Certification for Design: Re-shaping the Testing Pyramid for Composite Aerostructures (CerTest)

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Outline

- Background and motivation
- Overview of CerTest research challenges and methodology (process flow and how it works?)
- Steps towards demonstration of new methodology – Modelling, UQ & Calibration
- Summary / Vision

The prize?

REDUCED DEVELOPMENT TIME / TIME TO MARKET!

REMOVING/REDUCING BARRIERS TO INNOVATION POSED BY CURRENT PROCESSES

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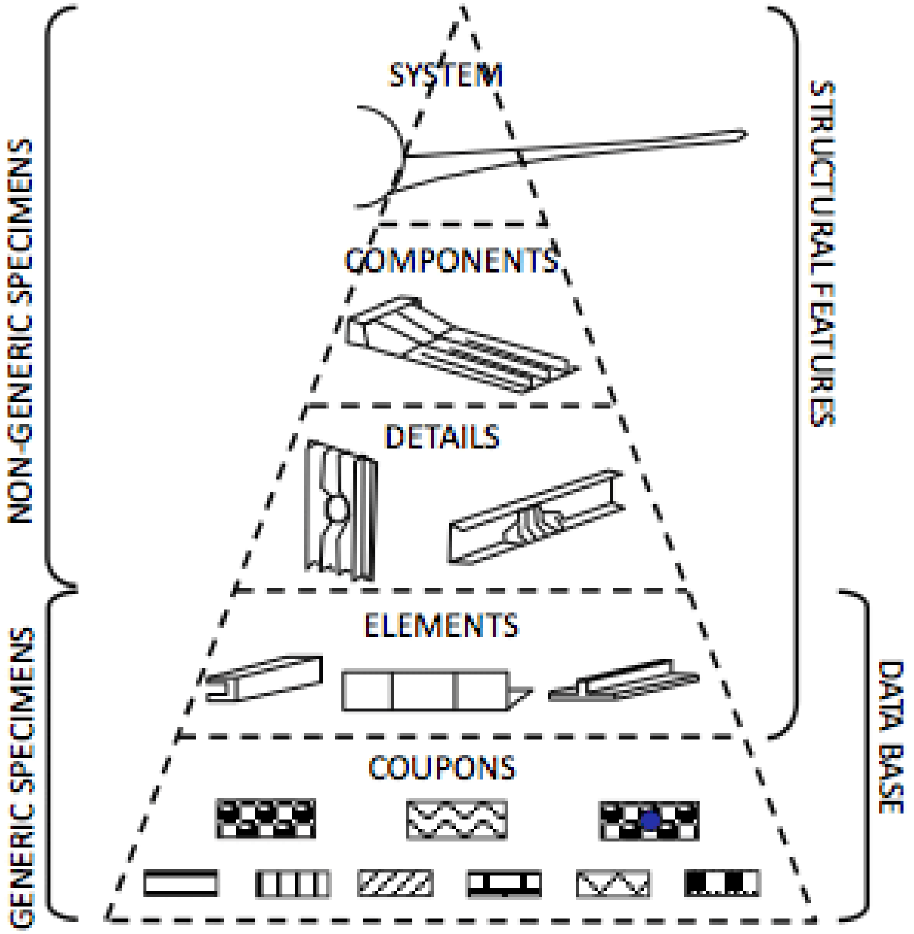
CERTEST

Background and motivation – what is the problem?

- Many tests on coupon and element (10-20cm) levels of testing pyramid – for certification
- Few test on component (1-10m) level – but full scale (>30m) tests are required for certification (very costly and time consuming)

Compliance with EASA/FAA regulations – currently “building block” approach / “testing pyramid”



- Coupon/element level representative of component/full structure?
- Costly (both time and money)
- Inhibits optimum design and innovation
- Proven record of trust and safe operation

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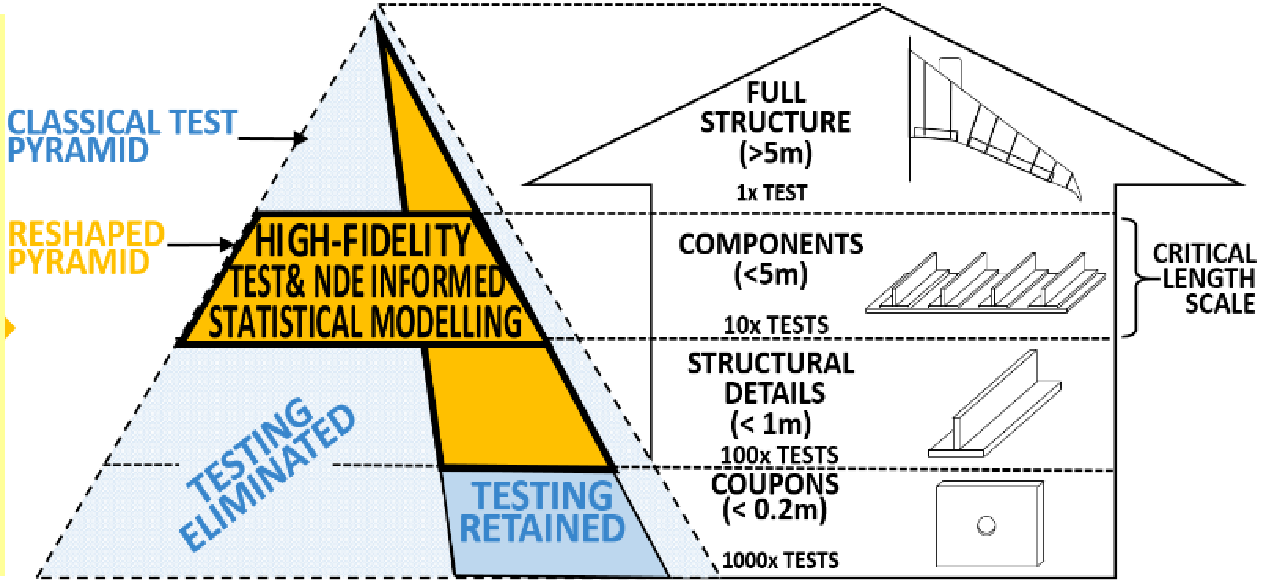
- Programme Grant: *"Certification for design – Reshaping the Testing Pyramid"*
- 2019-2025

CerTest Vision

Development and validation of scientific/engineering tools that will enable VIRTUAL composite structure performance validation - relying on less physical testing and accounting for uncertainty and variability on all levels

Key enabler – integration of multi-scale modelling and high-fidelity data-rich testing on structural scale via Bayesian learning and ”Design of Experiments”

- UQ CHALLENGE :New statistical frameworks must be created to design, model and test at the component/sub-structure level, safely accounting for uncertainty whilst exploiting new design opportunities including manufacturability



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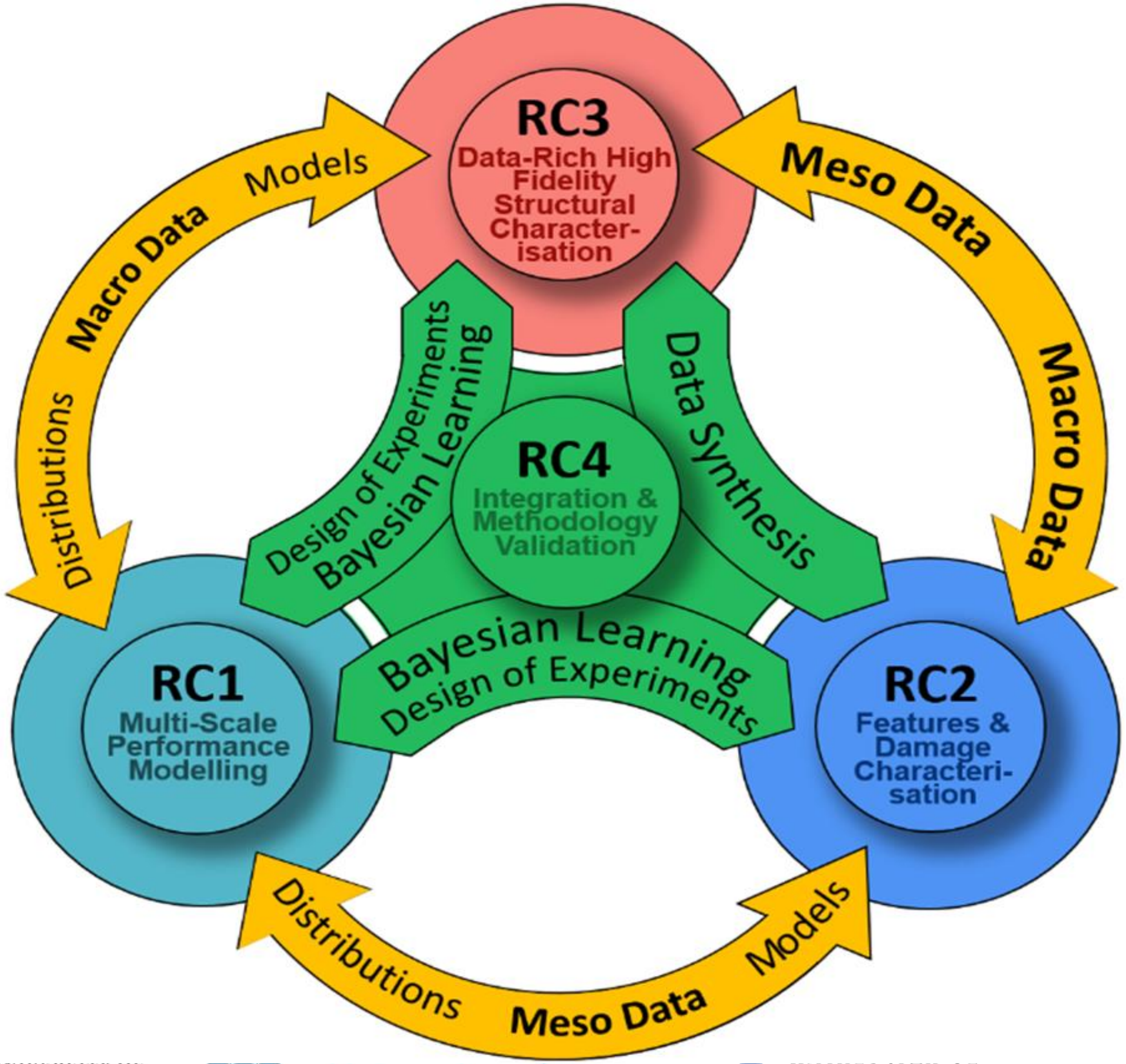
CerTest Operation

