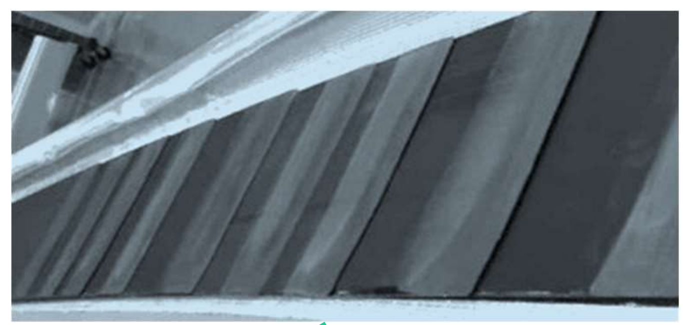
+ various hole sizes

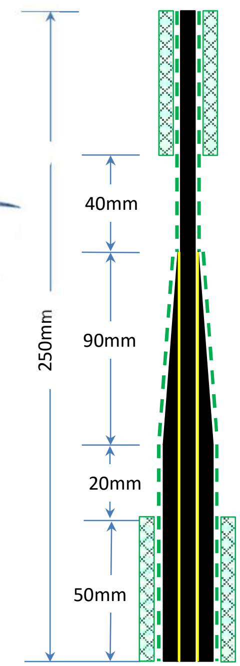


Wind demonstrator

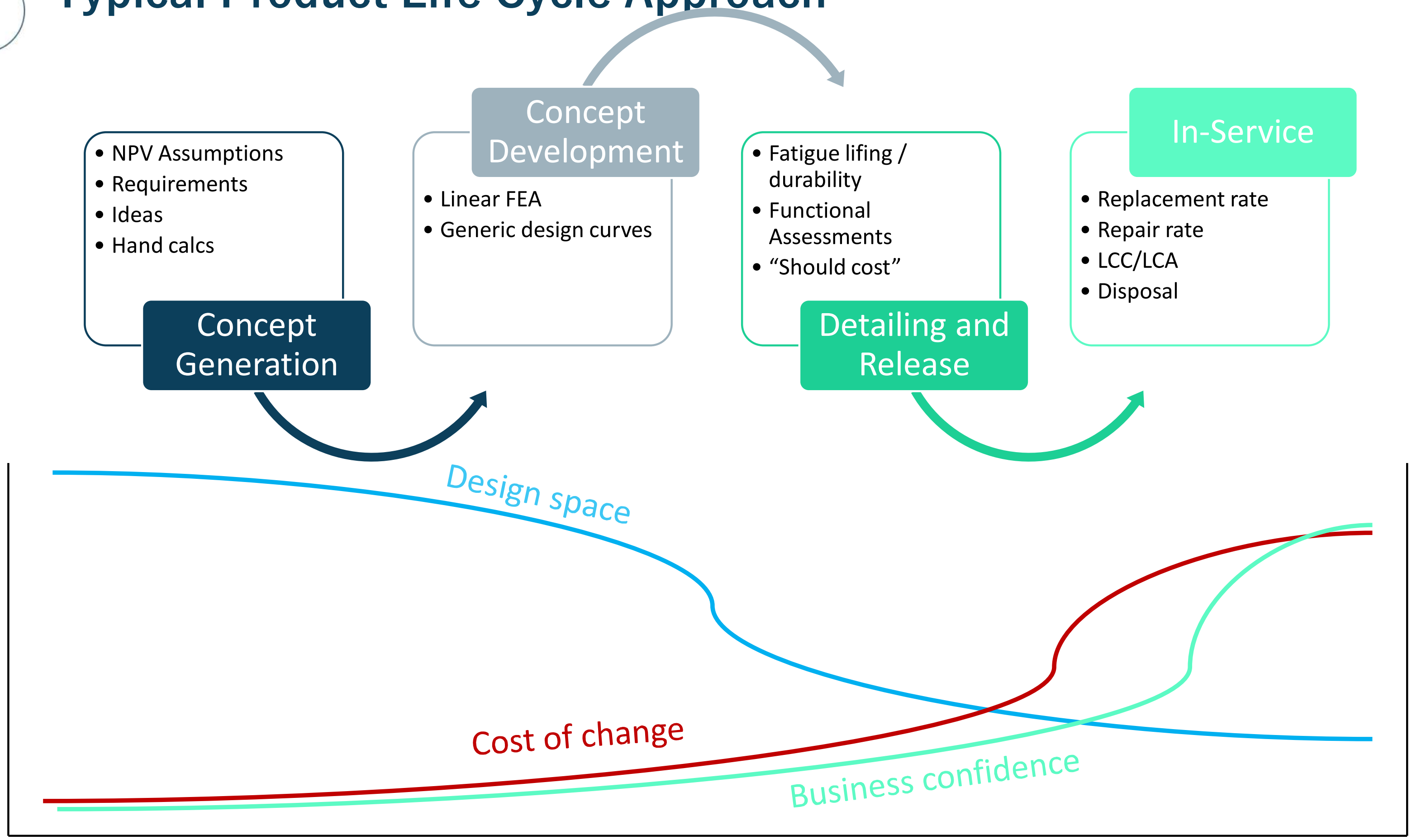








Typical Product Life Cycle Approach



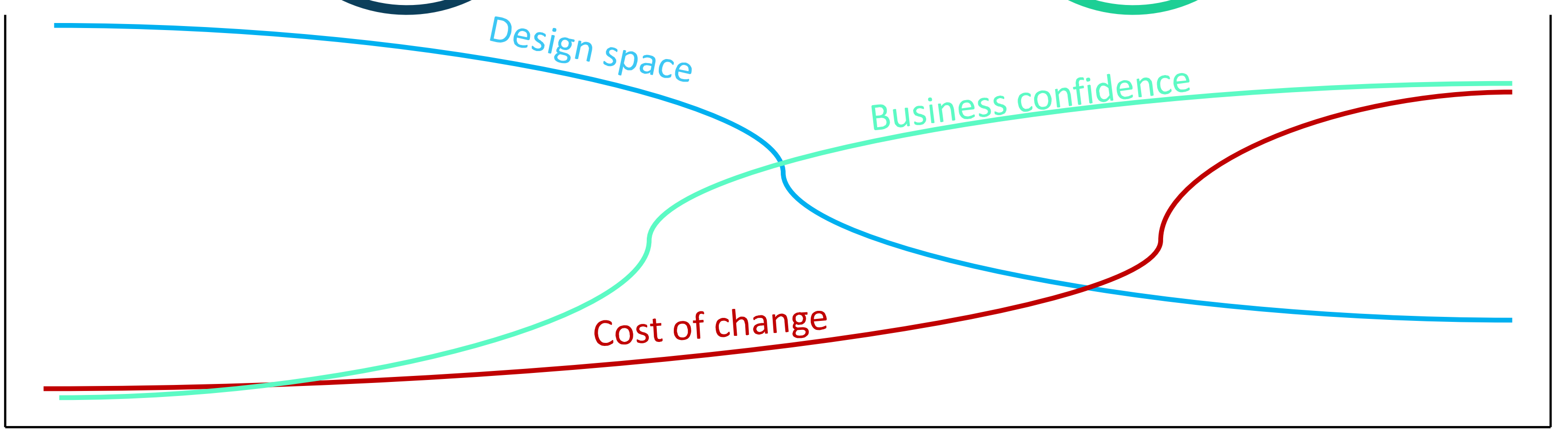
D-STANDART Value Chain

Concept Generation
- NPV Assumptions
- Requirements
- Ideas
- Hand calcs

Concept Development
- Linear FEA
- Generic design curves
- Fatigue lifing / durability
- LCC/LCA
- Disposal/Circularity

Detailing and Release
- Functional Assessments
- “Should cost”

