Doctoral thesis

On the generation of design allowables taking into account the material variability, the presence of defects and the random spatial distribution of FRP

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- Dr. Albertino Arteiro (U. Porto)

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ANALYSIS AND ADVANCED MATERIALS FOR STRUCTURAL DESIGN

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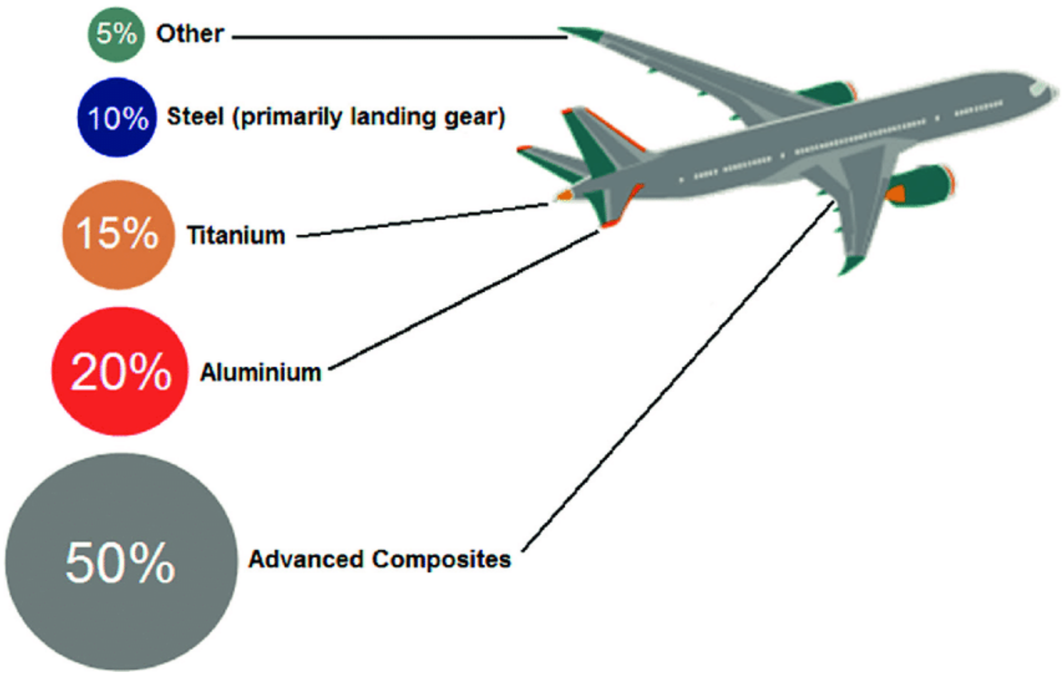
Introduction

- Composite materials are widely used thanks to their specific properties:
  - ✓ High mechanical performance
  - ✓ Low density



Material used in the aircraft Boeing 787

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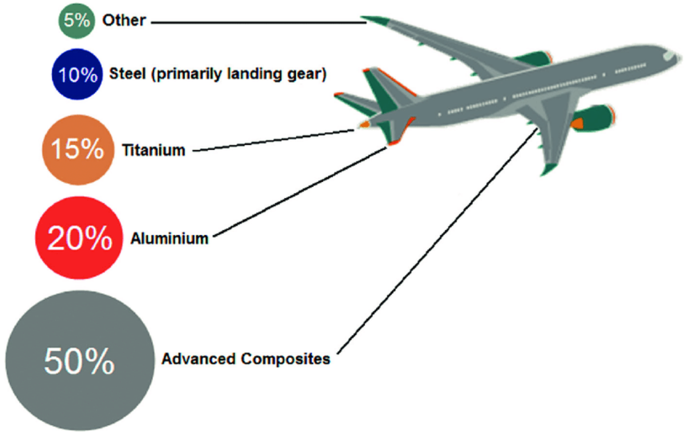

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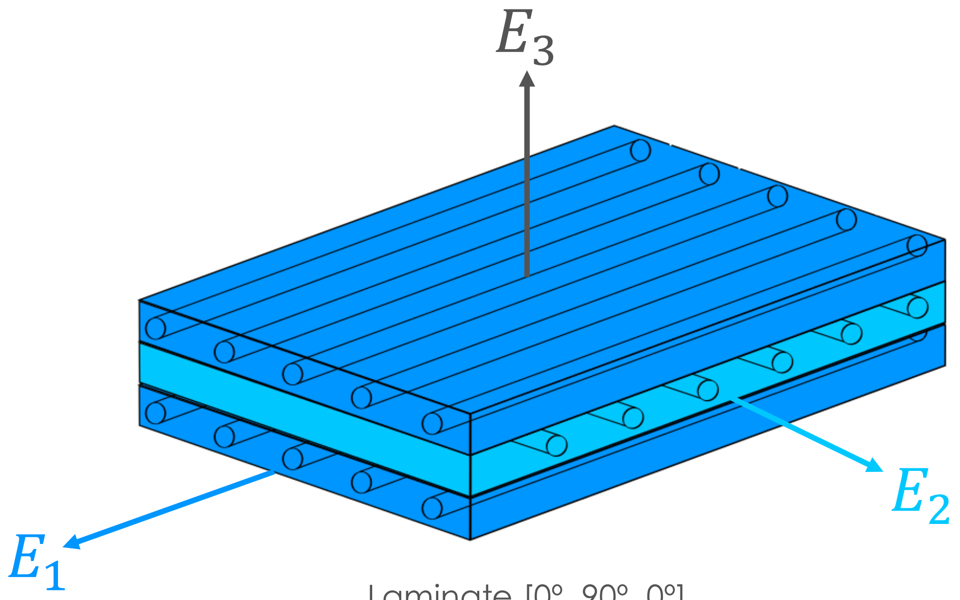
- However, the anisotropic behavior of composite structures make their design a complex process.



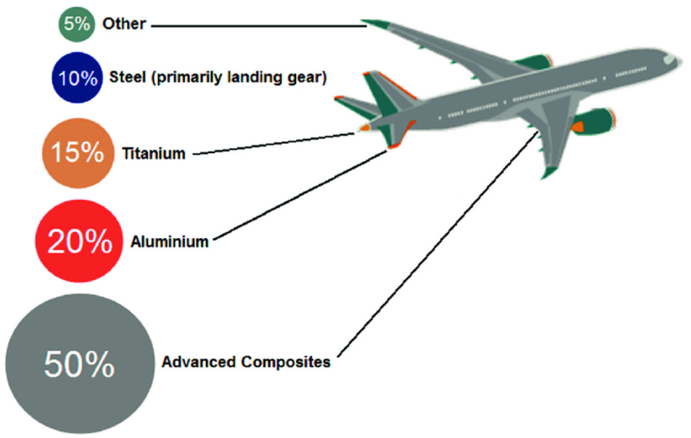
Laminate [0°, 90°, 0°]

Introduction

- Composite materials are widely used thanks to their specific properties:
  - ✓ High mechanical performance
  - ✓ Low density

- However, the anisotropy behavior of composite structures make their design a complex process.

- Moreover, the brittle nature of polymer composites means that failure initiates from a stress raiser.