RC1
Multi-scale Performance Modelling

RC2
Features and Damage Characterisation

RC3
Data-rich High Fidelity Structural Characterisation

RC4
Integration and Methodology Validation



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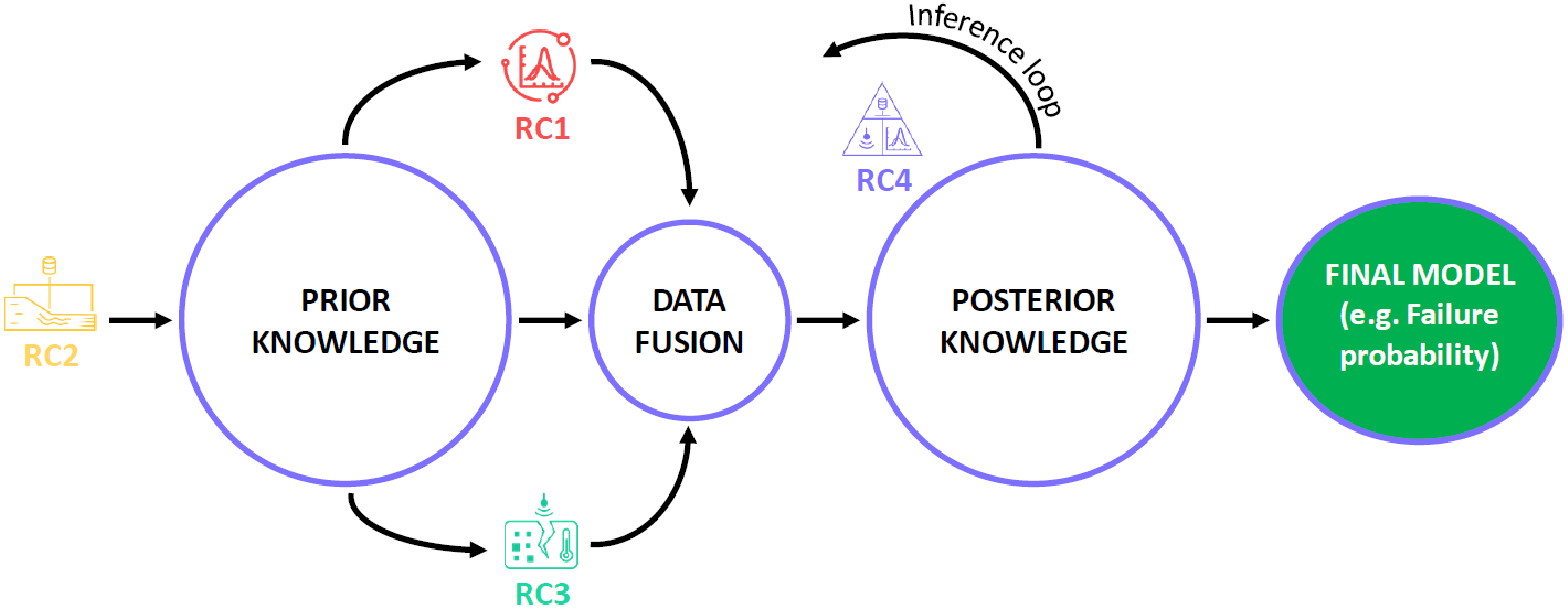
CerTest hypotheses

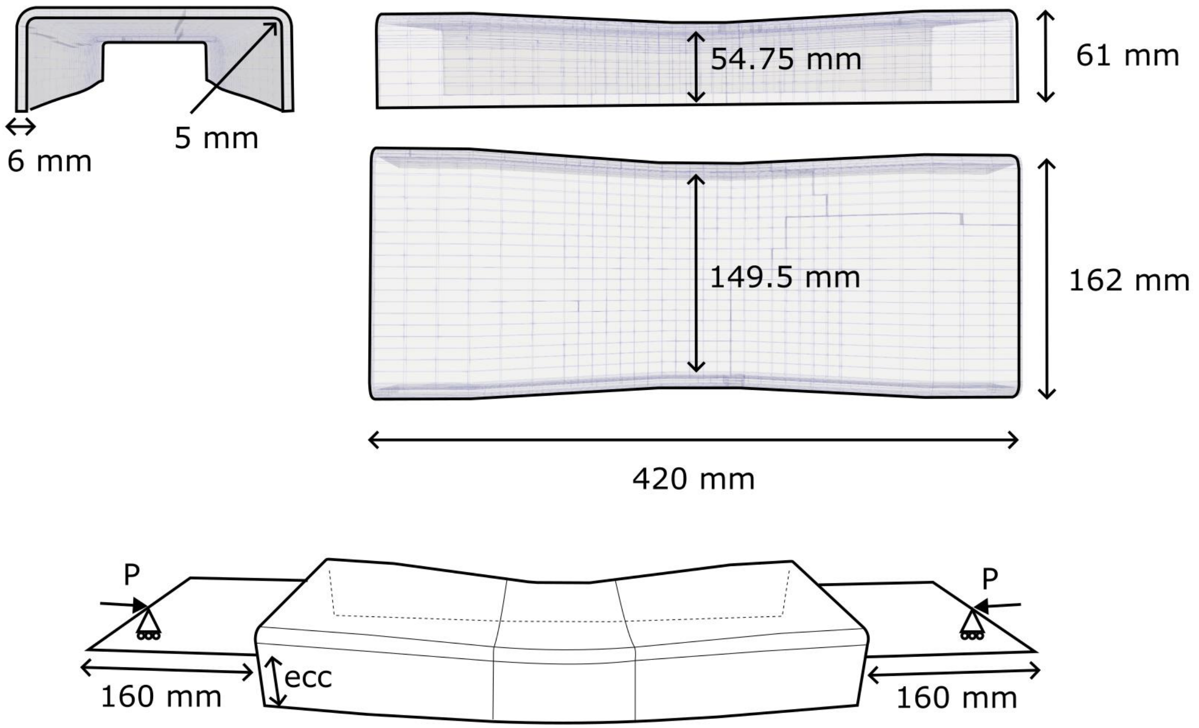


CerTest: 2-part status

1. **Calibration** using standard Finite Element Analysis and full field data for 1 physical test
2. **Multiscale modelling** using Spectral Generalized Finite Element Method (**MS-GFEM**)

- Applied to compressively loaded **C-spar** (university test article)
- 24 layers of unidirectional carbon fibre produces 6mm thickness
- Stacking sequence $[(+45/-45/0/90)_3]_S$

C-spar



CerTest status: Part 1 - Calibration

Bayesian Calibration of a Geometrically Nonlinear Finite Element C-spar Model using Digital Image Correlation

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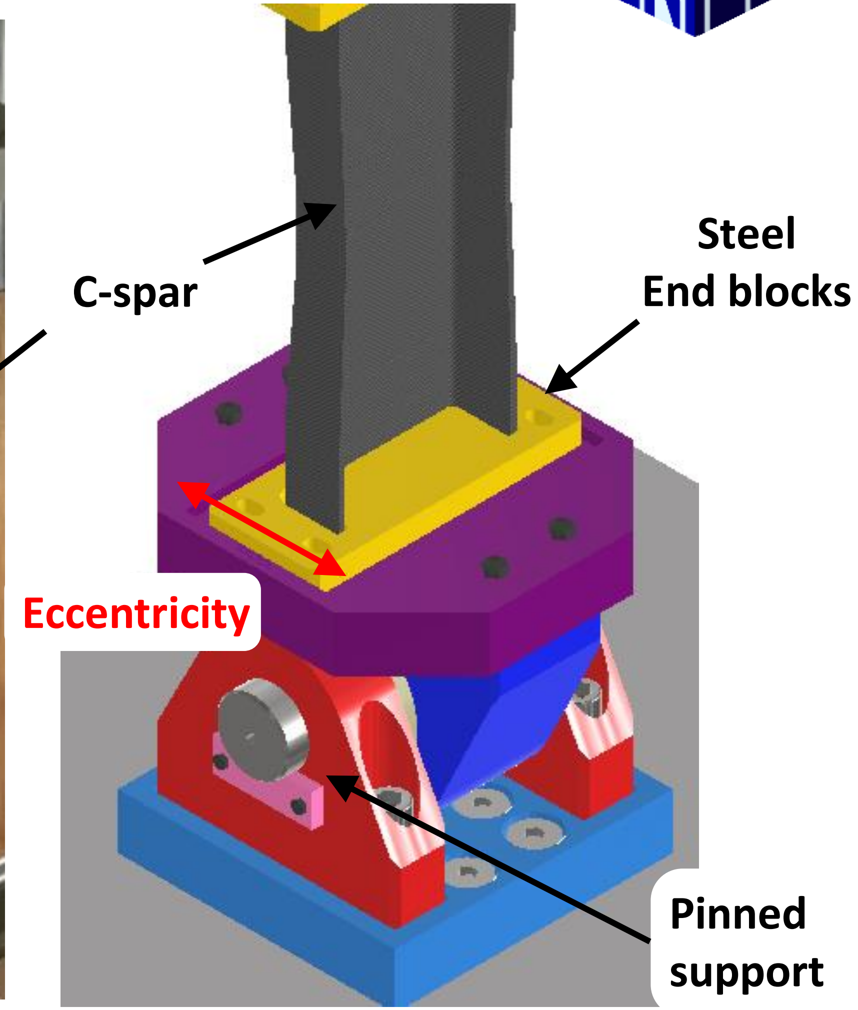
Calibration problem overview

- **Calibration** uses experimental data to inform model predictions while accounting for uncertainty due to unknown model inputs and observation errors
- Digital Image Correlation (DIC) data from Compression tests on a C-spar.
- +6mm load eccentricity relative to gauge section centroid.
- ABAQUS model with material, boundary condition, and geometric uncertainty.
- Main challenge is using large volumes of DIC data spanning both **time** and **space**, to calibrate **full-field** model output.