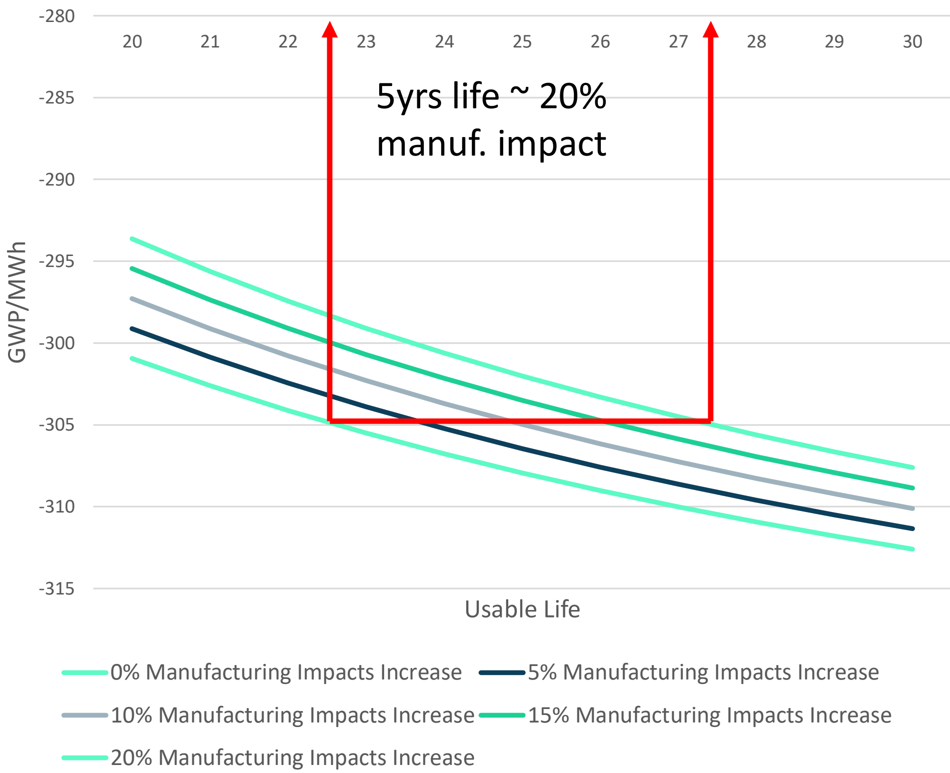
In-Service
- Watch the cash roll in!