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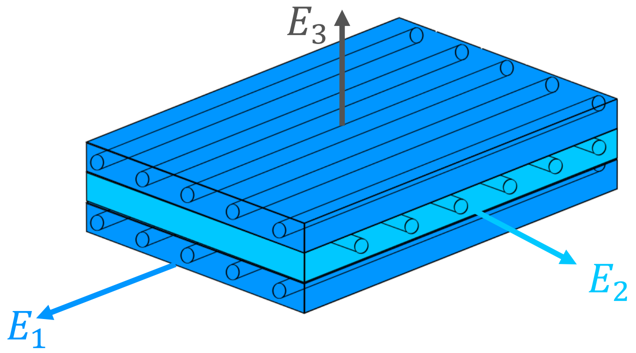

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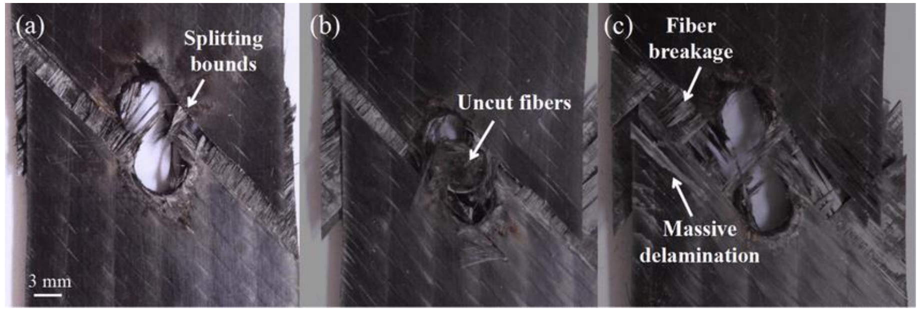


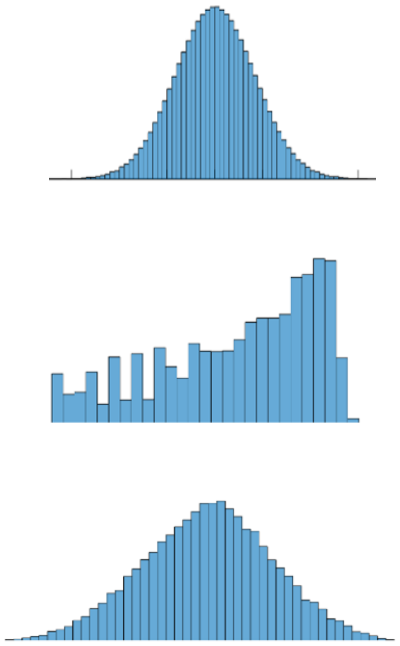
Damage on an open hole specimen

Introduction

- Uncertainties related to composite structures:

  - Loads
  - Material
  - Geometry
  - Manufacturing deffects

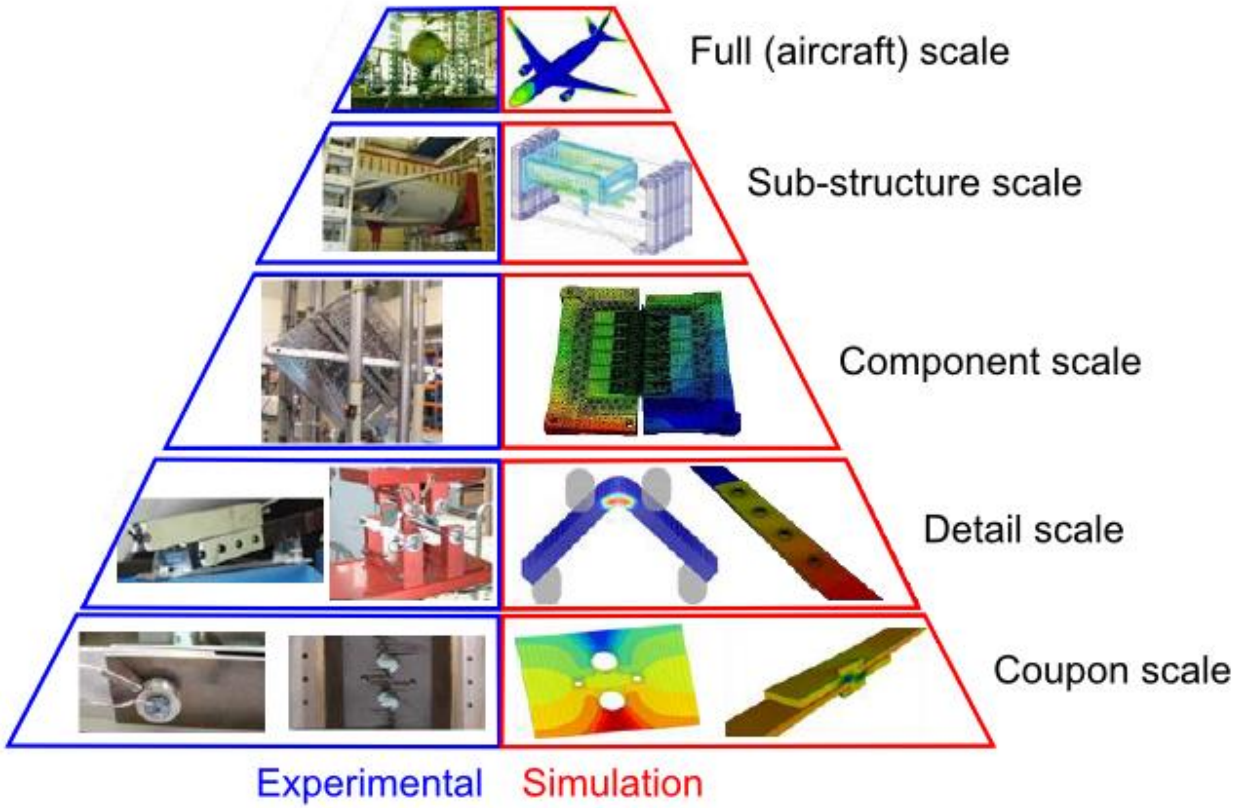
  …



Mean, CoV

Introduction

- Design of composite structures:



Pyramid of certification
[Composite Material Handbook, CMH-17]

Introduction

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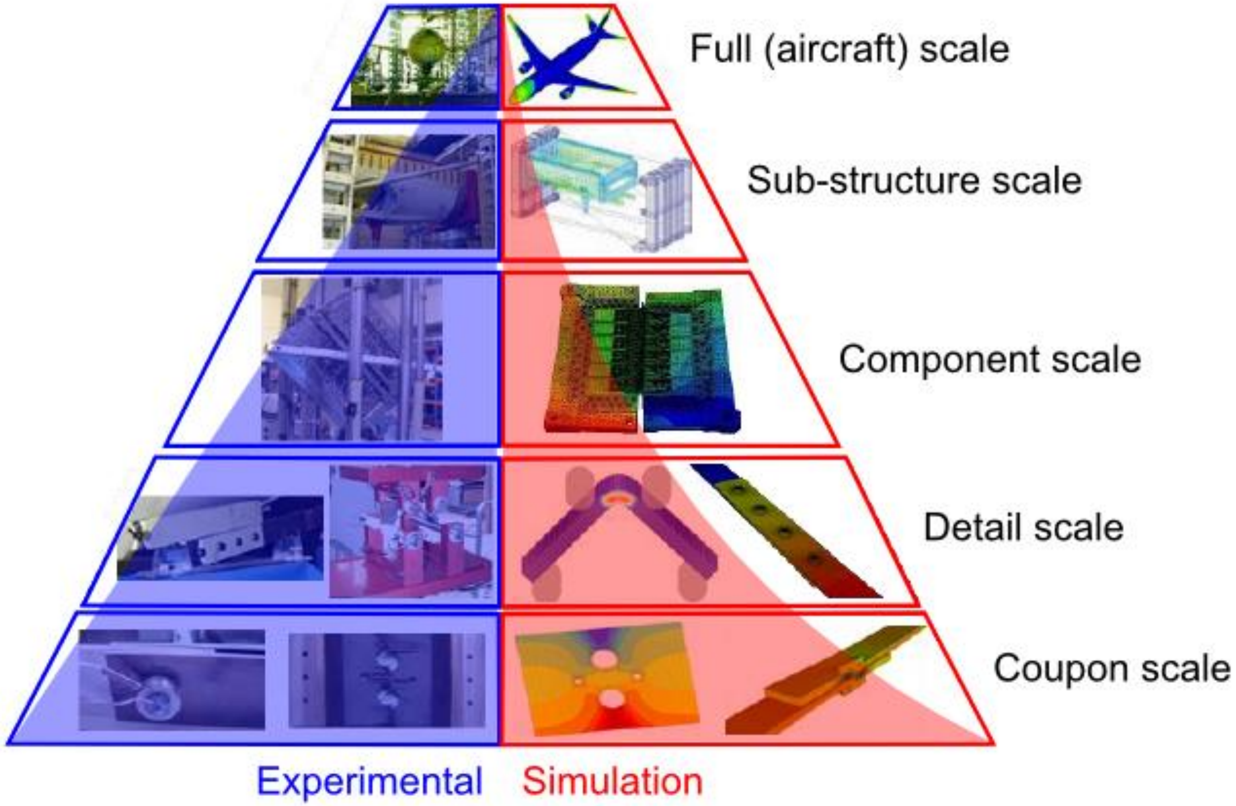


