Integrated Testing and Modelling of Composite Structures – A Journey Towards Virtual Testing and Certification by Analysis

O.T. Thomsen[1], J.M. Dulieu-Barton[1], S.R. Hallett[1], R. Butler[2], A.Rhead[2]

[1]Bristol Composites Institute, University of Bristol, Faculty of Engineering and Science, UK

[2]Materials and Structures Centre, Department of Mechanical Engineering, University of Bath, UK

Engineering and Physical Sciences Research Council

Outline

- Background and motivation
- CerTest
- Overview of research challenges and methodology (process flow and how it works?)
- Steps towards demonstration of new methodology
- Summary & CerTest status

The prize?

University of BRISTOL · UNIVERSITY OF BATH · University of Southampton · UNIVERSITY OF EXETER

Engineering and Physical Sciences Research Council

Outline

- Background and motivation
- Cer
- Ov hodology (process flow ar
- Ste
- Summary & CerTest stat

REDUCED DEVELOPMENT TIME / TIME TO MARKET!

REMOVING/REDUCING BARRIERS TO INNOVATION POSED BY CURRENT PROCESSES

The prize?

University of BRISTOL · UNIVERSITY OF BATH · University of Southampton · UNIVERSITY OF EXETER

Background and motivation – what is the problem?

- Mostly tests on coupon and generic element levels of testing pyramid – for certification purposes
- Few test on component/structural detail and full structure levels – but full scale tests are required for certification (very costly and time consuming)
- Full scale & component/structure tests

Background and motivation – what is the problem?

generic d – for

ctural ut full

ertifica ning)

cture te

Background and motivation – what is the problem?

generic d – for

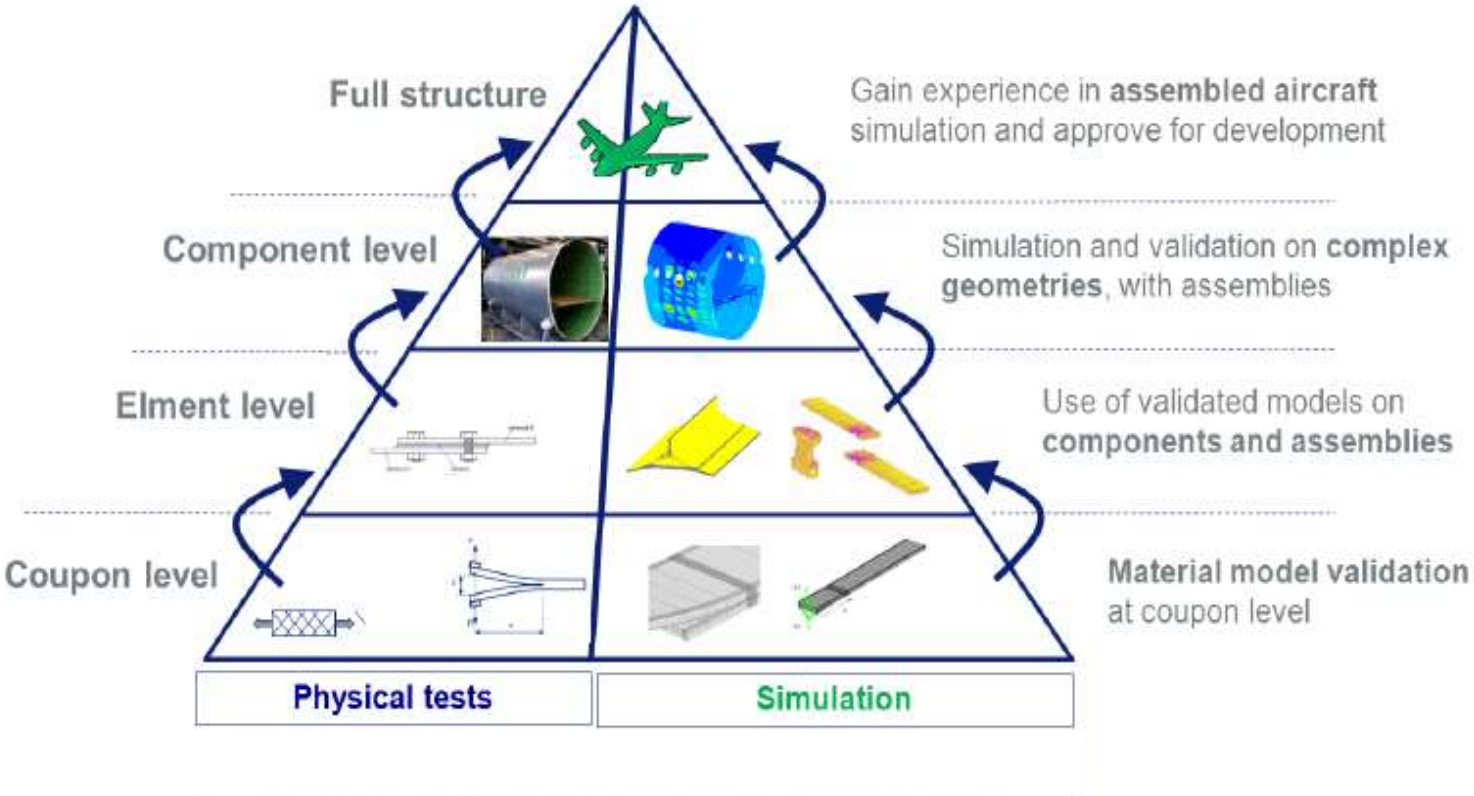
Complience with safety regulations – currently "building block" approach / "testing pyramid"