Test fixture design showing boundary conditions

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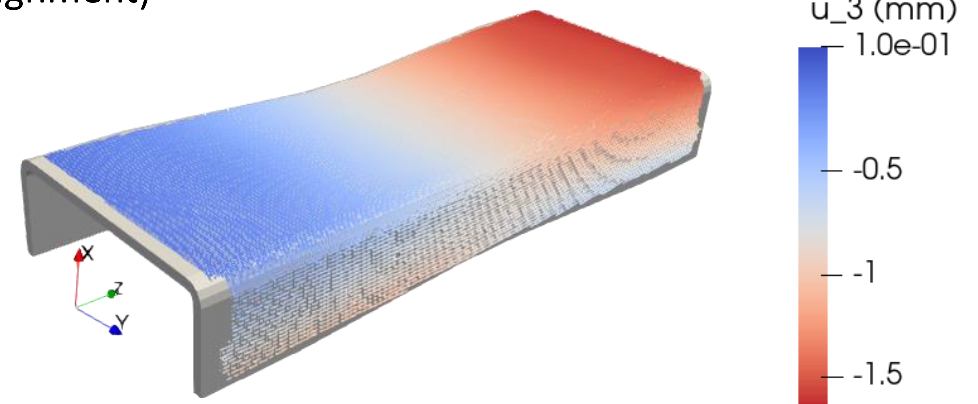
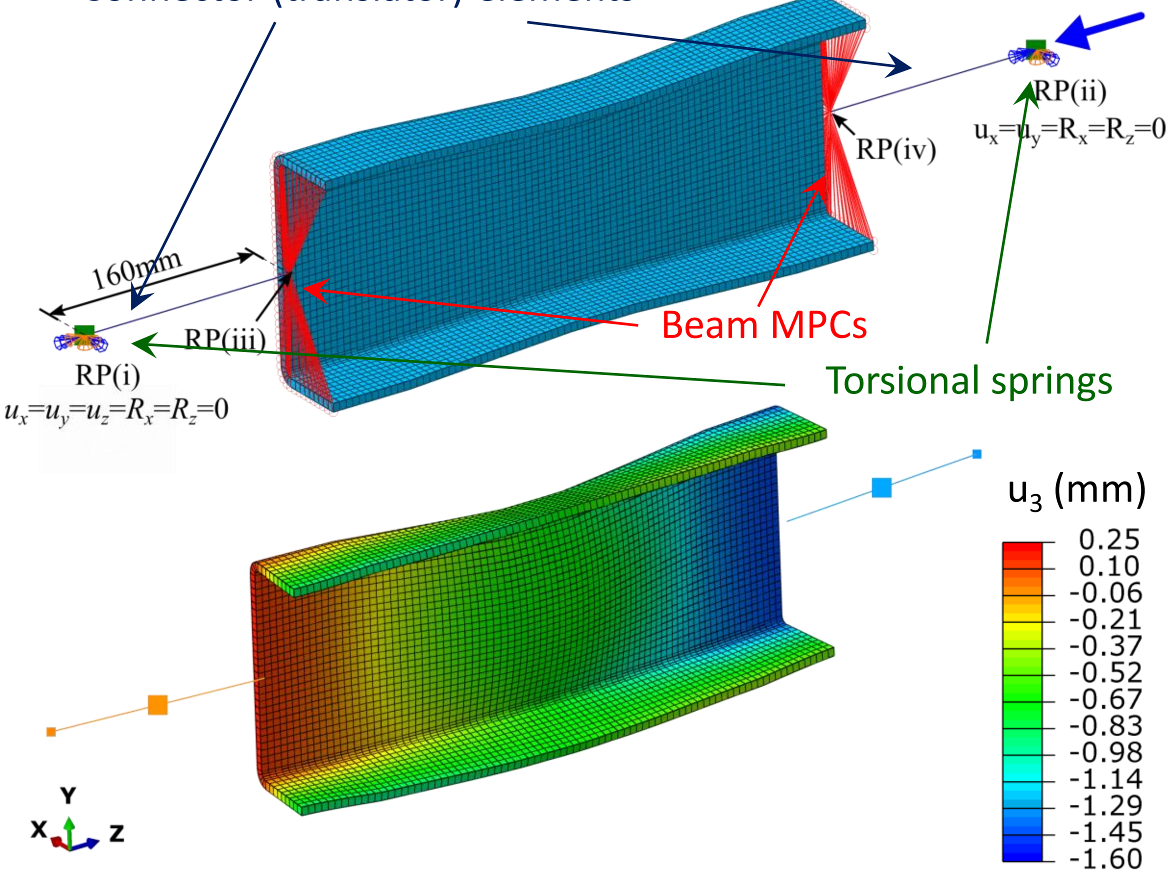
FE Model and DIC data

- ABAQUS model 5000 continuum **shell** elements; returns output at 10kN increments up to 200 kN
- Experimental point cloud has 40,000 displacement measurements for each load, interpolated to match ABAQUS solver increments.
- Uncertainty in boundary conditions modelled via:
  - Connector elements with uncertainty stiffness for rig compliance
  - Torsional springs with uncertain stiffness model resistance at bearing
  - *x* coordinate of reference points capture eccentricity error (misalignment)



DIC point cloud for longitudinal displacement at 200 kN overlaid on mesh



ABAQUS model showing boundary conditions, deformed shape, and longitudinal displacement field at 200 kN

Calibration methodology

- Following Higdon et al.[1], method for calibrating models with vector-valued output:

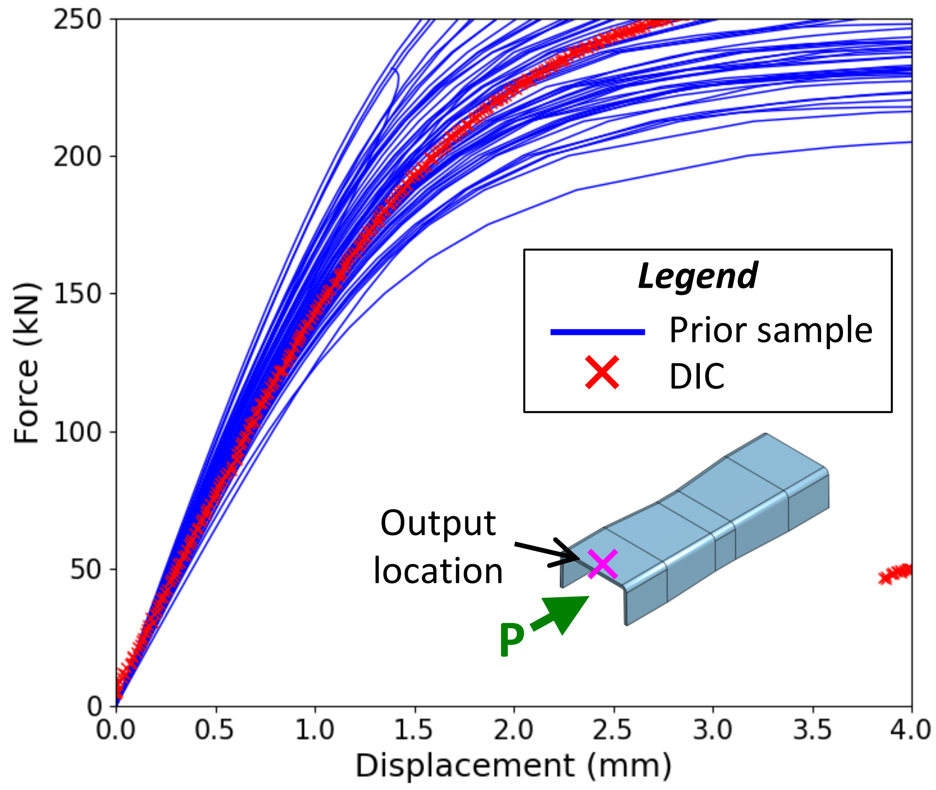
$$\boldsymbol{y} \quad = \quad \boldsymbol{\eta}(\boldsymbol{\theta}^*) \quad + \quad \boldsymbol{\varepsilon}$$

DIC Abaqus model Error

$\boldsymbol{\theta}^*$ = uncertain inputs we want to learn about:

Elastic modulus E_{11}, ply thickness t_{ply}, rig stiffness K_{rig}, bearing stiffness $K_{bearing}$, eccentricity error

- Solve an inverse problem to find $\boldsymbol{\theta}^*$ and $\boldsymbol{\varepsilon}$, given known $\boldsymbol{y}$.
- Gaussian process emulators fitted to output $\boldsymbol{\eta}$ from 50 Abaqus runs.
- Dimension of model output reduced through Singular Value Decomposition.
- **Prior distributions** specified based on existing test data, literature, and engineering judgment.
- Apply Bayes theorem to sample from the **posterior distribution** using Hamiltonian Monte Carlo (No-U-Turn Sampler, NUTS) in Stan[2].

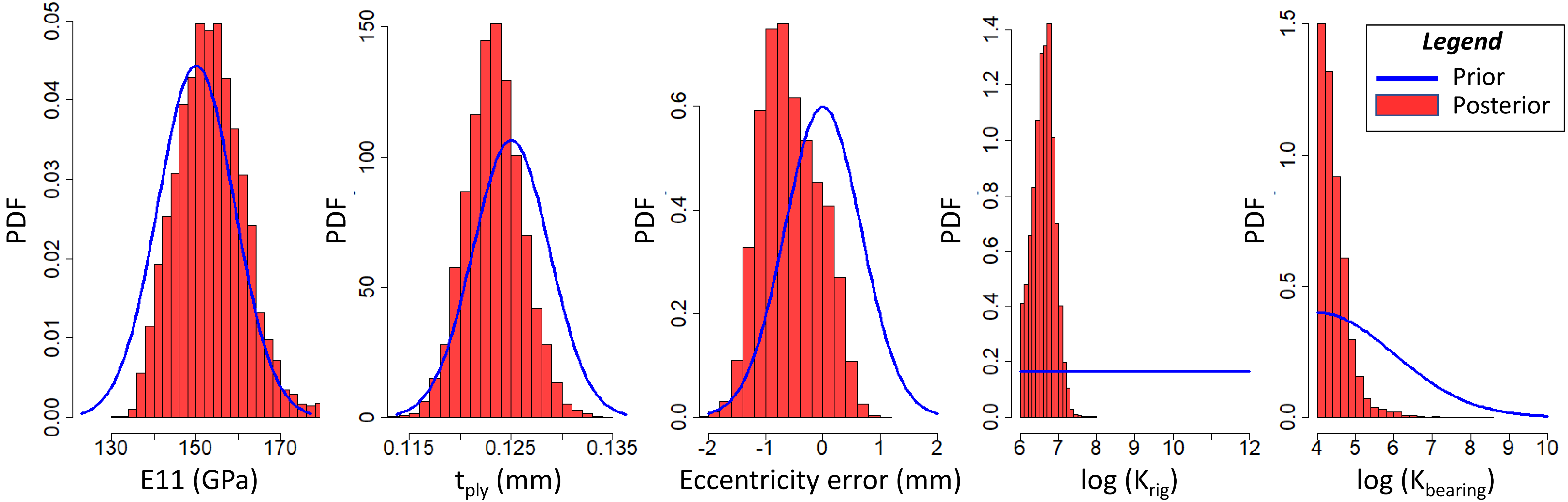


Extract of training data from fixed point on C-spar surface

[1] *D. Higdon et al, "Computer model calibration using high-dimensional output", Journal of the American Statistical Association, 2008*

[2] *Stan modeling language users guide and reference manual, Version 2.26.1, https://mc-stan.org*