Pyramid of certification
[Composite Material Handbook, CMH-17]

↓ Design time

⇩

↓ Experimental test campaigns

⇩

↑ Simulations

Introduction

- Composite structures:
  - ✓ Excellent specific mechanical properties
  - ❖ High effect by uncertainties

"In practice, today's simulation are providing a single result.

In front of the authorities, we wish to provide an envelop of uncertainty associated to the results accounting for variations of specimens (material, manufacturing artefacts, assemblies build stress, loading....)"

(M. Fouinneteau, ECOMASS-Composites 2019, Eindhoven)

Main objective

On the generation of **design allowables** taking into account the material variability, the presence of defects and the random spatial distribution of FRP

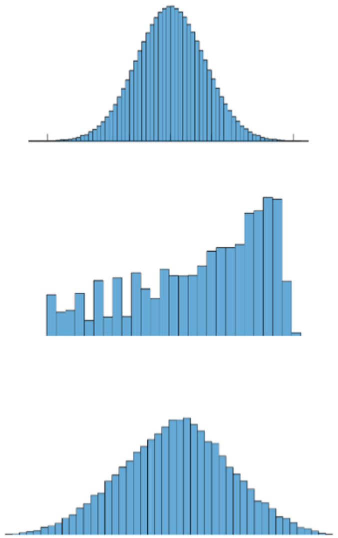
Loads

Material

Geometry

Manufacturing deffects

…



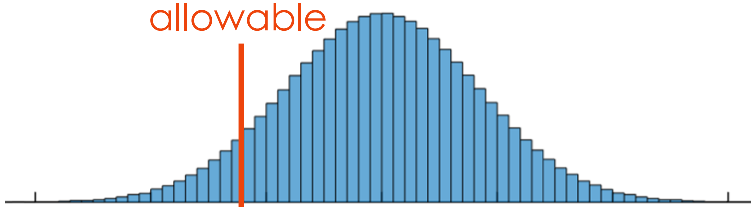
Mean, CoV

Analysis method

Analytical

Numerical

Design allowable



Maximum strength

Objectives

On the generation of **design allowables** taking into account the material variability, the presence of defects and the random spatial distribution of FRP

- **Objective 1**: How to determine the design allowables of different stress raisers?
  - Geometrical feature: Open Hole
  - Damage: impact on a surface
  - Presence of defects: fiber misalignment

Objectives

On the generation of design allowables taking into account the **material variability**, **the presence of defects** and the random spatial distribution of FRP

- **Objective 1**: How to determine the design allowables of different stress raisers?
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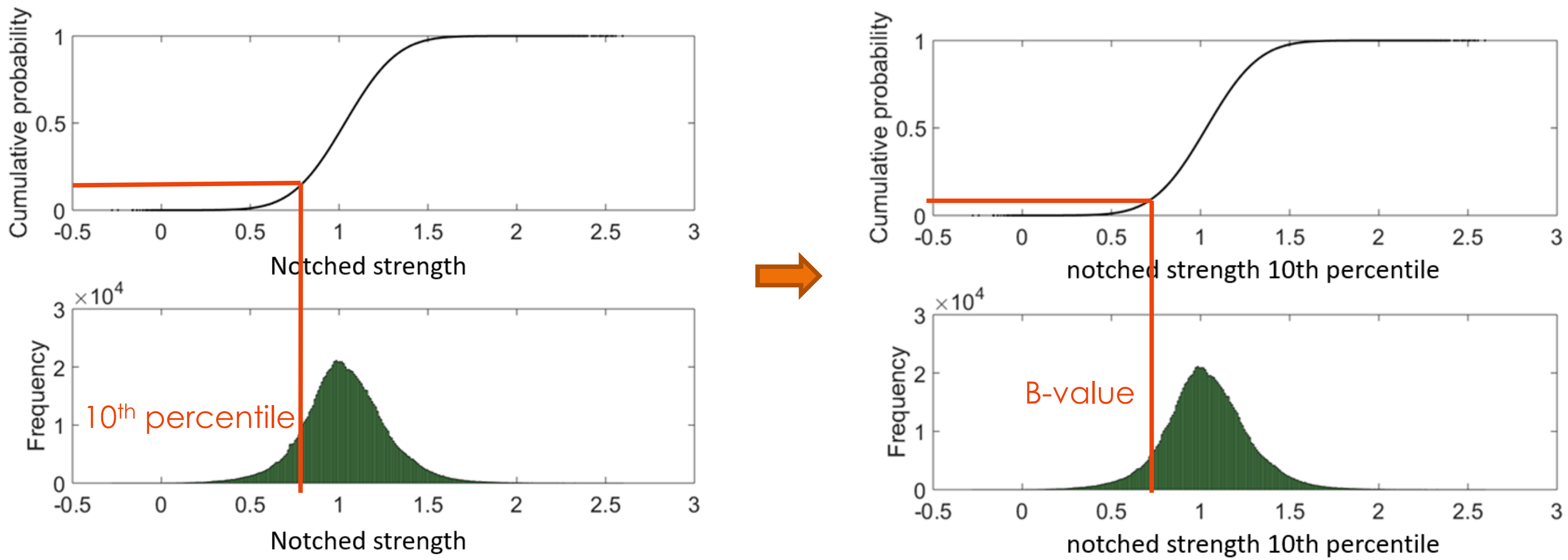
- **Objective 2**: How to determine the material variability with the presence of defects?