1. Coupon: a small test specimen for evaluation of basic laminate properties or properties of generic structural features
2. Element: A generic part of a more complex structural member
3. Detail/Component: a non-generic structural element of a more complex structural member
4. Component/Full structure: major three-dimensional structure - complete structural representation of a section of the full structure (or the full structure)

Engineering and Physical Sciences Research Council

Complience with safety regulations – currently "building block" approach / "testing pyramid"

1. Coupo
   proper
2. Elemer
3. Detail/
   membe
4. Compc
   represe



rties or

lex structural

lete structural

Engineering and Physical Sciences Research Council

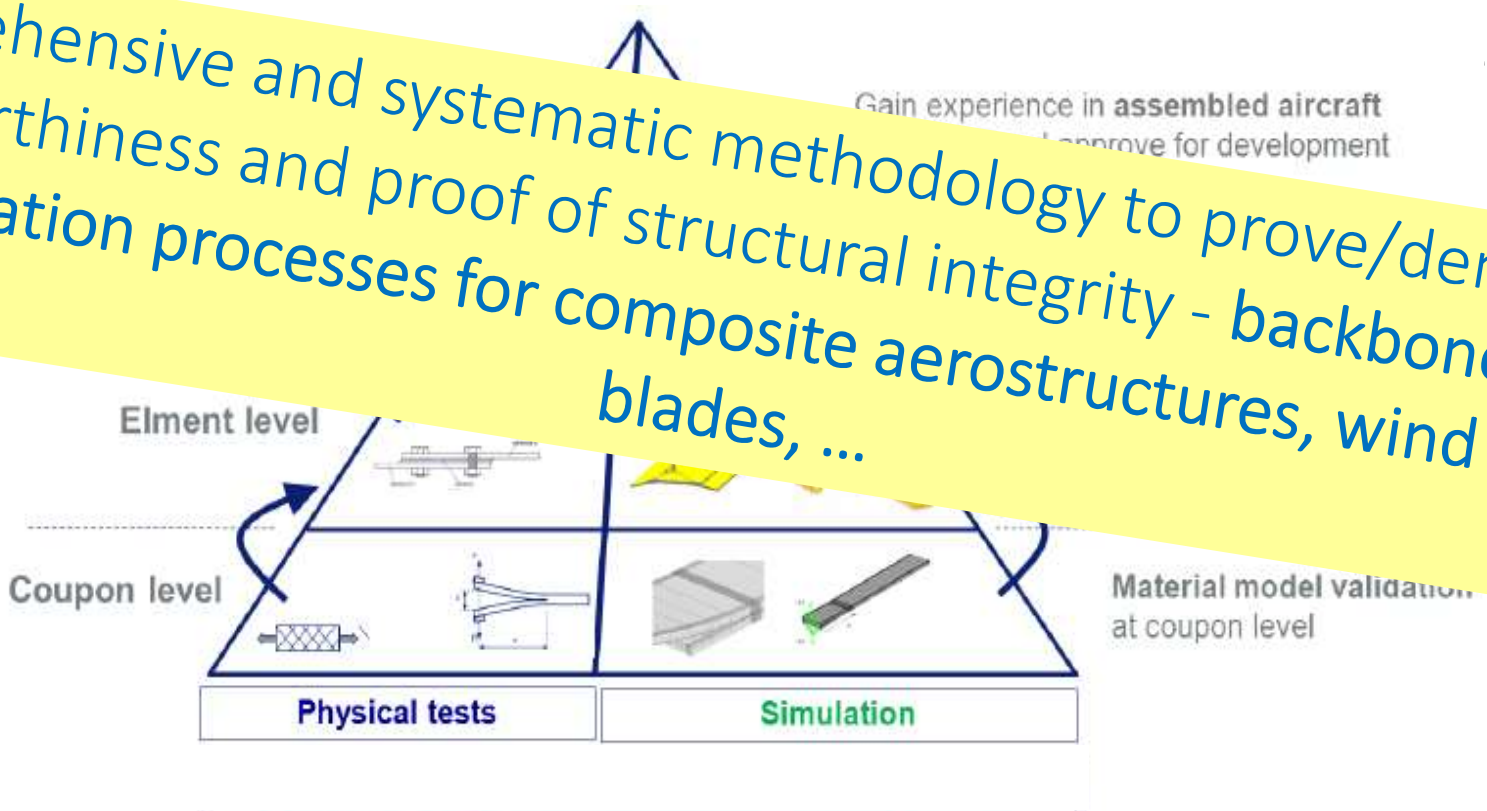
Compliance with safety regulations – currently "building block" approach / "testing pyramid"