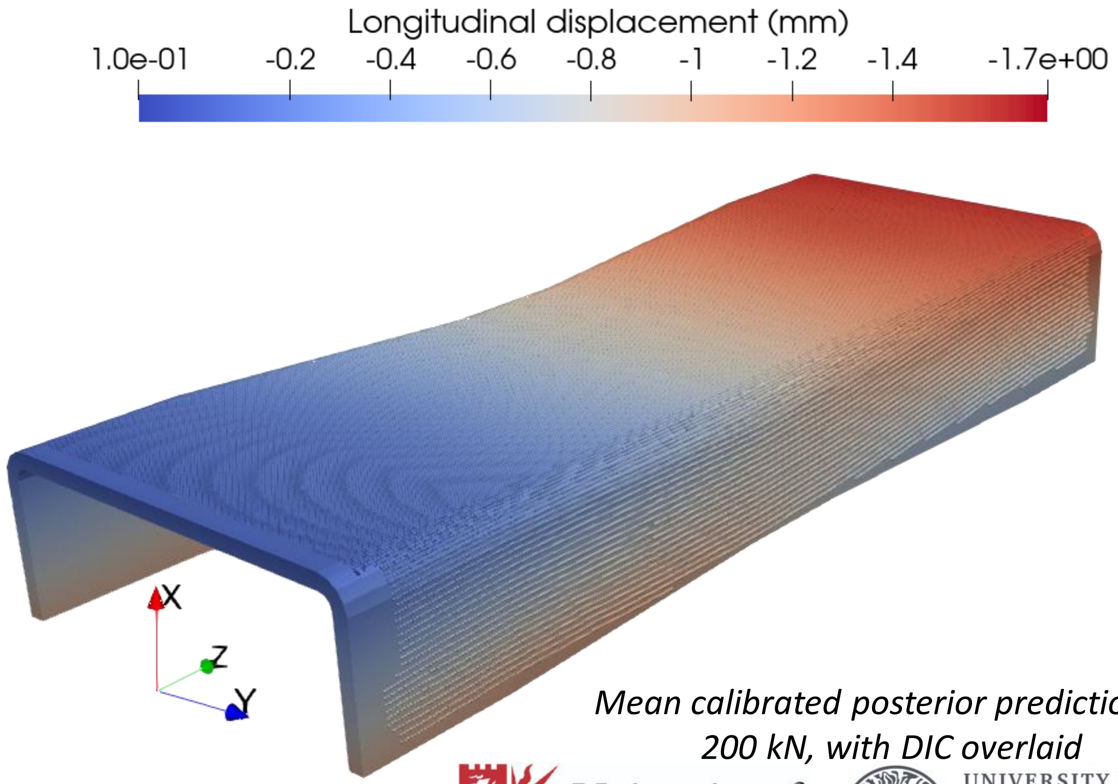
Results: Uncertain inputs



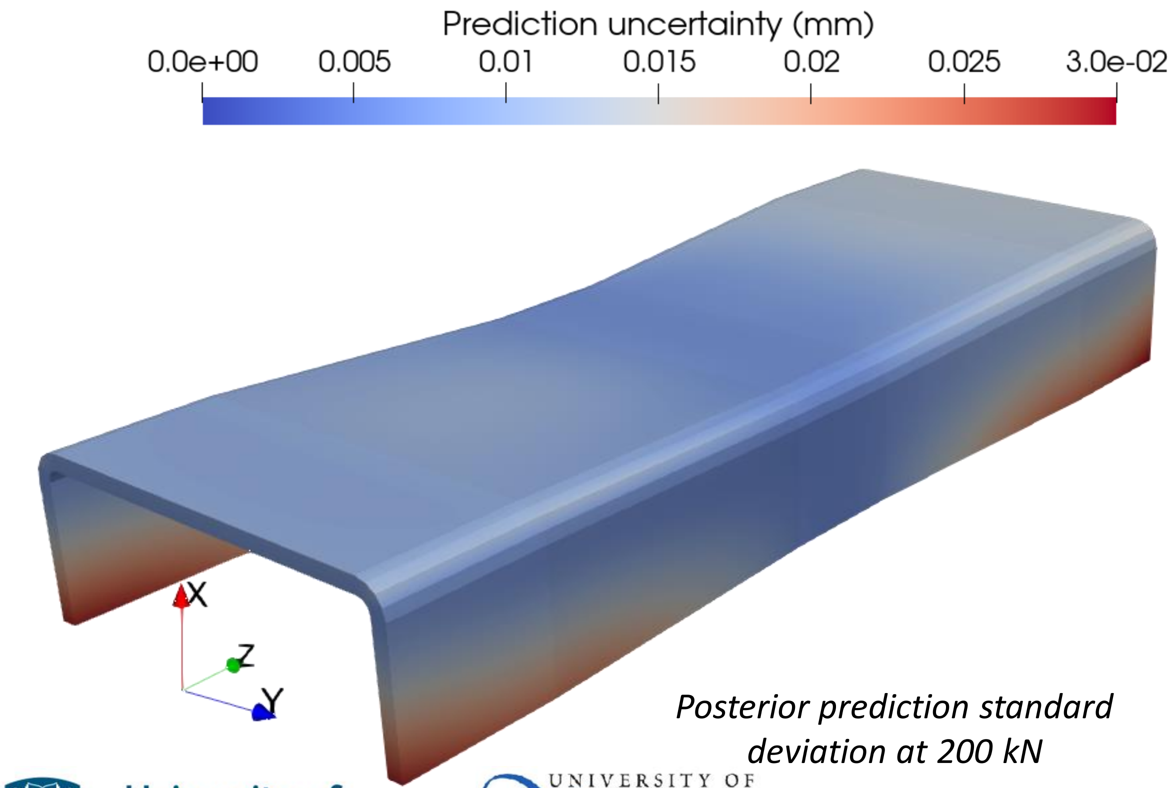
- Comparison of prior vs posterior *belief* in uncertain input values (not a measure of variability).
- K_{rig} shifts to low values indicating significant rig or machine compliance. Approx. 30% knockdown in overall stiffness.
- Bias in eccentricity indicates some misalignment within the end blocks.
- Reduction in uncertainty in all inputs.

Results: Calibrated predictions

- Run posterior samples through emulator and average out uncertainty to get prediction.
- Good agreement with DIC (point cloud overlaid)
- Standard deviation indicates highest regions of posterior uncertainty in boundary, indicating model is least confident in predictions in these regions.



Mean calibrated posterior prediction at 200 kN, with DIC overlaid



Posterior prediction standard deviation at 200 kN

CerTest status: Part 2 - Modelling

An optimal framework for assessing uncertain parameters in large-scale composites using nonlinear MS-GFEM

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2. *Interdisciplinary Center for Scientific Computing and Institute for Applied Mathematics, Heidelberg University, Heidelberg, Germany,*
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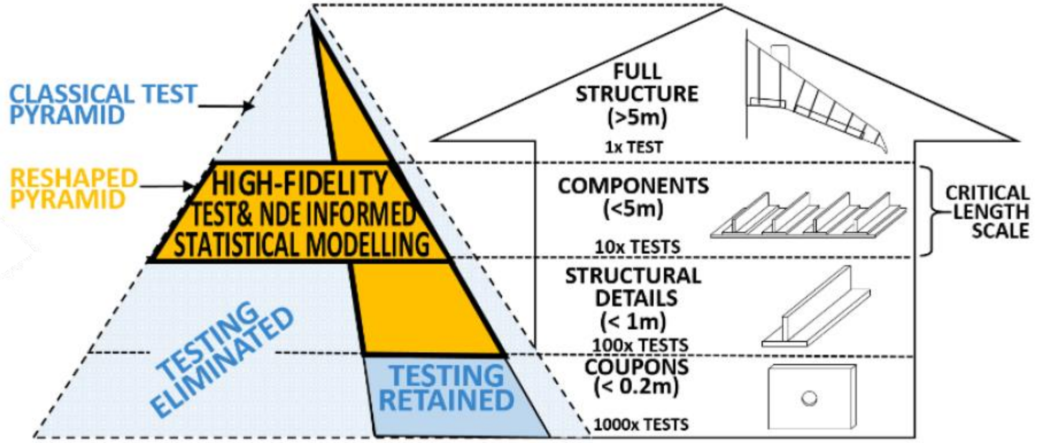
5. *digiLab, Exeter, UK.*

Multiscale Modelling



Problem:

- Multi-scale problem
  - Resolve stress distribution at the level required for delamination (**solid** elements)
  - Structural effect (Nonlinear Geometry)
  - Nonlinear effect (Material failure, cohesive zones)
- Uncertainty quantification (UQ) problem
  - Sub-component and upper levels
  - Virtual testing

Method objectives:

- Multi-scale method designed for UQ
- Imperfection assessment – No scale separation
- Leverage parallelisation
- Adapted to aerospace composites
- Not restricted by commercial software
- Implicit method

Dune

http://dune-project.org/

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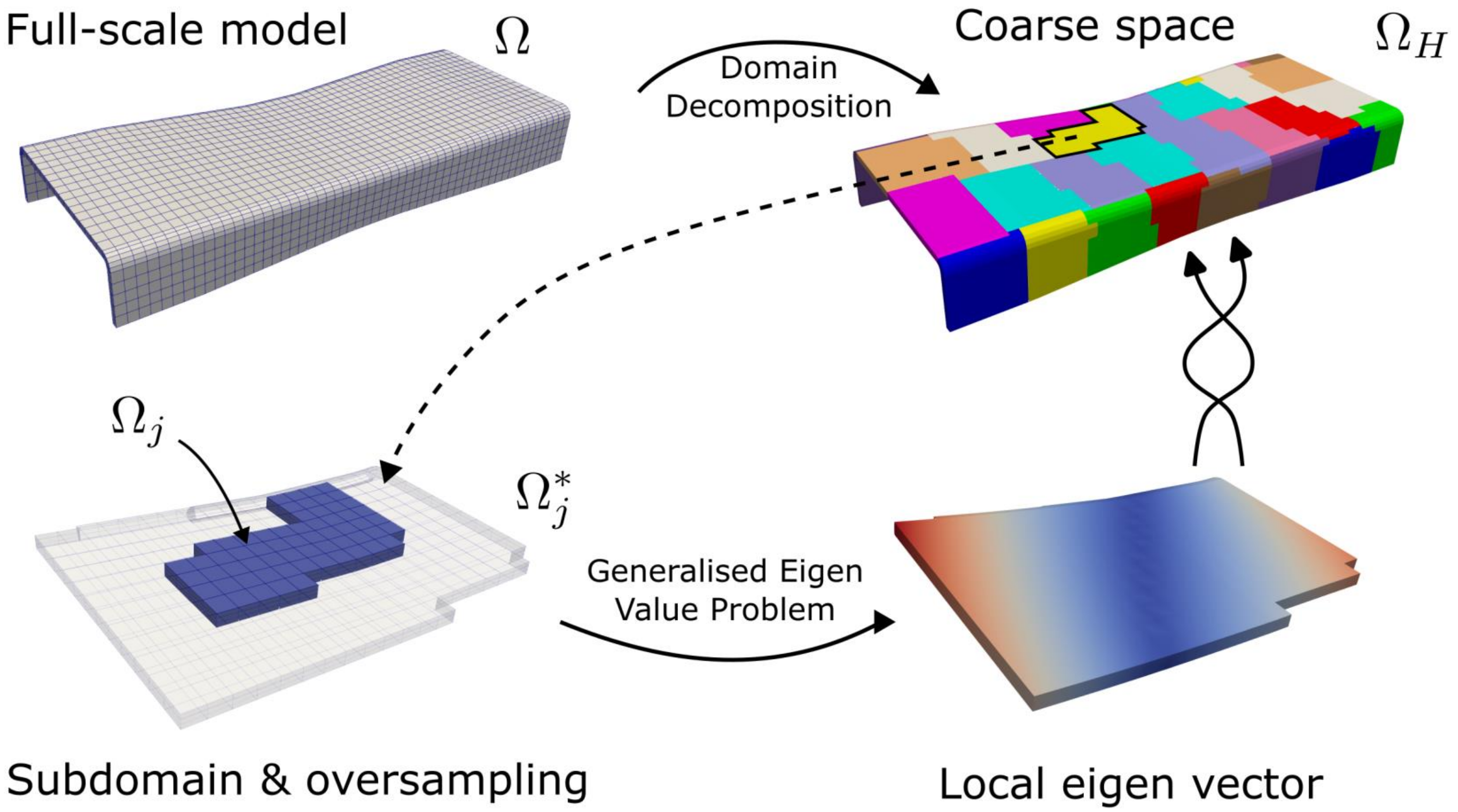
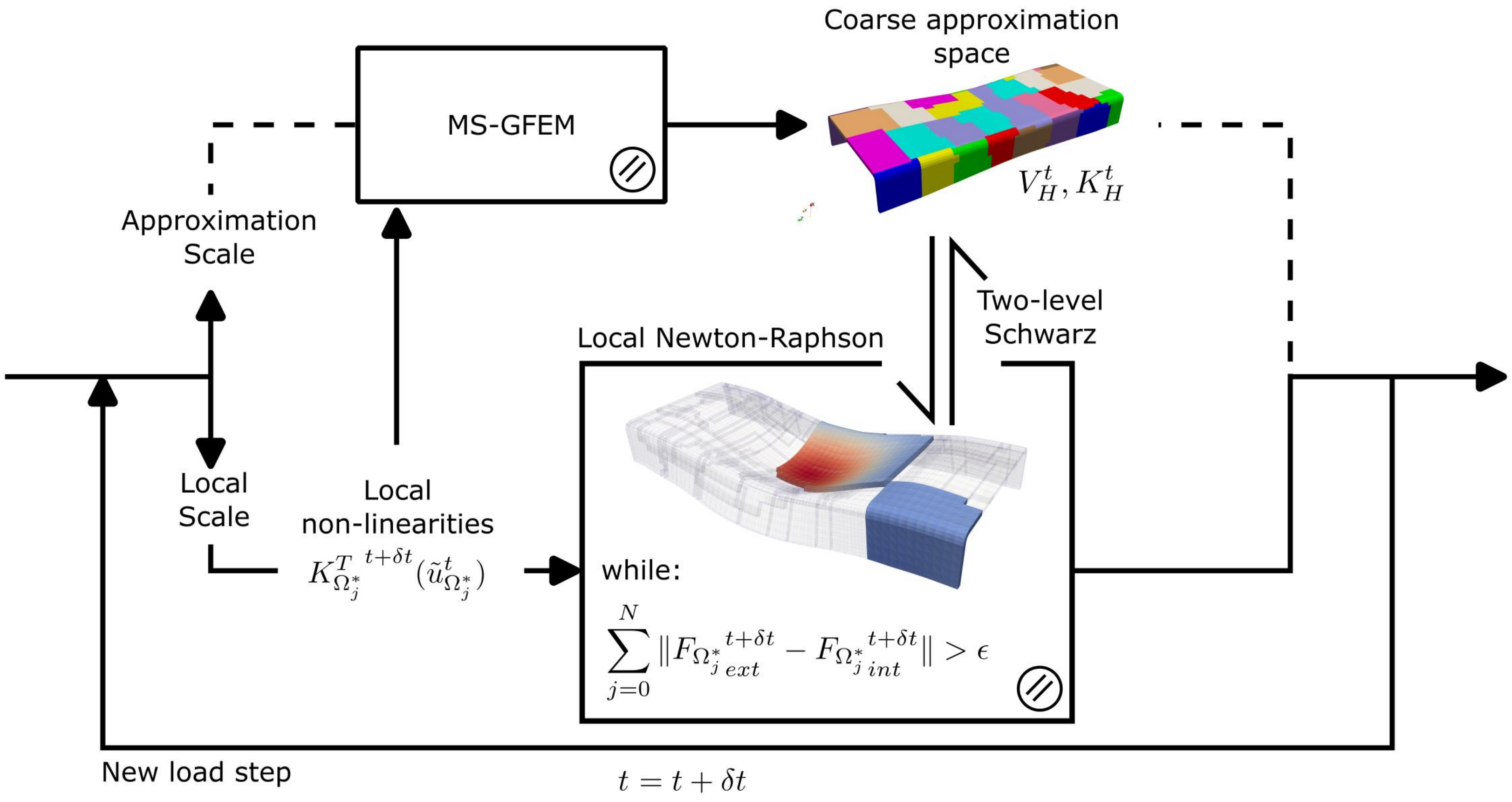
Multi-scale Spectral Generalized Finite Element Method (**MS-GFEM**):