Design allowables

- B-value as a design allowable

B-basis: *a value that at least 90% of the population of material values is expected to equal or exceed this tolerance bound with a 95% of confidence.*

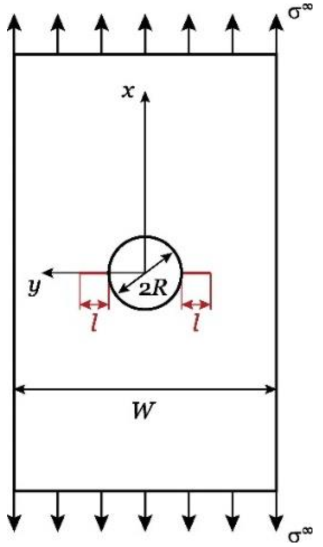


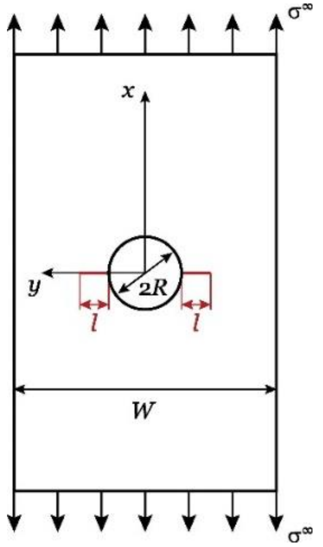
Design allowables. Analytically

- The notched strength can be calculated analytically following:

Camanho et al. 2012

$$\begin{cases} \frac{1}{l}\int_{R}^{R+l} \sigma_{xx}(0,y)dy = X^{L} \\ \int_{R}^{R+l} \mathscr{G}_{I}(a)da = \int_{0}^{l} \mathscr{R}(\Delta a)d\Delta a \end{cases}$$





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Laminate elastic properties

Laminate strengths

Laminate toughness

Design allowables. Analytically

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Camanho et al. 2012

Furtado et al. 2017

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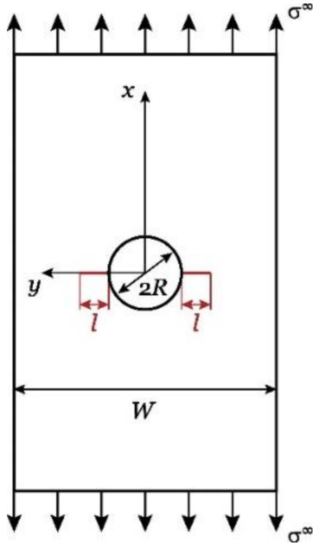


Laminate elastic properties ← E_1

Trace Theory and Master ply concept

Laminate strengths ← $X_{1,T}$

Omni strain and Unit circle

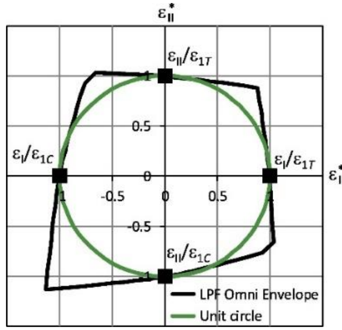
Laminate R-curve ← $\mathcal{R}_{ss}^{(0)}$

Analytical model based on fracture toughness

$$Tr = \frac{E_1}{0.88}$$

Tsai and Melo 2014

Lay-up	$\frac{E_1}{Tr}$	$\frac{E_2}{Tr}$	$\frac{G_{12}}{Tr}$	v_{12}
Master ply [0°]	0,88	0,052	0,031	0,32



$$\mathcal{K}_{IC}^{(i)} = \mathcal{K}_{IC}^{0}\frac{\mathcal{X}^{(i)}\Omega_{0}^{(i)}}{\mathcal{X}^{0}}$$

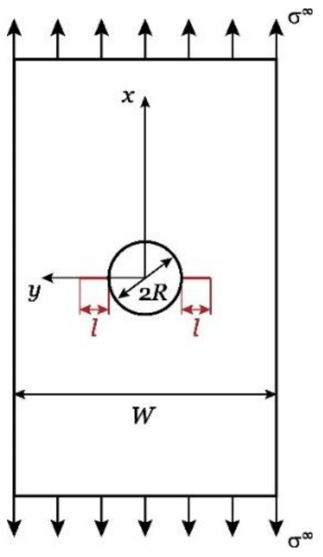
Camanho et al. 2007
Catalanotti et al. 2014

Design allowables. Analytically

- Input parameters of the case study:

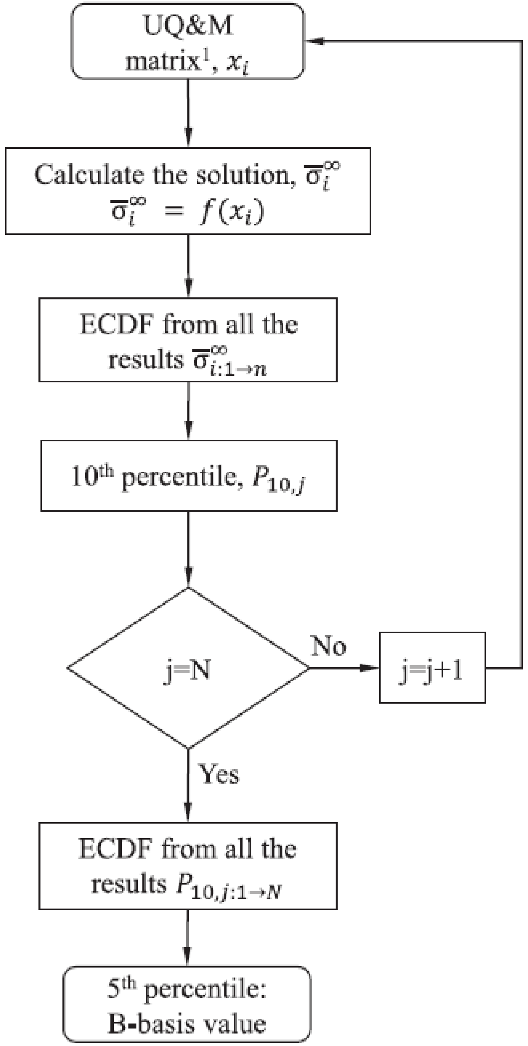
IM7/8552	E_1 [Gpa]	X_T [Gpa]	$\mathscr{R}_{ssT}$ [N/mm]
Mean value	171.42	2323.47	206.75
STDV	2.38	127.45	23.64

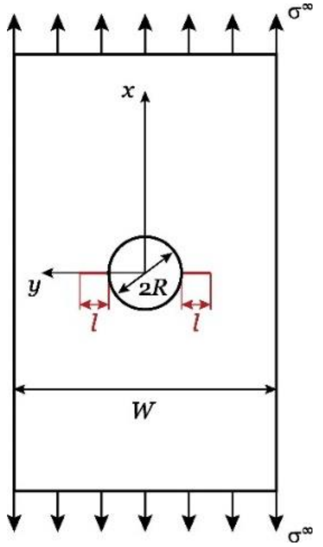
Geometry	W [mm]	$2R$ [mm]
Nominal value	12	2
Range	$\pm$ 0.2	$\pm$ 0.2