Comprehensive and systematic methodology to prove/demonstrate airworthiness and proof of structural integrity - **backbone of the certification processes for composite aerostructures, wind turbine blades, …**

rties or

memb

4. Compc al
repres



EVIDENCE – limitations to Building Block approach

- Failure models largely based on inputs derived from coupon tests comprising simple, mainly uniaxial, loading modes and unidirectional materials
- Large number of coupon tests to define “allowables” - relatively few tests mid-tier and top-tiers of pyramid (larger length scales)
- *Underlying assumption:* Material properties from tests at the coupon level can be used to define design allowables at greater length scales
- Coupon properties do not represent the “in-situ” properties well
- Transfer/upscaling of ”allowables” from coupon level to higher levels leads to large knock-down factors, lack of understanding of MoS and reliability on structure/system level
- Excessively costly (especially top-tier) and time consuming

Engineering and Physical Sciences Research Council

Can we do things more efficiently (safer, cheaper, faster)?

- Reduce bottom tier of pyramid?
- Coupon tests still required – but at reduced levels/numbers (how many?)
- Reduce/eliminate top tier of pyramid?
- Modelling & testing integrated – validation: Mid-tiers of pyramid structural scale
- Models used to inform tests – tests used validate/inform models – *Data Fusion* & *Design of Experiments*
- High-fidelity tests – calibration/validation of model predictions
- Models benchmarked/challenged and validated via SUFFICIENTLY COMPLEX TESTS (geometry and load complexity) on **structural** length scales

Engineering and Physical Sciences Research Council

Can we do things more efficiently (safer, cheaper, faster)?

- Redu[illegible] bottom tier of pyramid?
- Cou[illegible] but at reduced levels/numbers (how many?)
- Red[illegible]
- Mo[illegible] scale
- M[illegible] *f* *Ex*
- High-fidelity [illegible]
- Models benchmarked/challenged and [illegible] etry and load complexity) on **structural** length scales

If successful …

generic methodology/framework would be transferable to other emerging materials/ manufacturing technologies (AM, 3D printing, …)

Engineering and Physical Sciences Research Council

composites-certest.com

CerTest

- Programme Grant: *"Certification for design – Reshaping the Testing Pyramid"*
- Grant award: £6.9M, 2019-2025

Engineering and Physical Sciences Research Council

CERTIFICATION FOR DESIGN: RESHAPING THE TESTING PYRAMID

University of BRISTOL

UNIVERSITY OF BATH

University of Southampton

UNIVERSITY OF EXETER

AIRBUS

BAE SYSTEMS

Rolls-Royce

GKN AEROSPACE

NATIONAL COMPOSITES CENTRE

cfms

The Alan Turing Institute

University of BRISTOL

UNIVERSITY OF BATH

University of Southampton

UNIVERSITY OF EXETER

Engineering and Physical Sciences Research Council

composites-certest.com

CerTest

- Programme Grant: *"Certification for design – Reshaping the Testing Pyramid"*
- Grant award: £6.9M, 2019-2025

Engineering and Physical Sciences Research Council

CERTIFICATION FOR DESIGN: RESHAPING THE TESTING PYRAMID

EASA European Aviation Safety Agency

University of Southampton

University of Exeter

AIRE

Rolls-Royce

GKN AEROSPACE

National Composites Centre

cfms

The Alan Turing Institute

University of Bristol

University of Bath

University of Southampton

University of Exeter

Engineering and Physical Sciences Research Council

composites-certest.com

CerTest

- Programme Gr
  "Certification f
  – Reshaping th
  Pyramid"
- Grant award:
  2019-2025