- **Spectral Reduced Order Model**
- **Multi-scale parallel solver**
- **Scalability**

Bénézech, J, et al. Scalable multiscale-spectral GFEM with an application to composite aero-structures, 2023, accepted manuscript to JCP https://doi.org/10.48550/arXiv.2211.13893

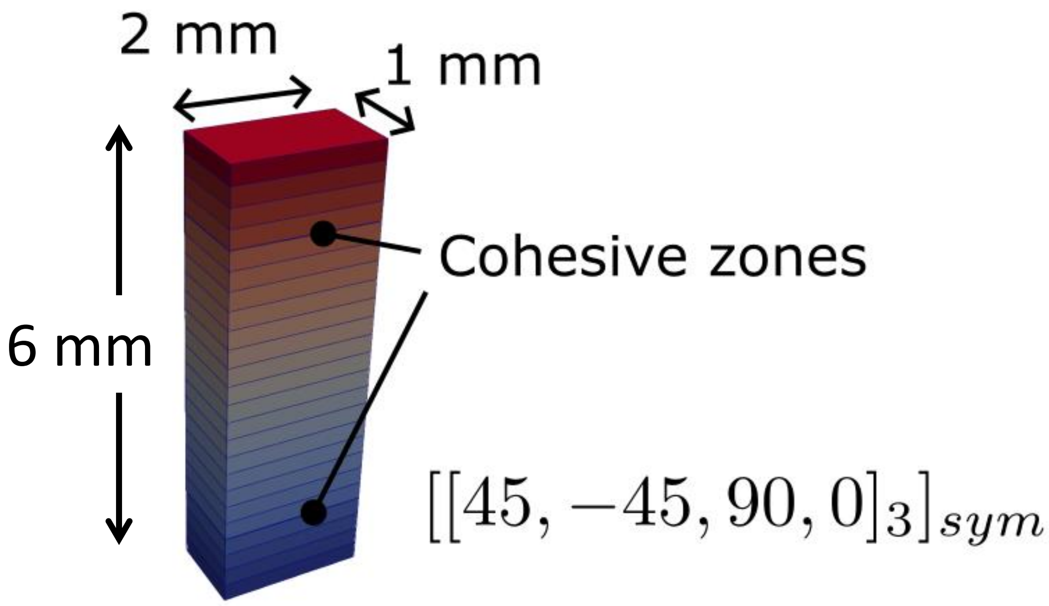
Optimal nonlinear framework

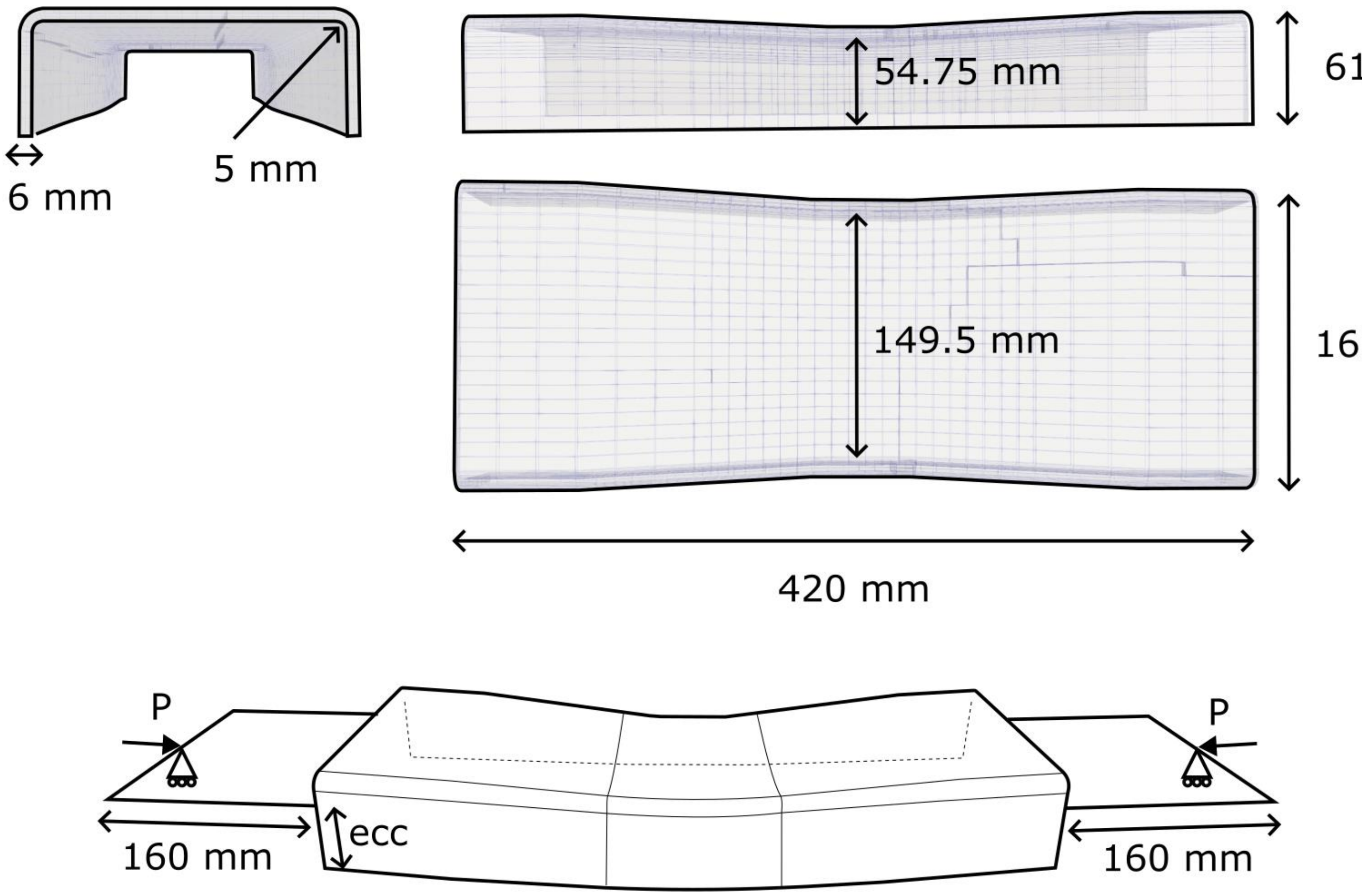


- **Incomplete Newton-Raphson**
  - **Optimisation of the number of approximation space update in the nonlinear framework**
  - **Nonlinearities at the subdomain scale**