Design allowables. Analytically

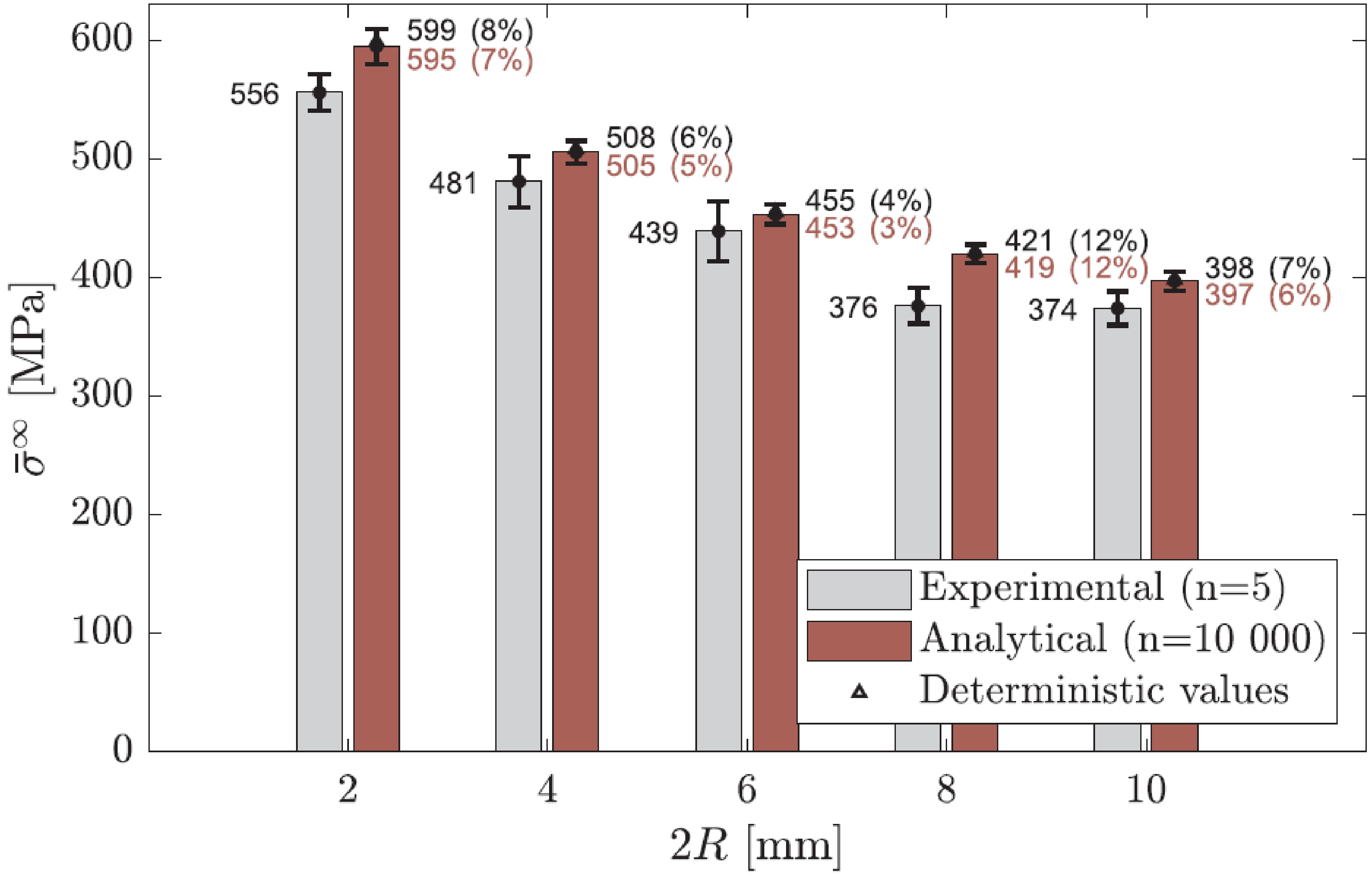
- Methodology:

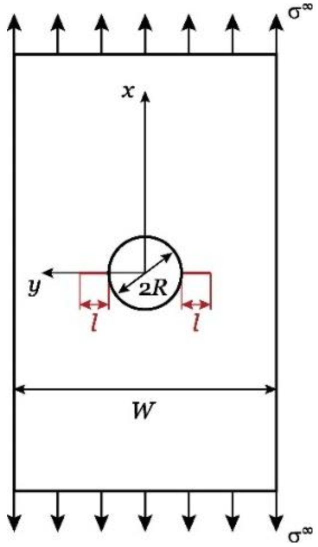




Design allowables. Analytically

- Results:





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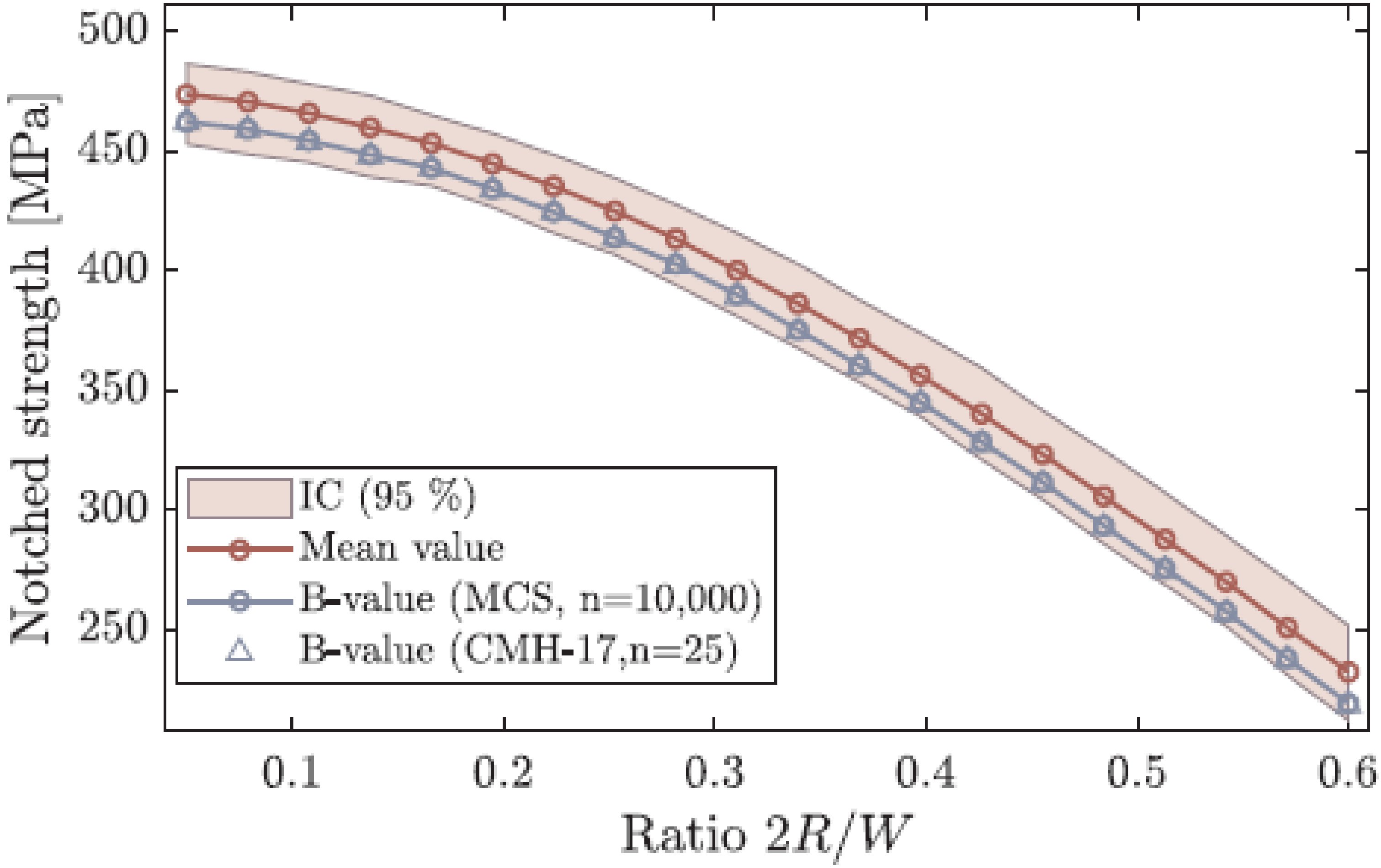
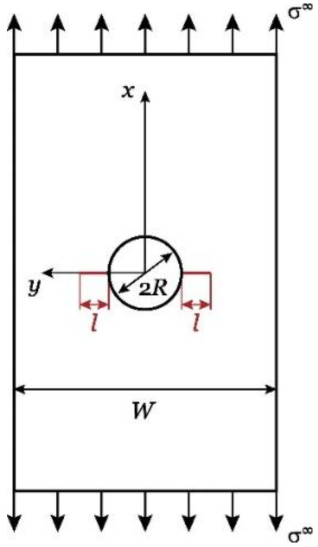