RTIFICATION
R DESIGN:
SHAPING THE
STING PYRAMID

UNIVERSITY OF EXETER

GKN AEROSPACE

g

University of BRISTOL

UNIVERSITY OF BATH

University of Southampton

UNIVERSITY OF EXETER

Engineering and Physical Sciences Research Council

Aim – 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”

University of BRISTOL · UNIVERSITY OF BATH · University of Southampton · UNIVERSITY OF EXETER

Engineering and Physical Sciences Research Council

Aim – D… …will enable VIRTUA… …physical testing …

…integration of multi-scale modelling… …ta-rich … …L"Design of Experiments"

Decisive move towards virtual testing and validation (and DIGITAL CERTIFICATION) – reduce reliance on physical testing

CHALLENGE – *UQ = Uncertainty Quantification*:

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

University of BRISTOL BATH Southampton

Engineering and Physical Sciences Research Council

RC1
Multi-scale Performance Modelling

RC2
Features and Damage Characterisation

RC3
Data-rich High Fidelity Structural Characterisation

RC4
Integration and Methodology Validation

- RC1 – lead: Richard Butler (Bath)

  Focus: Multi-scale statistical modelling framework incorporating Bayesian statistics – load response & damage (HPC & surrogate models/GPEs)

- RC2 – lead: Stephen Hallett (Bristol)

  Focus: NDE toolset for damage & intrinsic meso-scale features, as-designed & deviations from design - knowledge base of structurally important features and in-service damage

- RC3 – lead: Janice Barton (Bristol)
  - Focus: Data-rich experimental techniques - evolving stress/strain due to features, defects and damage - high-fidelity data-rich testing - complex loading

- RC4 – leads: Ole Thomsen (Bristol) / Andy Rhead (Bath)
  - Focus: Integration of data-rich experimental procedures and statistical/multi-scale models - Bayesian Learning and DoE

University of Bristol · University of Bath · University of Southampton · University of Exeter

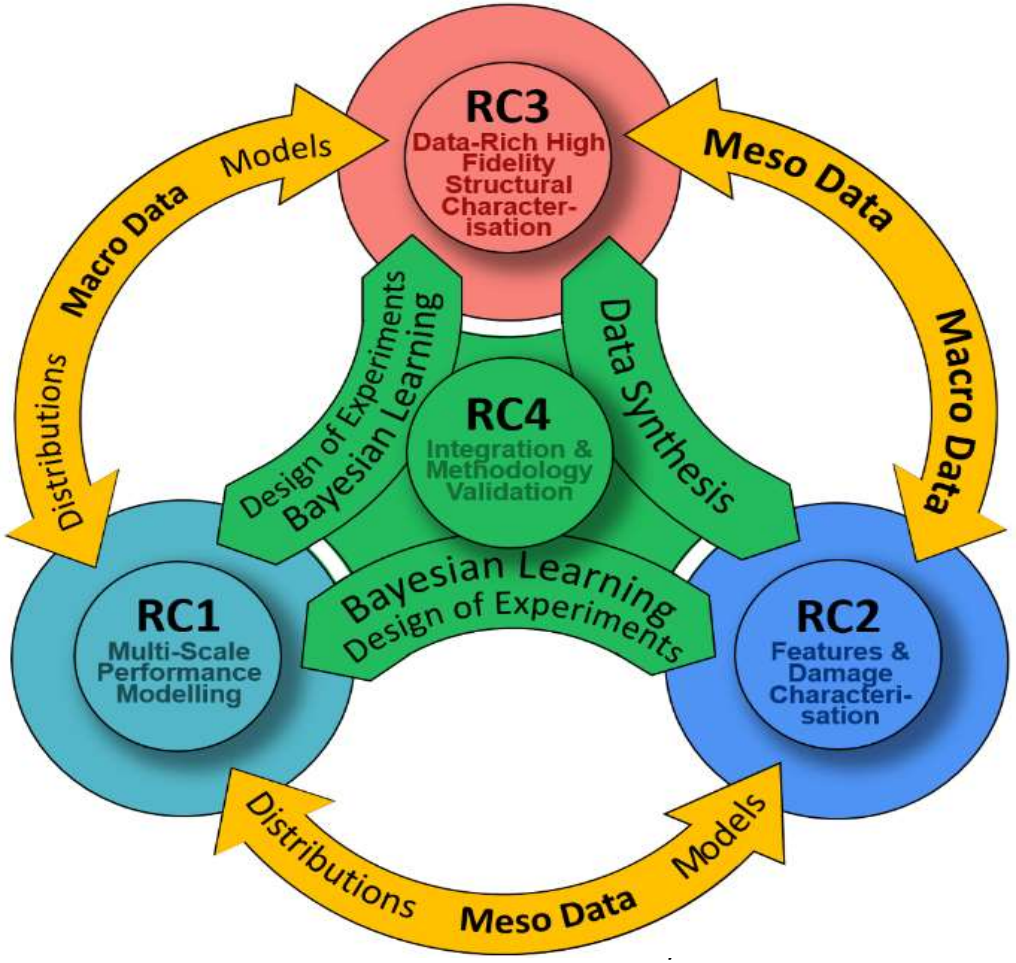
Engineering and Physical Scien Research Cou