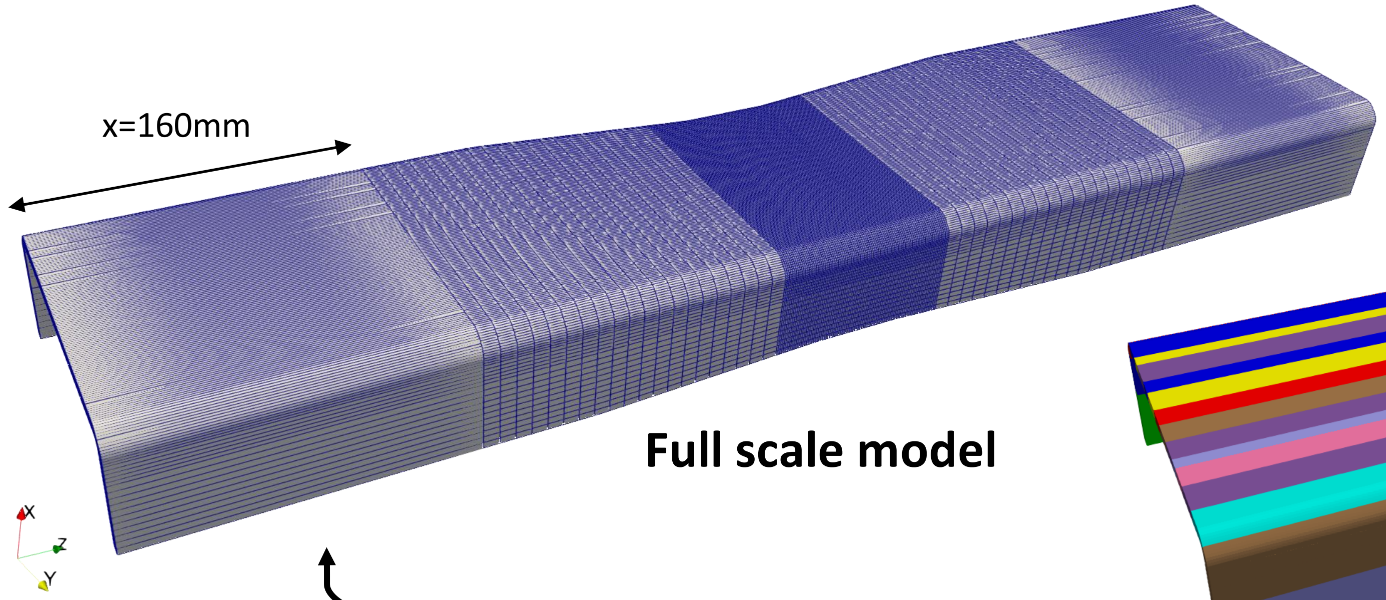
C-spar geometry and mesh

Solid model of 6mm thick laminate



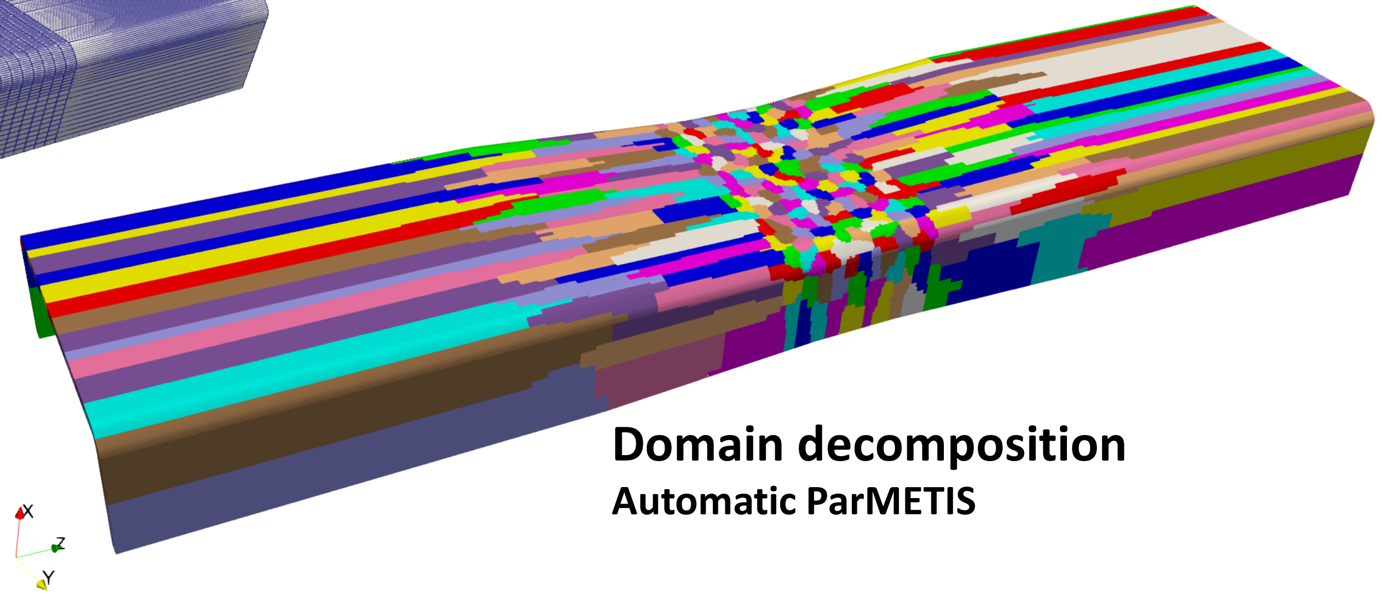


Nonlinear MS-GFEM: Application to the CerTest demonstrator



Full scale model

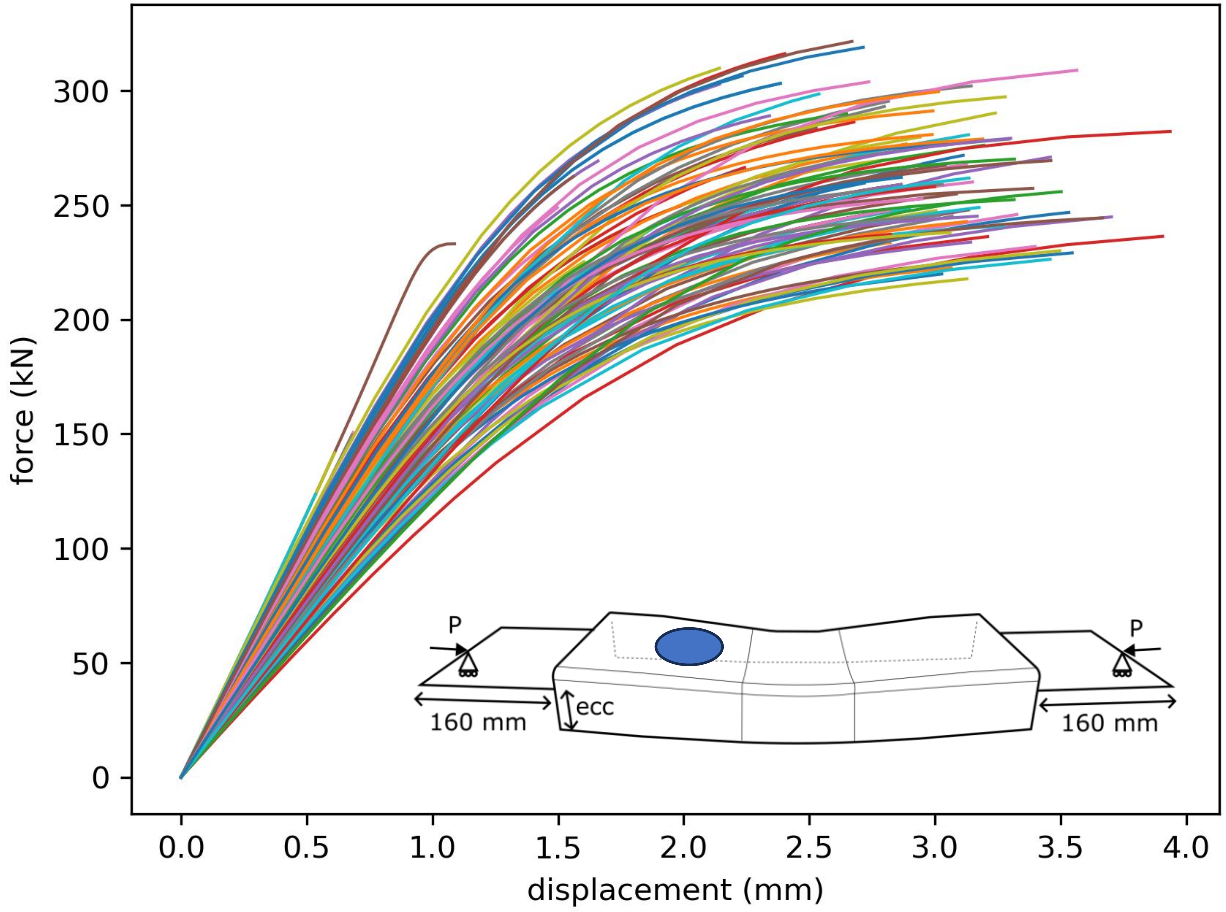
Boundary elements
Simply supported boundary condition



Domain decomposition
Automatic ParMETIS

- Full meso-scale → **2.1 Millions degrees of freedom** (linear elements)
- University of Durham HPC: Hamilton8
  - ➢ 120 standard compute nodes, each with 128 CPU cores (2x AMD EPYC 7702), 256GB RAM and 400GB local SSD storage.
- 320 processors used (4 nodes)
  - 7342 DoF per subdomain
  - 25,000 DoF in the coarse space
  - Model order reduction factor: **90**

Nonlinear MS-GFEM: Application to the CerTest demonstrator



Parameters:

Elastic properties: $\mathbf{E_i}$ $\mathbf{G_{ij}}$ $\boldsymbol{v_{ij}}$

Fracture properties of ply: $\mathbf{X_T}$ $\mathbf{X_C}$ $\mathbf{Y_T}$ $\mathbf{Y_C}$ $\mathbf{S_L}$ $\mathbf{Y_{3T}}$ $\mathbf{S_{13}}$

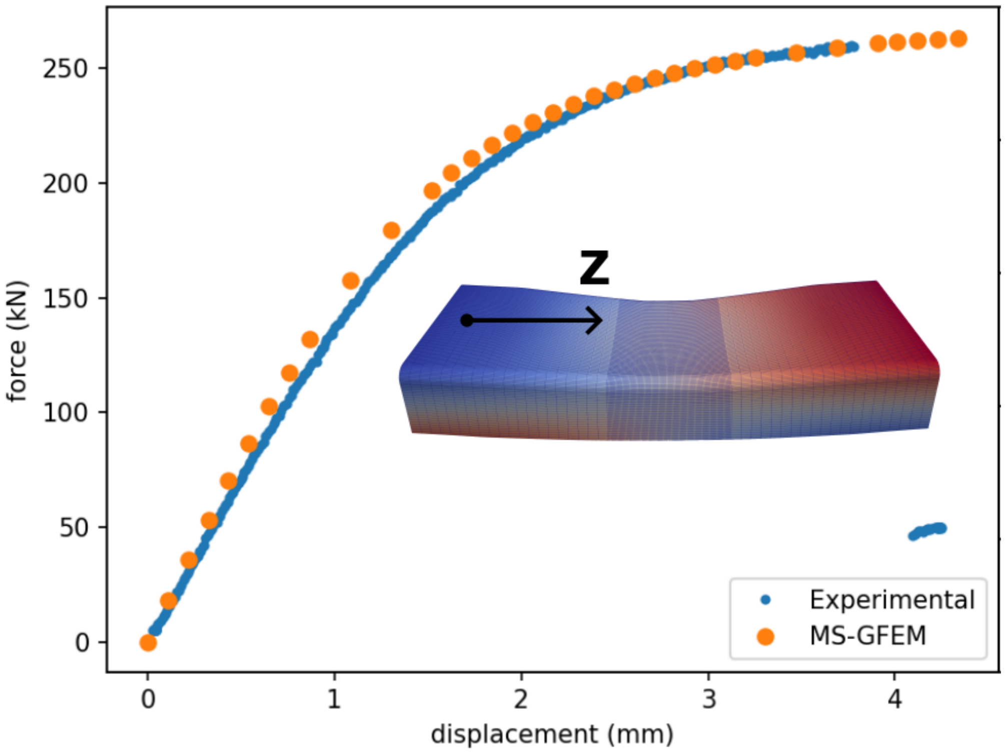
Cohesive properties: $\mathbf{N_{cz}}$ $\mathbf{T_{cz}}$ $\mathbf{S_{cz}}$ $\mathbf{G_{IC}}$ $\mathbf{G_{IIC}}$ $\mathbf{G_{IIIC}}$ **BK** $\mathbf{K_p}$