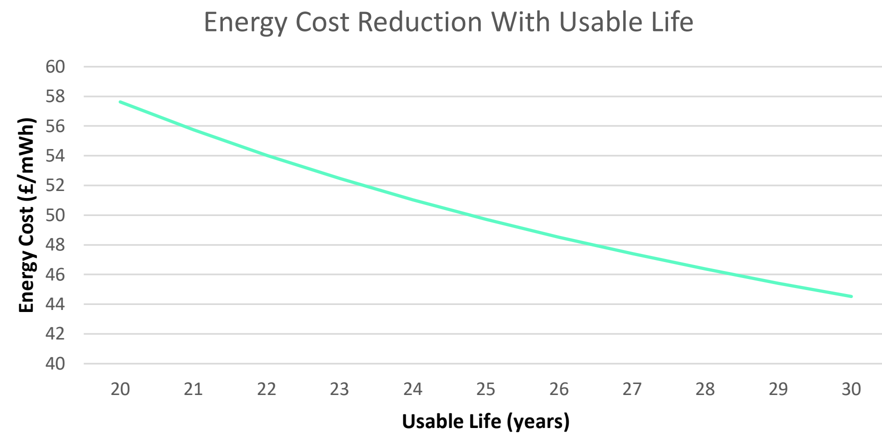


Relationship of LCA/C to Durability – Wind Energy Case Study

Wind Farm

Functional GWP with Life and Manufacturing Impact Increase

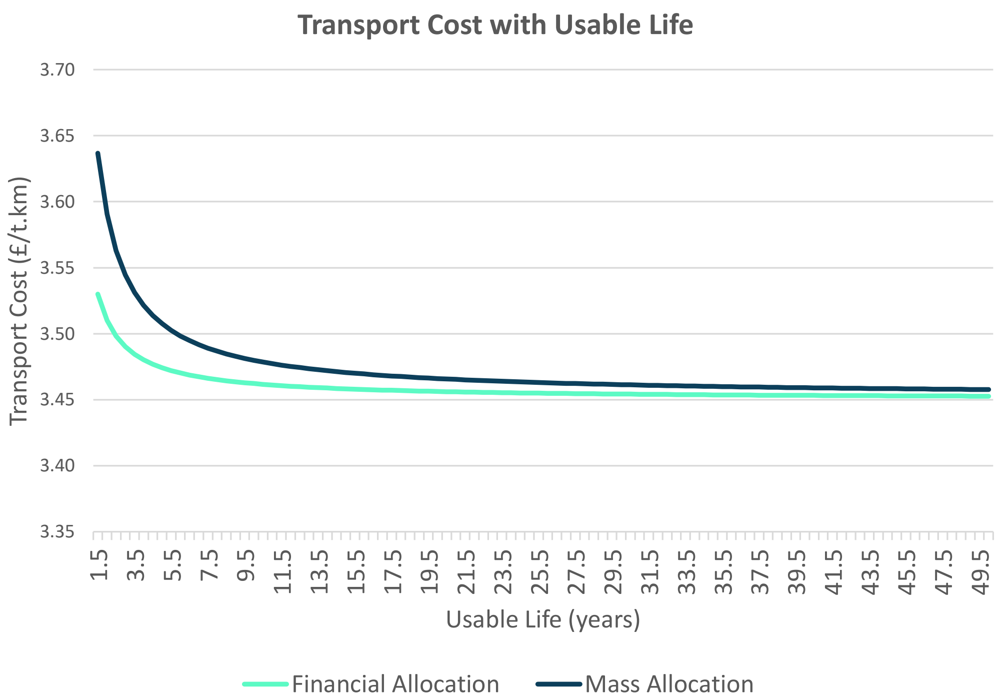




Life Extension (years)	LCOE ($/MWH)	Cost Savings (% from standard life)
(20+) 1	55.7	3.1
(20+) 5	49.7	13.9
(20+) 10	44.5	24.3

Relationship of LCA/C to Durability – Aerospace Case Study

Airbus A350



- Manufacturing costs are quickly eclipsed by use phase, plateauing after 20 years
- Extension of life has minimal cost reductions, with a 10-year life extension only reducing lifecycle cost by 0.07%