RC1
Multi-scale Pe
Modell

RC
Features an
Characte

Data-ricl
Structural

Inte
Method



CERTEST

odelling framework incorporating
nse & damage (HPC & surrogate

tol)

& intrinsic meso-scale features,
design - knowledge base of
and in-service damage

)

al techniques - evolving
, defects and damage - high-
mplex loading

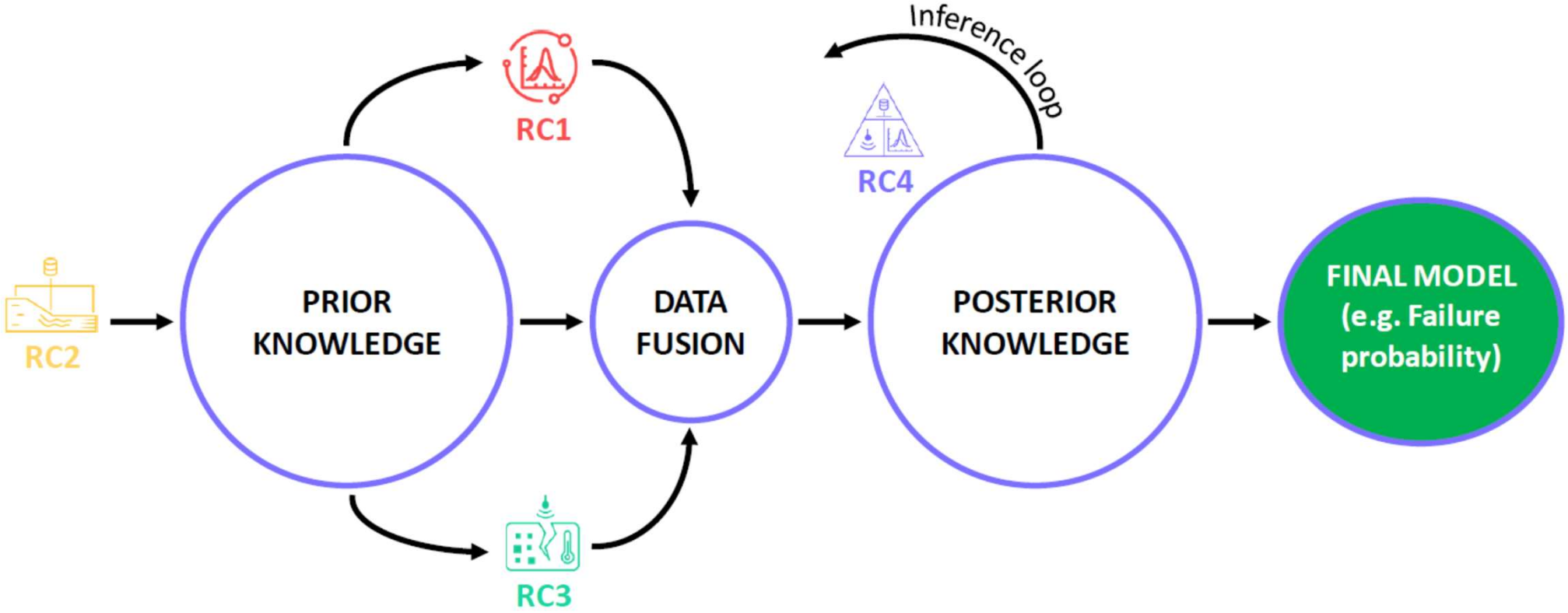
l) / Andy Rhead (Bath)

ch experimental procedures and
s - Bayesian Learning and DoE

University of BRISTOL
UNIVERSITY OF BATH
University of Southampton
UNIVERSITY OF EXETER

Engineering and Physical Sciences Research Council

CerTest hypotheses



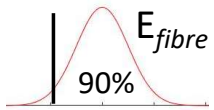
University of BRISTOL · University of BATH · University of Southampton · University of EXETER

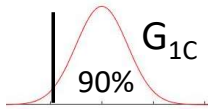
Engineering and Physical Sciences Research Council