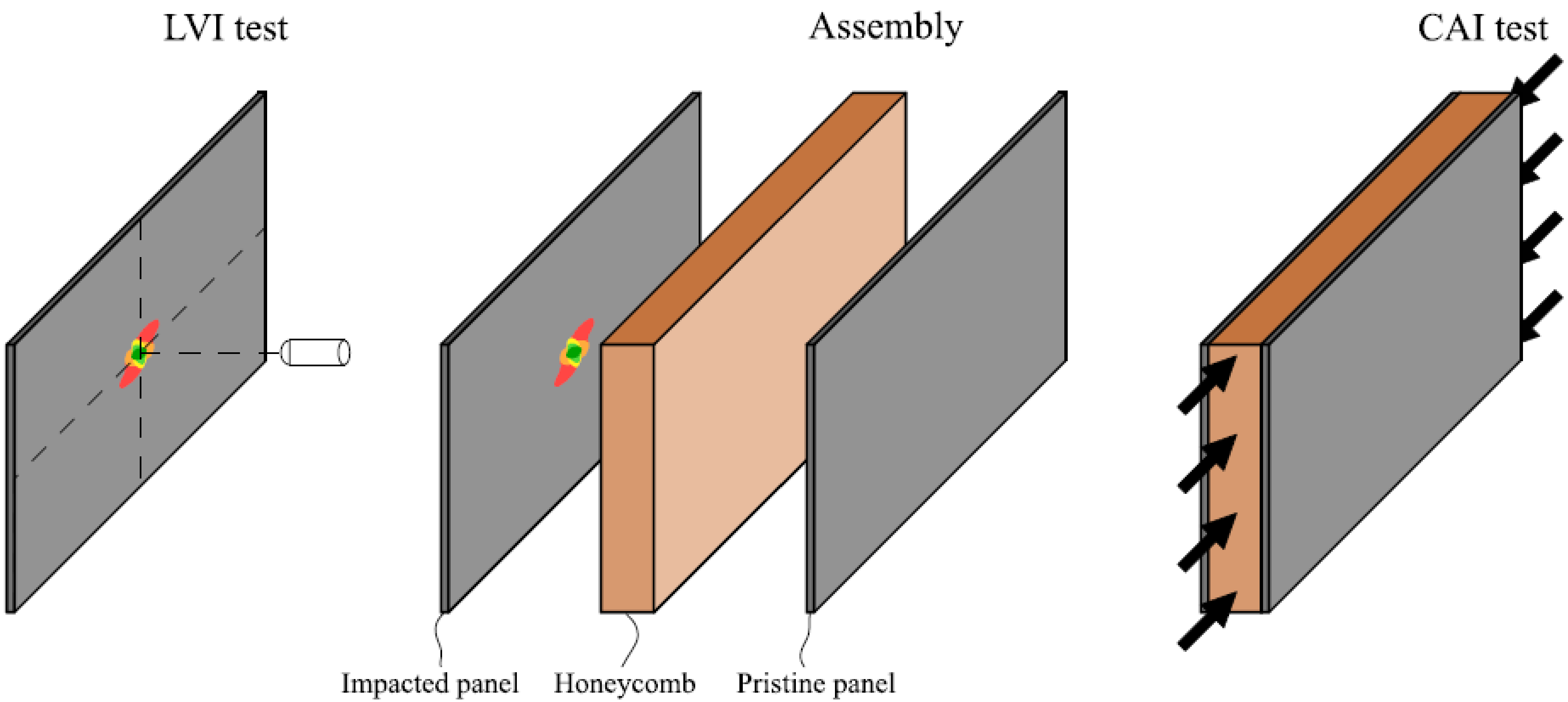


Design allowables. Analytical

- Limitations:
  - Balanced laminates
  - Inter-laminar damage is not considered
  - Failure mechanism?

Design allowables. FEM

- Determination of the CAI after the LVI:



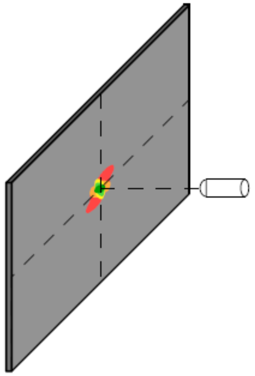
Design allowables. FEM

Input parameters of the case study:

Technical characteristics of the LVI and CAI laboratory test.

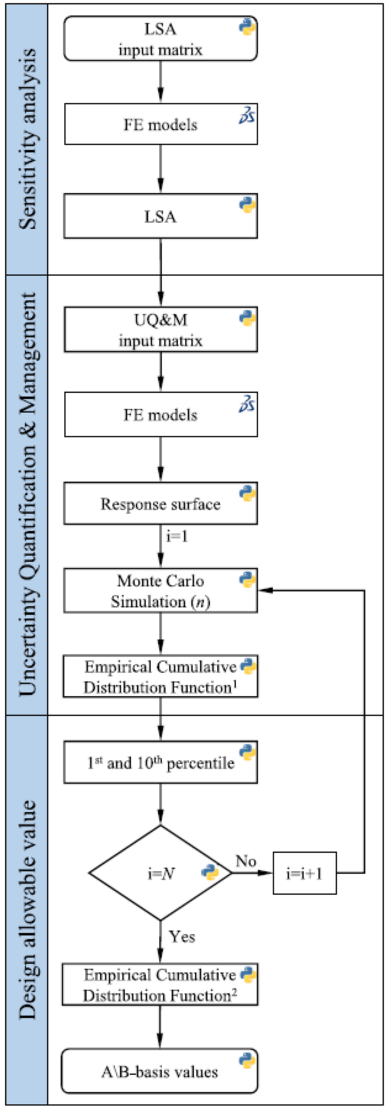
Material type	UD tape - CFRP	
Stacking sequence	$[45/135/90/0/0]_s$	
Specimen dimensions	225 × 150	mm
Thickness of the laminate	1.84	mm
LVI test window	125 × 125	mm
Impact energy	25	J
Impactor mass	3.2	kg
Honeycomb type	HRH-10–6.0–0.96	
Thickness of the honeycomb	30	mm

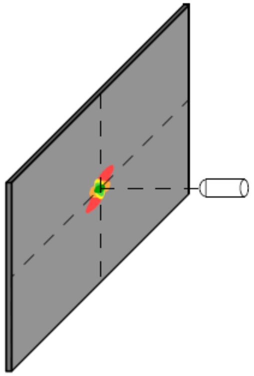
Symbol	Input parameter
m_{imp}	Impactor mass
μ	Friction coefficient
$\mathcal{G}_{Ic}$	Mode I interlaminar fracture toughness
$\mathcal{G}_{IIc}$	Mode II interlaminar fracture toughness
BK_η	B-K exponent parameter for mixed mode propagation
τ_{II}	Mode II interlaminar strength
ρ	Density
E_{11}	Young Modulus in fibre direction
E_{22}	Young Modulus in matrix direction
ν_{12}	Major Poisson ratio
ν_{23}	Transverse Poisson ratio
G_{12}	Shear modulus
X_T	Fibre tensile strength
X_C	Fibre compression strength
f_{XC}	Portion of X_T
f_{XC}	Portion of X_C
Y_T	Matrix tensile strength
Y_C	Matrix compression strength
S_L	Matrix shear strength
S_{LP}	Matrix shear yield stress
K_P	Shear plasticity parameter
$\mathcal{G}_{XT}$	Tensile fibre fracture toughness
$\mathcal{G}_{XC}$	Compression fibre fracture toughness
$f_{\mathcal{G}XT}$	Portion of $\mathcal{G}_{XT}$ dissipated by the first branch
$f_{\mathcal{G}XC}$	Portion of $\mathcal{G}_{XC}$ dissipated by the first branch
E_{33H}	Longitudinal Young Modulus of the honeycomb
ν_{12H}	Transverse Poisson ratio of the honeycomb
C_H	Coefficient of the honeycomb[1]
G_{12H}	Shear modulus of the honeycomb
G_{13H}	Shear modulus of the honeycomb
G_{23H}	Shear modulus of the honeycomb