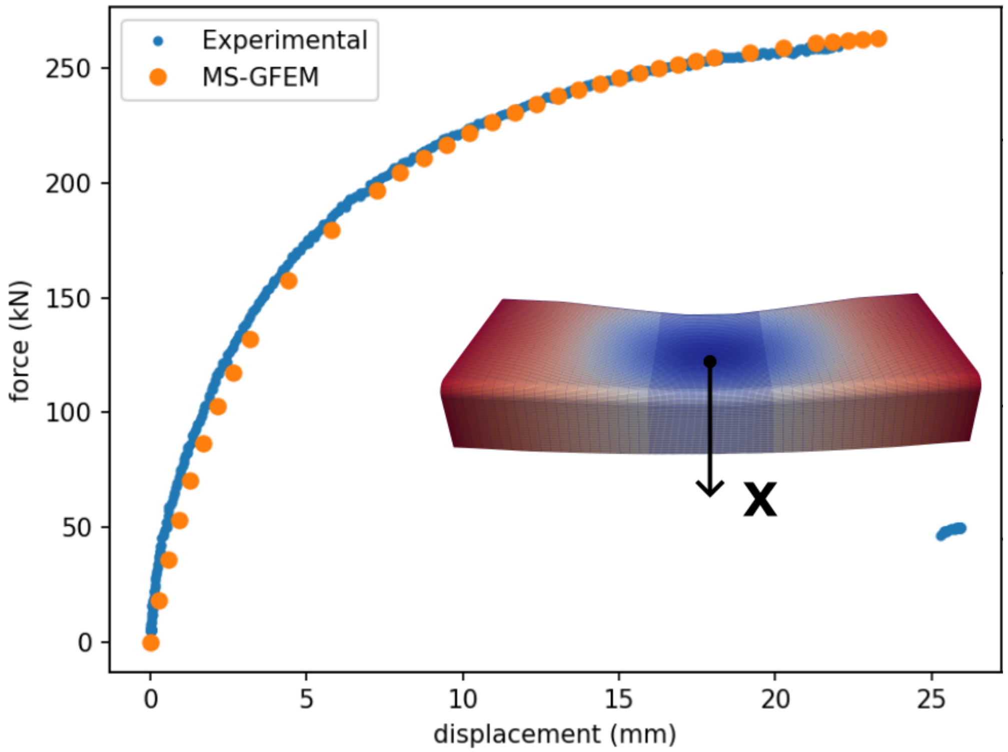
Boundary conditions: **Ecc** $\mathbf{E_{rig}}$

Defect parameters: $\mathbf{x_{delam}}$ $\mathbf{z_{delam}}$ **#Interlayer**

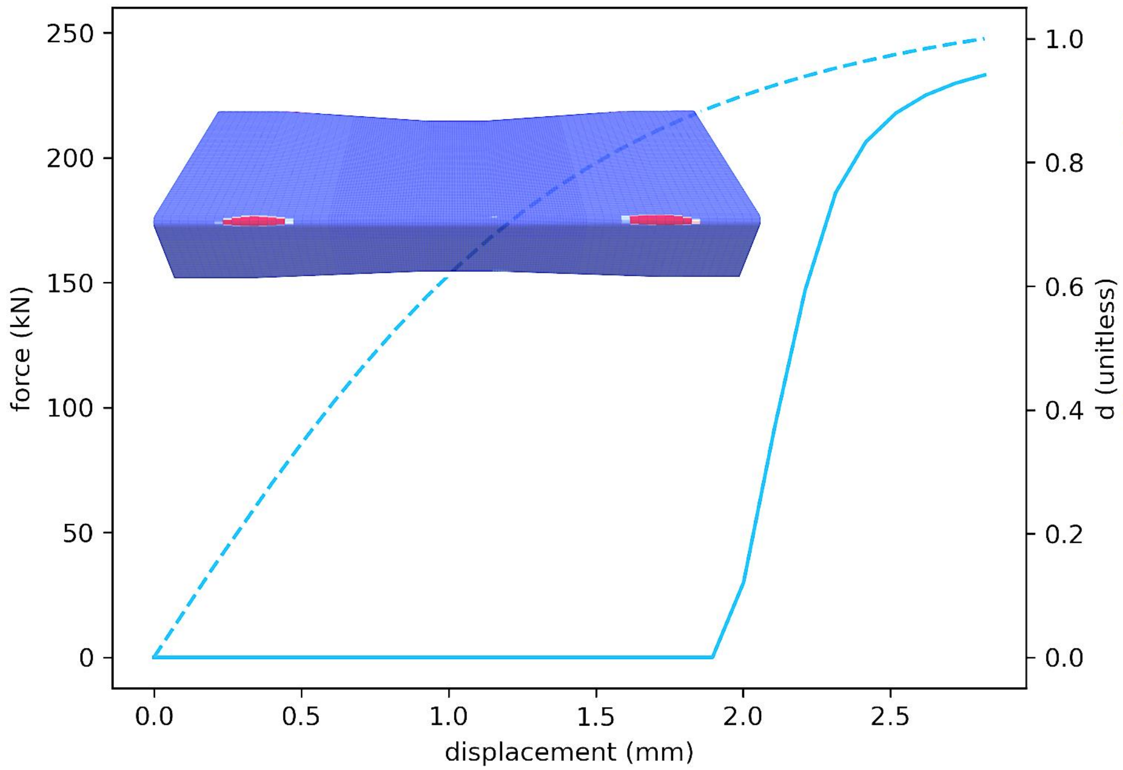
- **120+ runs**
- **~ 4 minutes** per load increment (CS construction + Newton iterations)
- 1 to 3 hours on 320 processors HPC per simulation

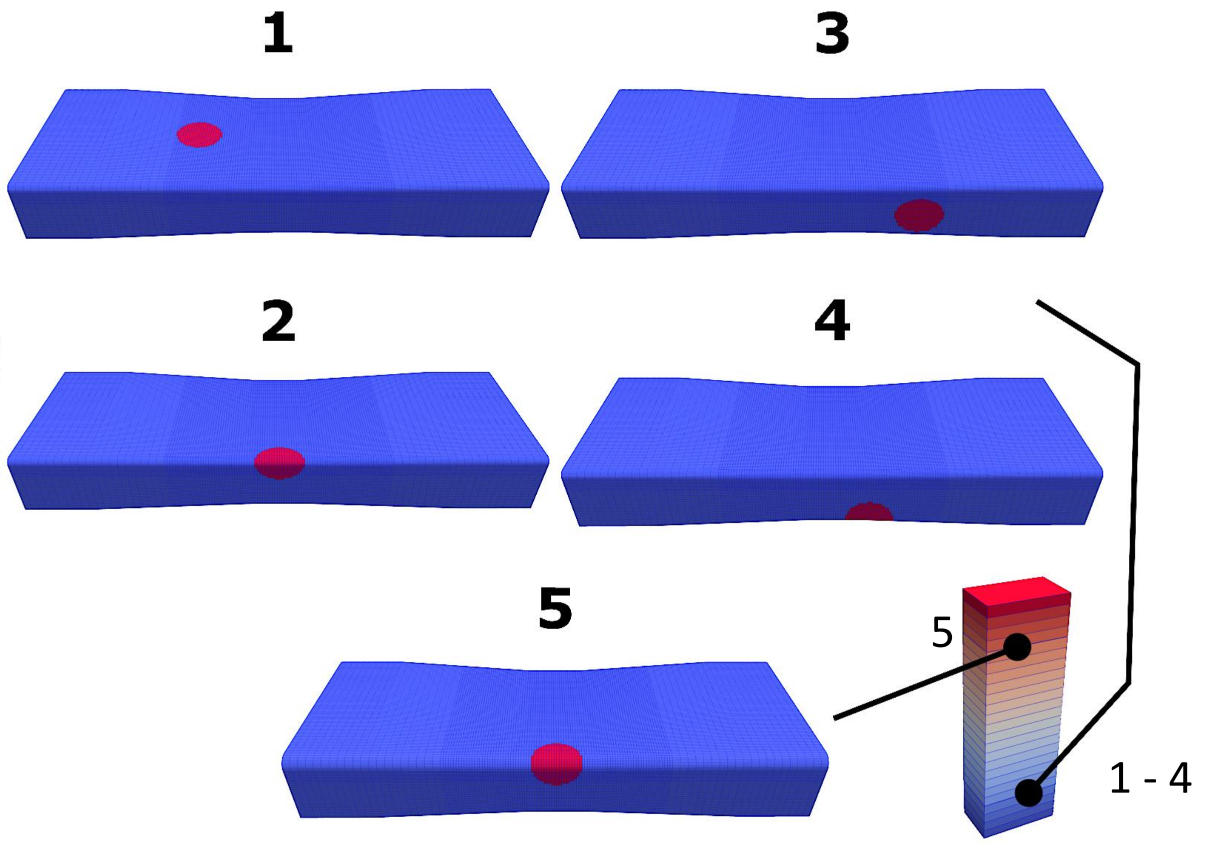
Nonlinear MS-GFEM: Comparison with experimental DIC data