Coupons

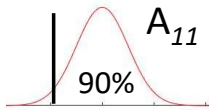
Material

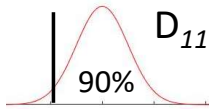
Current:



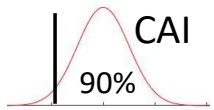


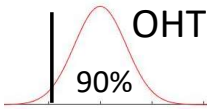
Laminate





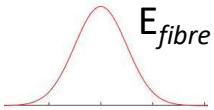
Laminate with feature

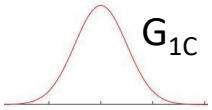




CerTest:

Material

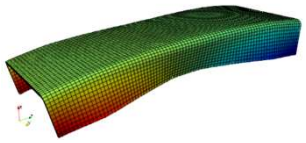




Model/design

Models with no defects and fixed properties

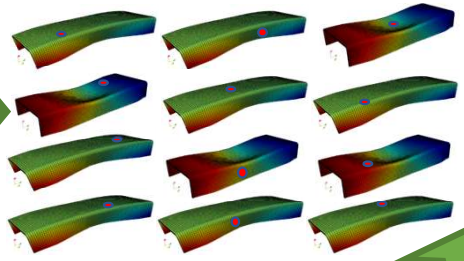
B-basis allowables – single value



Limited design space

Rapid models with defects and uncertain properties

Full distributions



Wide design space

Test

Validation of conservative design

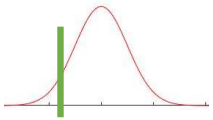
Test pyramid

Single value
Limit load
pass/fail

Most informative test

Reduced Test pyramid

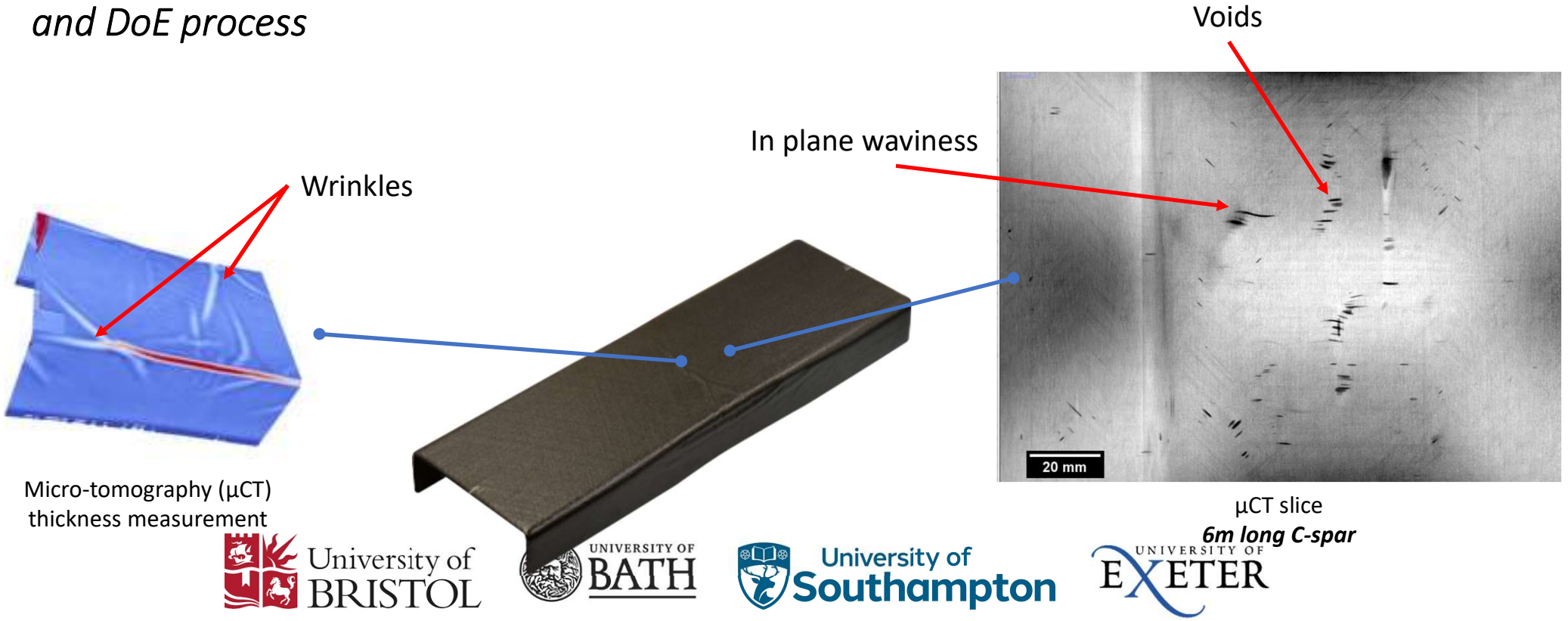
Learning about material & physics



Sufficiently probable strengths
>
limit load

CerTest – steps towards demonstration of methodology

- C-spar with delamination - combined loading – demonstrator: *Full Bayesian loop and DoE process*