Design allowables. FEM

- Methodology:





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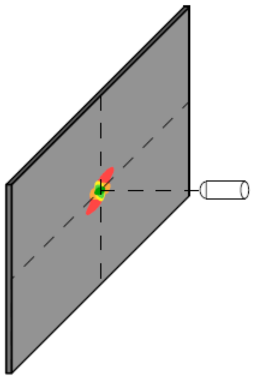

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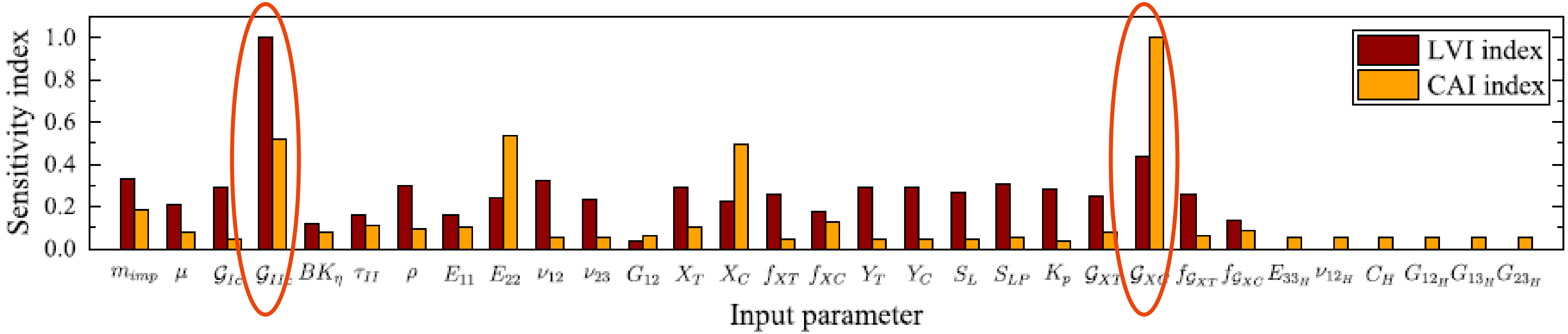

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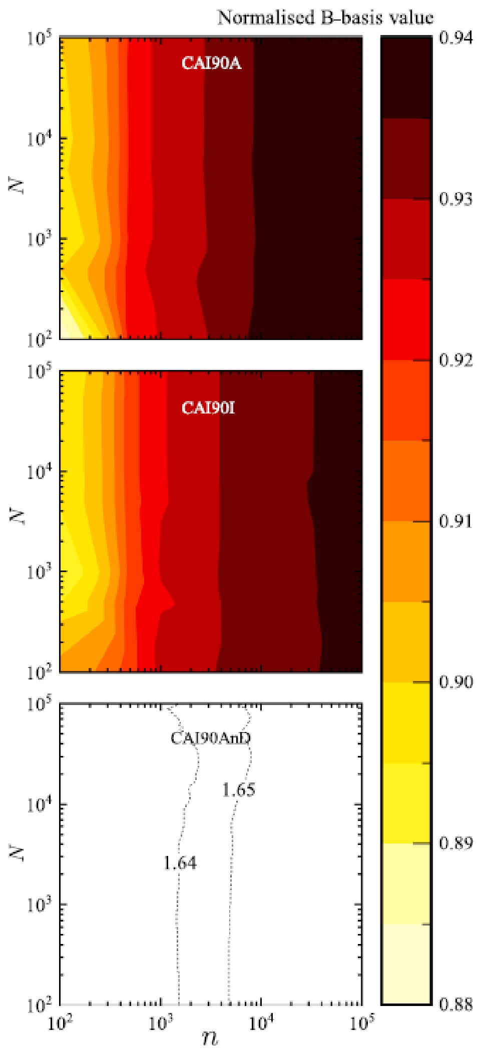

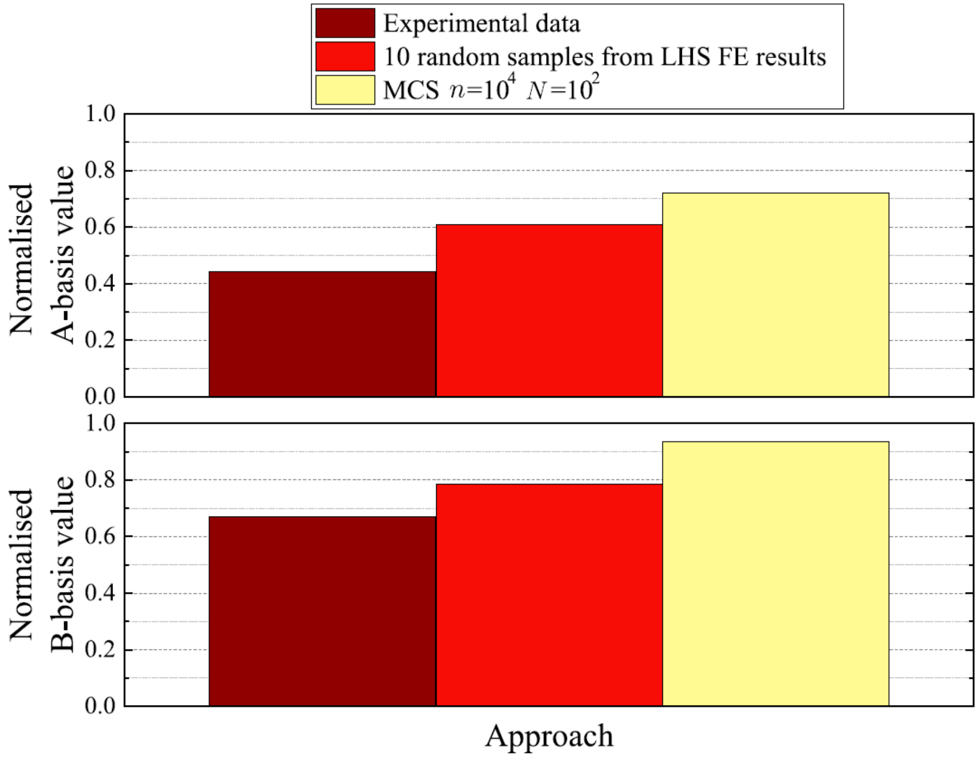

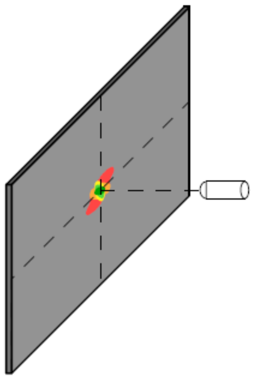

Design allowables: presence of defects

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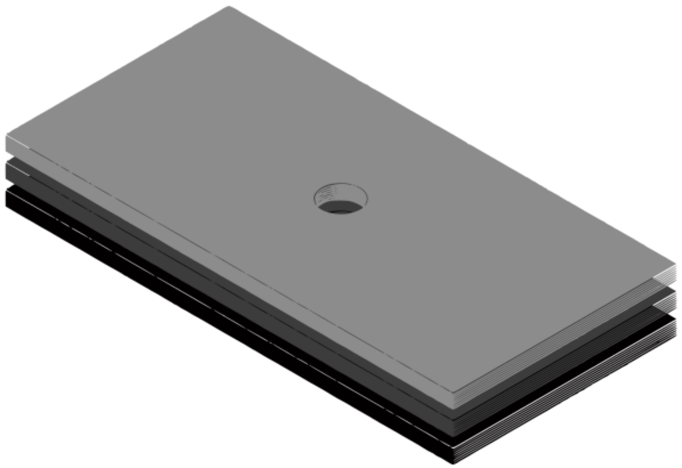
Uncertainty of the material properties