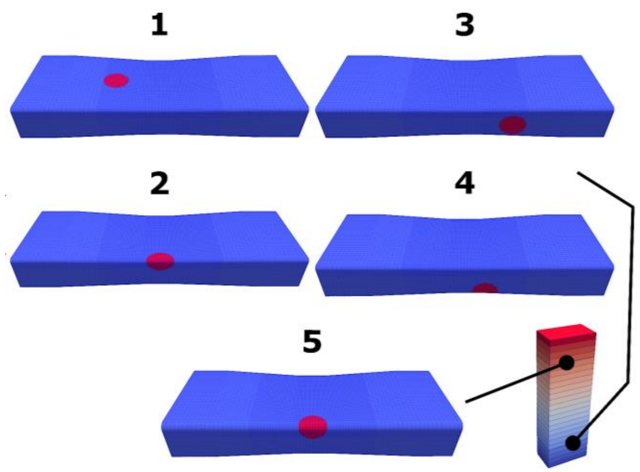


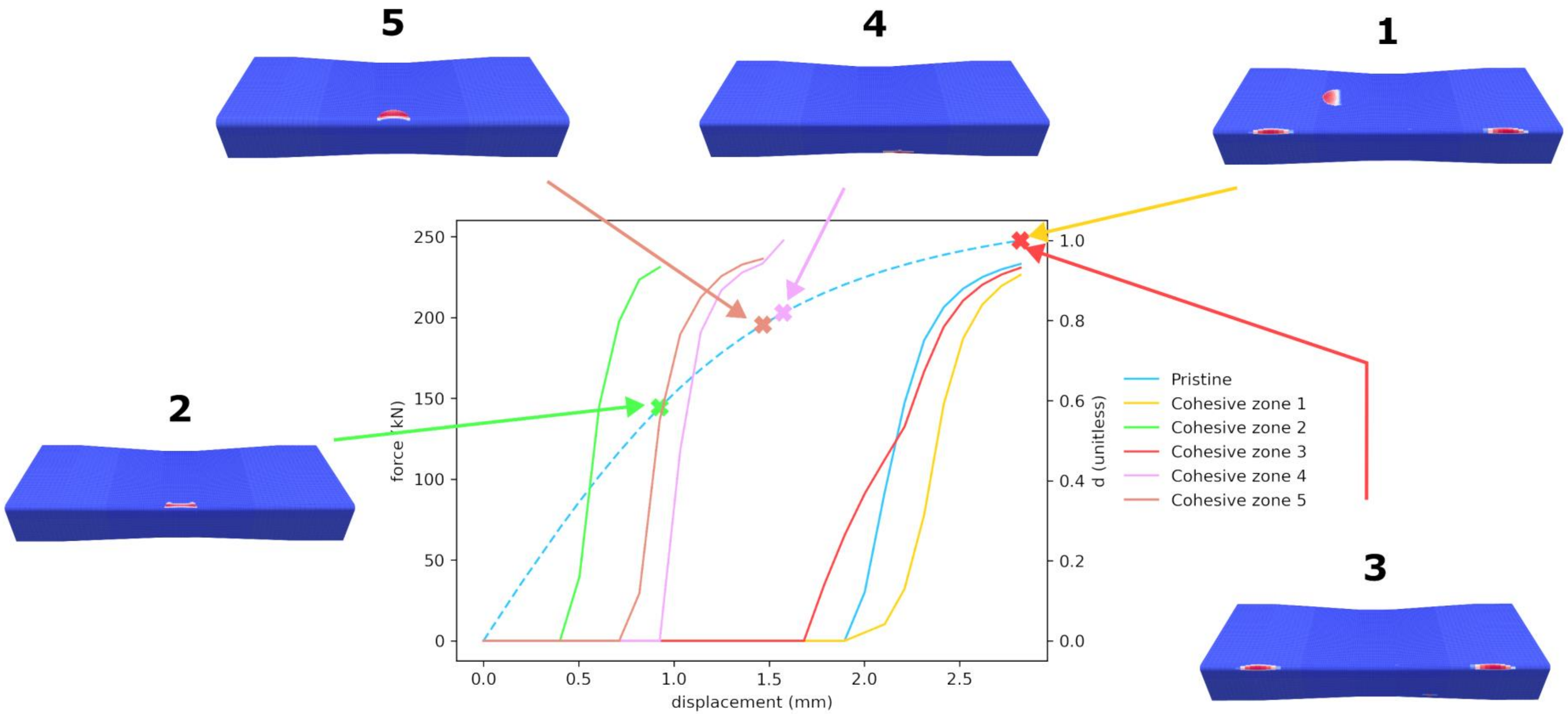
Nonlinear MS-GFEM: Exploration of uncertain defect position





Nonlinear MS-GFEM: Exploration of uncertain defect position





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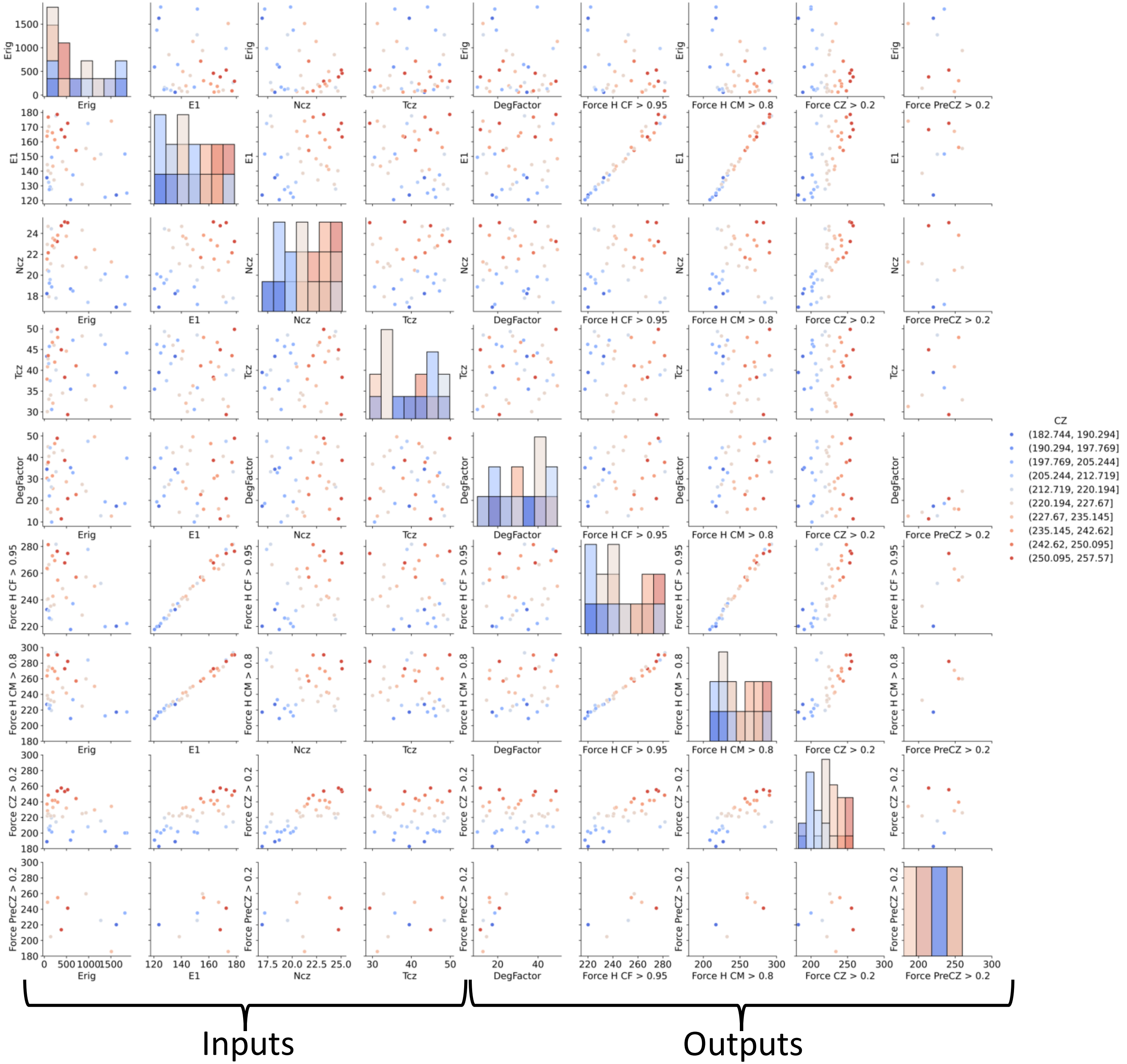
Nonlinear MS-GFEM: UQ – Calibration

Data training for emulator
→ digiLab



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MS-GFEM modelling achievements

- Implementation & test of the **nonlinear MSGFEM**

- Very **efficient, parallel and scalable method** design for large-scale problem
  - ➢ Nonlinear solution for 2.1 M DoFs problem in 1-3 hours

- **No scale separation assumption**: **ANY defect** – region | shape | size
  - ➢ Independent of the domain decomposition

- **But** model only accounts for initiation of failure – not propagation of damage leading to collapse
- Requirements specify two limiting strengths: initiation and collapse (separated by FoSafety)

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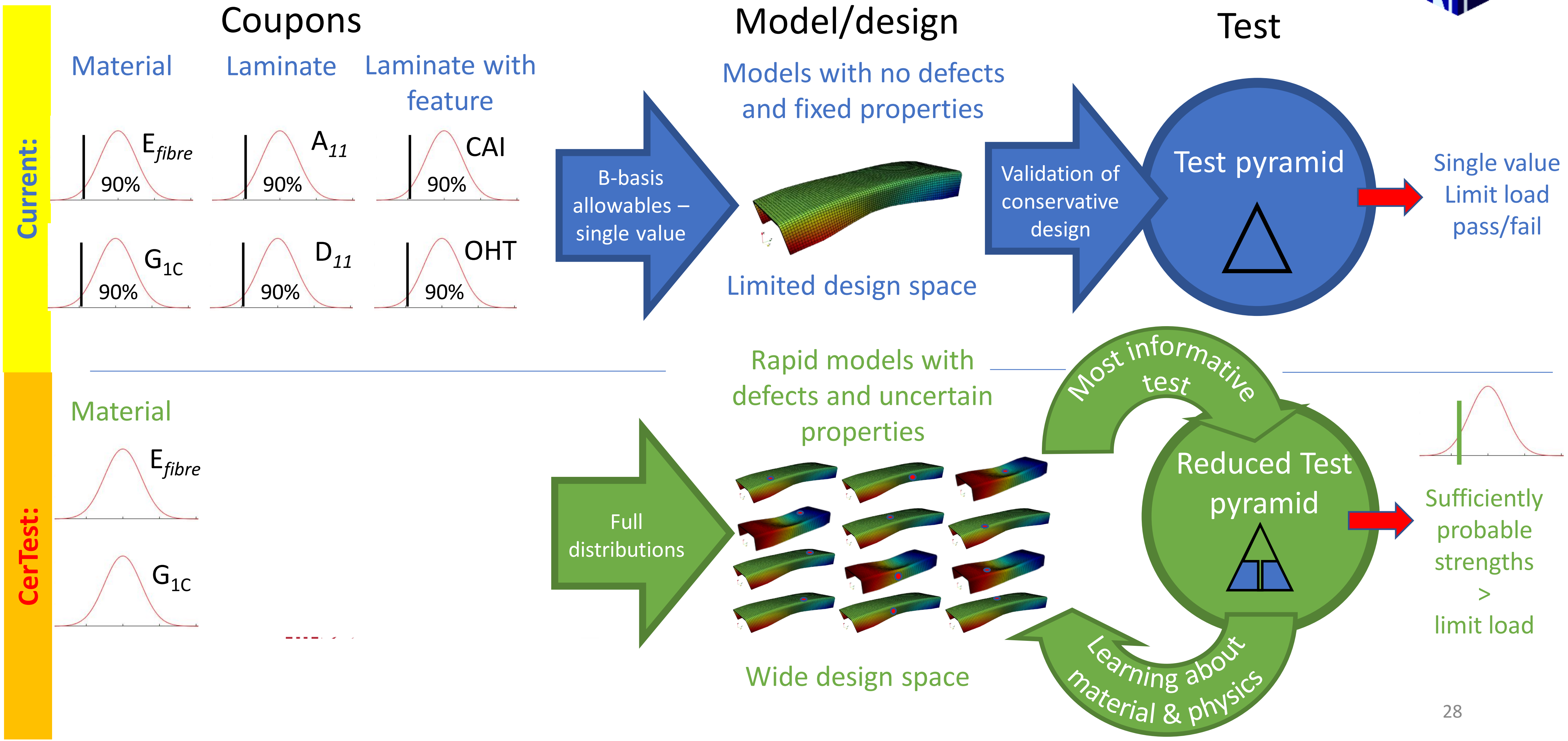
SUMMARY - Competing test pyramids



Ongoing Work & Future Challenges

Ongoing Work

- Demanding problem: >50 uncertain (but correlated) variables; expensive model; expensive tests
- Pre and post failure data from 5 experimental tests and 200 simulations is being used to calibrate failure properties and controlled defects
- We have undertaken (pre-failure) Design of Experiments with maximum information gain as the objective
- UQ and DoE will be undertaken to indicate defect locations for future experiments
- Aim is then to indicate probability of failure at part scale for a given number of experimental tests

Future Challenges

- Can we present industry with a viable methodology to reduce time to market and increase innovation?
- Can we build trust in the safety of such an approach, avoiding unexpected failure modes at full aircraft level?
- Success requires further work (modelling, testing, defect characterization), collaborative uptake and regulatory approval
- This will open new opportunities for design including fibre steering, cryogenic applications, and rapid uptake of new materials

Thank you for your attention!

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Questions?