06

EMMC & EMCC

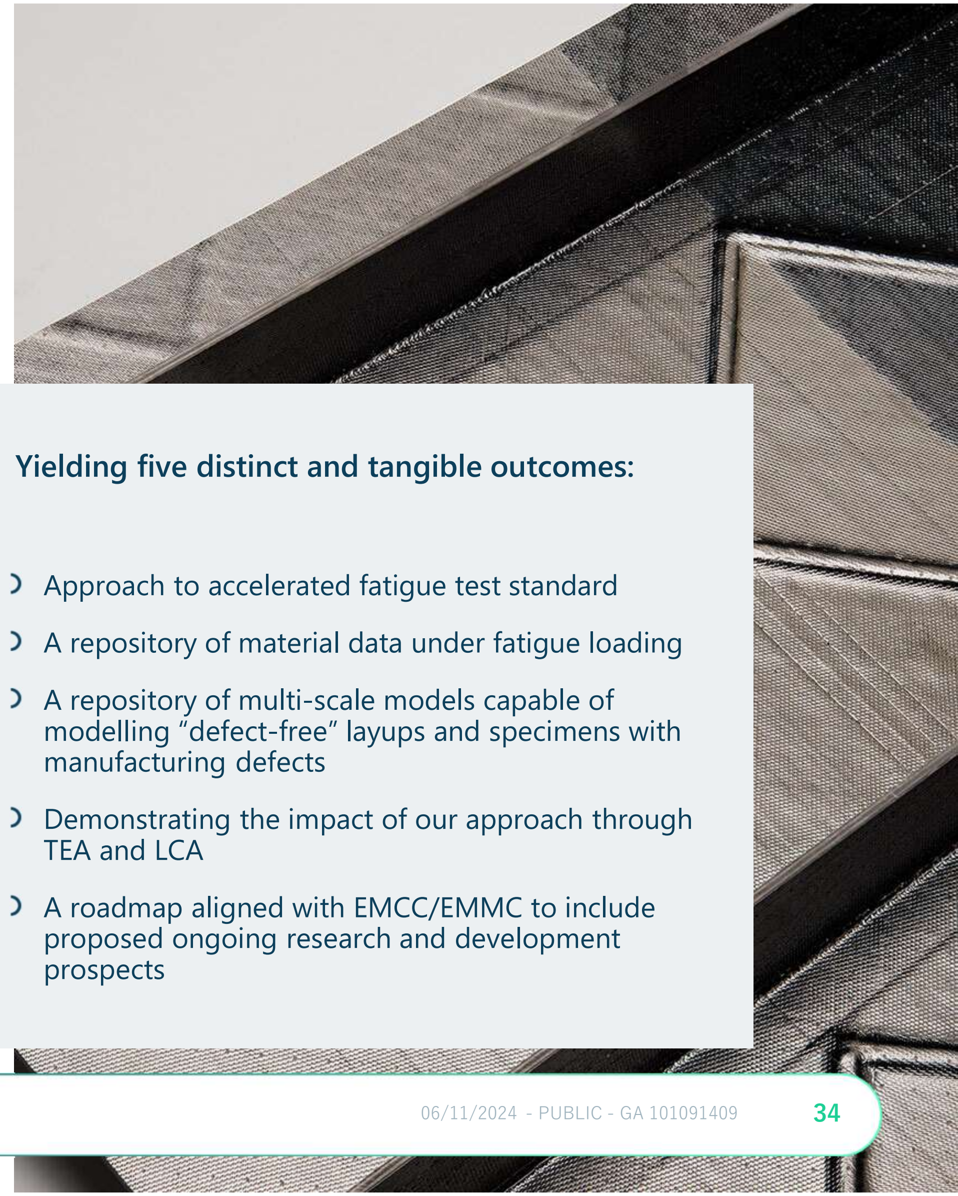
Alignment

Chapter 6

EMMC & EMCC alignment

D-STANDART

Priority to align with EMMC and EMCC objectives at proposal stage



Five complimentary activities:

- Test methodology
- Material characterisation
- AI-enable material modelling
- Life-cycle assessment
- Digital thread

Yielding five distinct and tangible outcomes:

- Approach to accelerated fatigue test standard
- A repository of material data under fatigue loading
- A repository of multi-scale models capable of modelling “defect-free” layups and specimens with manufacturing defects
- Demonstrating the impact of our approach through TEA and LCA
- A roadmap aligned with EMCC/EMMC to include proposed ongoing research and development prospects

Chapter 6

EMMC & EMCC contributions

Addressing their objectives

Contribution to EMMC objectives

- "to promote modelling by means of physics-based and data-driven models in industry" – EMMC White Paper
- "The goal is to strengthen the link between materials modelling and experiments by developing improved post-processing models with the necessary physics contents [...]" – EMMC website

Contribution to EMCC objectives

- "To support establishing a community of European stakeholders in the process of developing and improving characterisation tools in order to bring [...] advanced materials in Europe into end products more successfully." – EMCC website
- "[...] roadmap for characterisation techniques for engineering and upscaling of [...] advanced materials in Europe. [...] support the strengthening of Europe's industrial capacity and competitiveness" – EMCC website

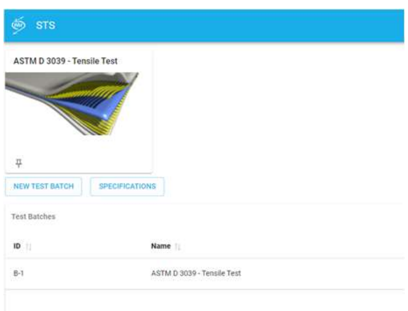
D-STANDART specific objective: **Develop fatigue behaviour models** at the **micro-and meso-scale** levels, and **AI surrogate models** at the **meso-scale** level. To develop a finite-element based, validated probabilistic meso-mechanical modelling framework for the prediction of the fatigue performance of laminates. Exploit AI trained surrogate models for fatigue **prediction of macro-scale structures**.