Engineering and Physical Sciences Research Council

CerTest – steps towards demonstration of methodology

- C-spar with delamination - combined loading – demonstrator: *Full Bayesian loop and DoE process*
- Larger scale demonstrator – possibly *"wing-box" like component seeded with manufacturing defects*

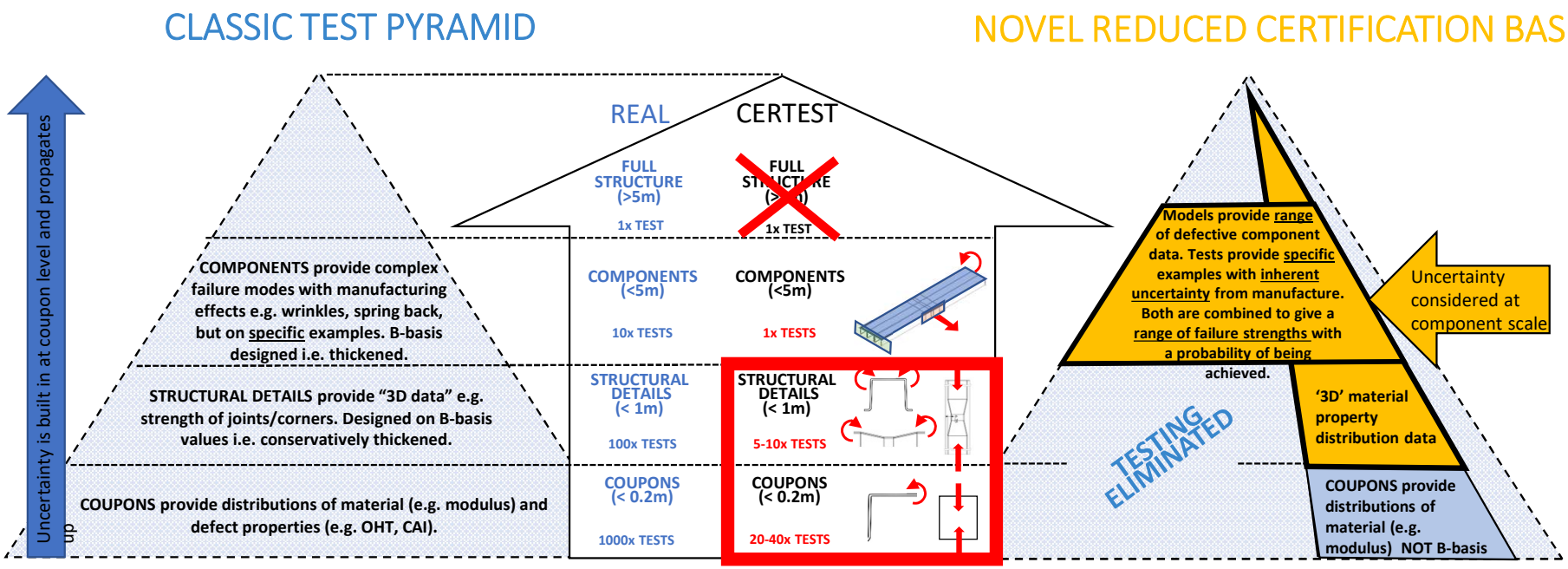
University of BRISTOL

UNIVERSITY OF BATH

University of Southampton

Engineering and Physical Sciences Research Council

SUMMARY - Competing test pyramids and availability of data



University of BRISTOL · UNIVERSITY OF BATH · University of Southampton · UNIVERSITY OF EXETER

CerTest (www.composites-certest.com) status

- Academic:
  - Conferences and workshops: ca. 50 presentations/papers
  - Peer review journal papers: 40+ published or accepted for publication (mostly in Q1 journals)
- Academic and industrial impact
  - CerTest workshops on “modernising composites regulations”: ICCM21, Xi’an, China, 2017; ICCM22, Melbourne, Australia, 2029; ICCM23, Belfast, 2023; ECCM21, Nantes, France, July 2024
  - International academia, industry and regulators
- Public showcase events to held in 2025 (TBD) – target audience: industry, RTOs, regulators and policy makers

Engineering and Physical Sciences Research Council

CerTest “deliverables”