Chapter 6

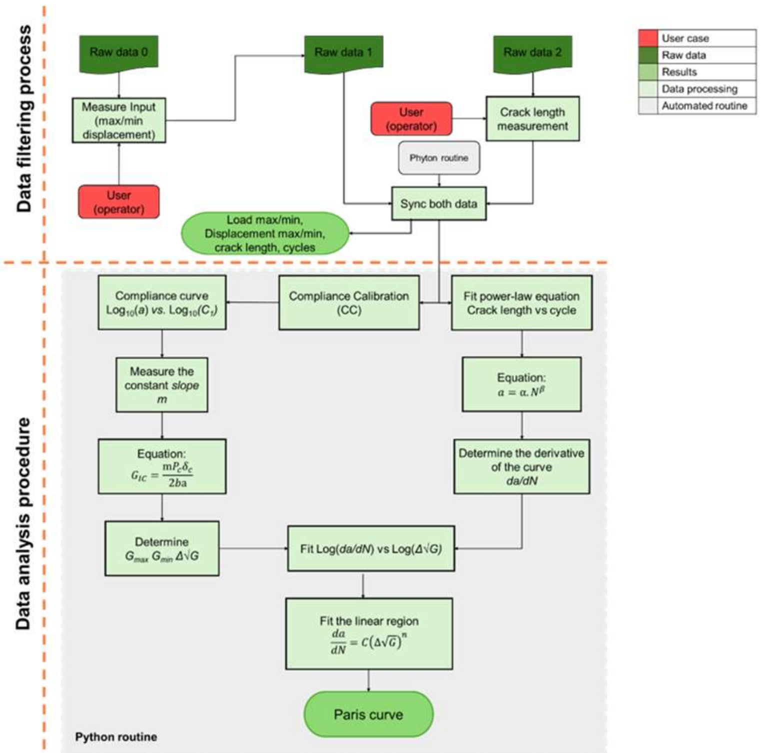
EMMC & EMCC contributions

Use of CHADA/MODA/EMMO

- CHADA and MODA templates in use for meta-data capture within D-STANDART
- CHADA / EMMO integrated into digital thread infrastructure



1. Plate		
1.1	Number	*Group 1*
1.2	Name	*TUD-Group 1 - (0-0) – 01*
1.3	Name convention	*Figure 1* *TUD - Institution* *Group 1 = The first manufacturing group (each group has 4 plates);* *(0-0) = Orientation at the delamination layer (0//0)* *01 = Number o repetition of the same configuration*
1.4	Material	IM7/8552 Unidirectional carbon fiber composite (Hexcel)
1.5	Lay-up	*[0_{11}/0//0/0_{11}]* *Note: Double slash (//) means the delamination region*
1.6	Organisation	Technische Universiteit Delft (TUD)
1.7	User	*Francisco Maciel Monticeli*
1.8	Manufacturer data sheet	*Document reference: Figure 2 Hexply datasheet* - *Hand lay-up to manufacture the laminate plates.* - *Process type: Autoclave* - *Cure step 1: 110 °C for 60 min* - *Cure step 2: 180 °C for 120 min* - *Pressure: 7 bar* - *Vacuum: 0.2 bar*



07

Cross-fertilisation

Synergy with sister projects

Chapter 7

Cross-fertilisation

Synergy with sister projects

Project No.	Acronym	Title
101091409	D-STANDART	Durability Modelling of Composite Structures with Arbitrary Lay-up using Standardized Testing and Artificial Intelligence
101091621	AddMorePower	Advanced modelling and characterization for power semiconductor materials and technologies
101091534	KNOWSKITE-X	Knowledge-driven fine-tuning of perovskite-based electrode materials for reversible Chemicals-to-Power devices
101091687	MatCHMaker	Open data and industry driven environment for multiphase and multiscale Materials Characterization and Modelling combining physics and data-based approaches
101092211	CoBRAIN	Integrated Computational-Experimental material Engineering of Thermal Spray coatings
101091912	AID4GREENEST	AI powereD characterization and modelling for GREEn STeel technology

Thank you!

Contact points for any question:

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in

zenodo

d-standart.eu

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D-standart

for Durability Modelling of Composites

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