- Computationally efficient multi-scale modelling frameworks, including surrogate modelling techniques and Gaussian Process Emulators (GPE) for fast approximation of complex load-response/damage behaviour
- Novel Non-Destructive Evaluation (NDE) techniques based on Eddy Current Techniques (ECT)
- Database of manufacturing defects and as-designed features in composite aerostructures that underpins a high-fidelity parametrisation based on new descriptors
- Demonstration of low-cost infrared imaging procedure for quantitative Thermoelastic Stress Analysis (TSA)
- Full-Field Data Fusion (FFDF) of experimental and numerical data enabling statistical comparisons
- Advanced substructure/component testing facility incorporating full-field imaging, and novel hybrid testing platform and methodology enabling virtually augmented testing
- “CerTest methodology” for performance validation (certification) through DoE and Bayesian inference - Novel process for integration of numerical and experimental data - key enabler for achieving overall CerTest objectives

University of BRISTOL · UNIVERSITY OF BATH · University of Southampton · UNIVERSITY OF EXETER

Engineering and Physical Sciences Research Council

Follow on activity from CerTest:

- **Deployment of CerTest methodologies/methods** across sectors and technologies - TRL3/4+: Experimental methods (imaging), multiscale modelling tools, statistical methods, data fusion/merger tools, advanced component and structure testing and "CerTest methodology" – new Centre for Doctoral Training at UoB (*CDT ISCE), Innovate UK, Horizon Europe, …* *ONGOING*
- **Follow on research projects** – focus on TRL 1-3 challenges – *EPSRC, Horizon Europe, International/Bilateral …*

University of Bristol · University of Bath · University of Southampton · University of Exeter

Engineering and Physical Sciences Research Council

CerTest at 2024 SEM Annual Conference

Monday 3rd June:

- Face-Sheet/Core Debonds in Composite Sandwich Structures – Fusion of Full-Field Imaging Data and FE Simulations **#17387** | *Emily HL Leung–University of Bristol; Riccardo Cappello–University of Bristol; Janice M. Dulieu-Barton–University of Bristol; Ole T. Thomsen–University of Bristol*
- Damage Identification in GFRP Laminates Using Thermoelastic Stress Analysis **#17845** | *Irene Jiménez-Fortunato–University of Southampton; Alex Quinlan–Western Michagan University; **Janice M. Dulieu-Barton**–University of Bristol*
- Thermal and White Light Imaging Data Fusion for Complex CFRP Structures **#17539** | *Geir Ólafsson–University of Bristol; Rafael Ruiz Iglesias–University of Bristol; Janice M. Dulieu-Barton–University of Bristol*
- A Tool to Obtain the Coefficients of Thermal Expansion for CFRP Composites using Full-Field Data Fusion **#17536** | *Rafael Ruiz Iglesias–Universityof Bristol; Geir Olaffson–University of Bristol; Riccardo Cappello–University of Bristol; Ole Thomsen–University of Bristol; Janice Dulieu-Barton–University of Bristol*
- Michael Sutton Int'l Student Paper Competition:
  - Hybrid Approach for Understanding the Thermoelastic Response of CFRP Multidirectional Laminates **#18026** | *Rafael Ruiz Iglesias–University of Bristol*
  - Investigation of the Non-Adiabatic Thermoelastic Effect in Face-Sheet/Core Debonded Composite Sandwich Structures **#18025** | *Emily HL Leung–University of Bristol*

Tuesday 4th June:

- Novel Composite Substructure Testing Approaches Utilizing Multi-Camera Full-Field Imaging **#17580** | *Tobias Laux–University of Bristol; Riccardo Cappello–University of Bristol; JackS. Callaghan–Bangor University; Geir Ólafsson–University of Bristol; Stephen W. Boyd–University of Southampton; Duncan A. Crump–University of Southampton; Andrew F. Robinson–University of Southampton; Ole T. Thomsen–University of Bristol;Janice M. Dulieu-Barton–University of Bristol*
- Validation of a Numerical Model for Predictions of the Thermoelastic Effect in Laminated Composite Structures **#17570** | *Riccardo Cappello–University of Bristol; Rafael Ruiz-Iglesias–University of Bristol; Geir Olafsson–University of Bristol;Giuseppe Pitarresi–University of Palermo; Giuseppe Catalanotti–Kore University of Enna; Janice Dulieu-Barton–University of Bristol*

University of Bristol · University of Bath · University of Southampton · University of Exeter

Engineering and Physical Sciences Research Council

Thank you for your attention!

Questions?

University of BRISTOL

UNIVERSITY OF BATH

University of Southampton

UNIVERSITY OF EXETER