Uncertainty of the geometry

Uncertainty of the defects: misalignment



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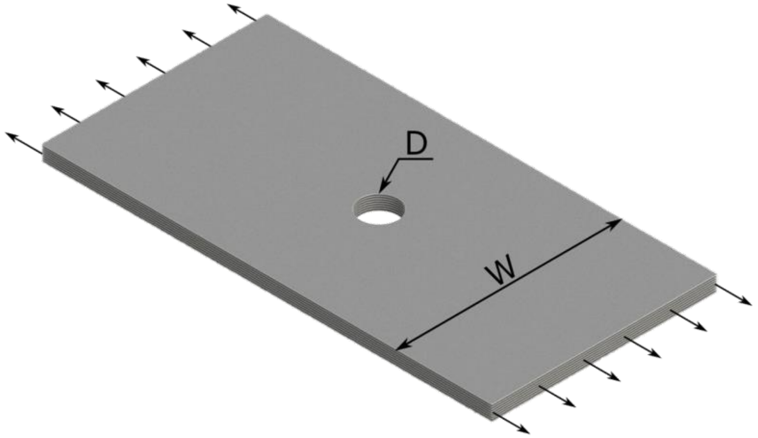

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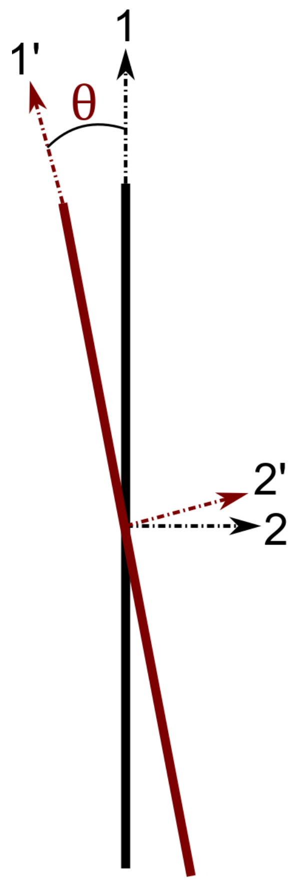

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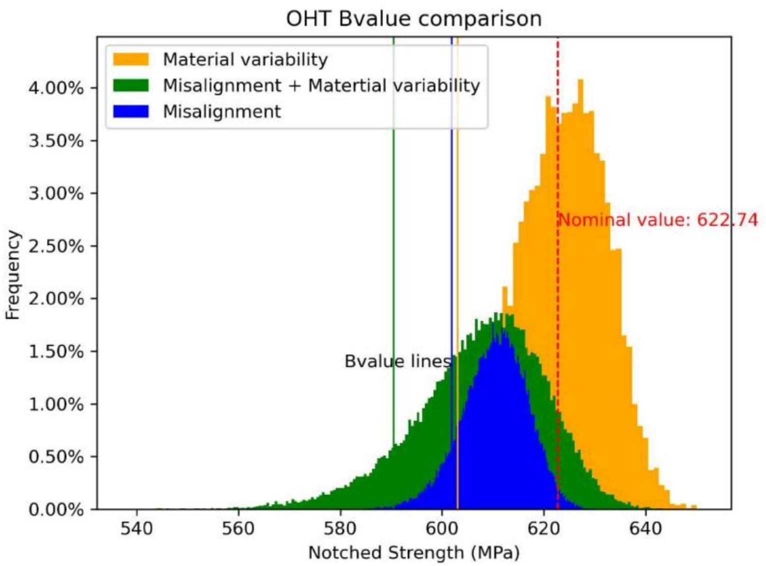

Uncertainty of the material properties

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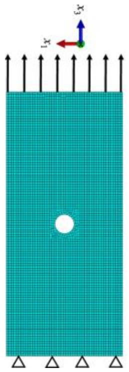
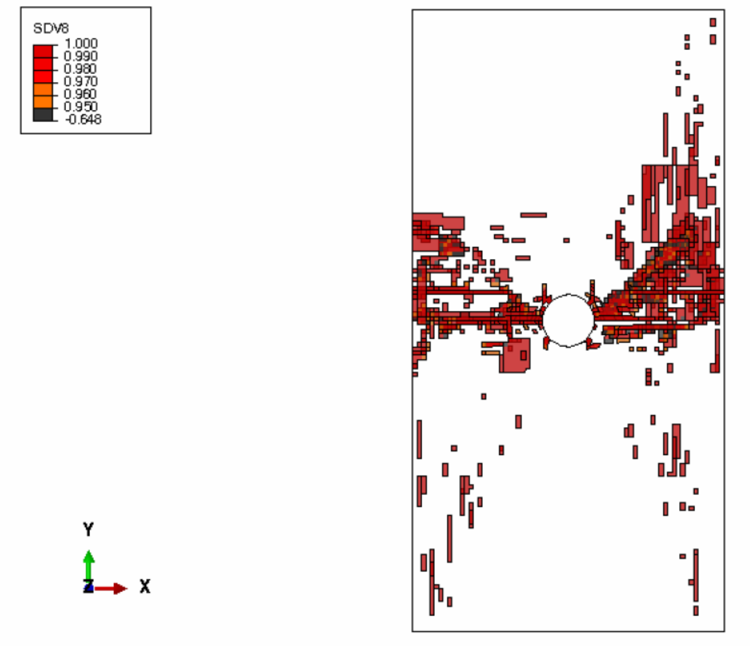
Uncertainty of the defects: misalignment

Low fidelity model: Analytical

- B-value
- Knock-down factor
- ...

Design allowables: presence of defects





Uncertainty of the material properties

Uncertainty of the geometry

Uncertainty of the defects: misalignment

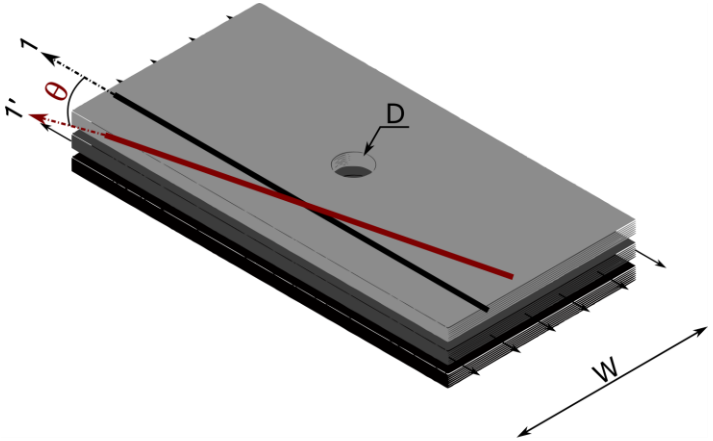
Low fidelity model: Analytical

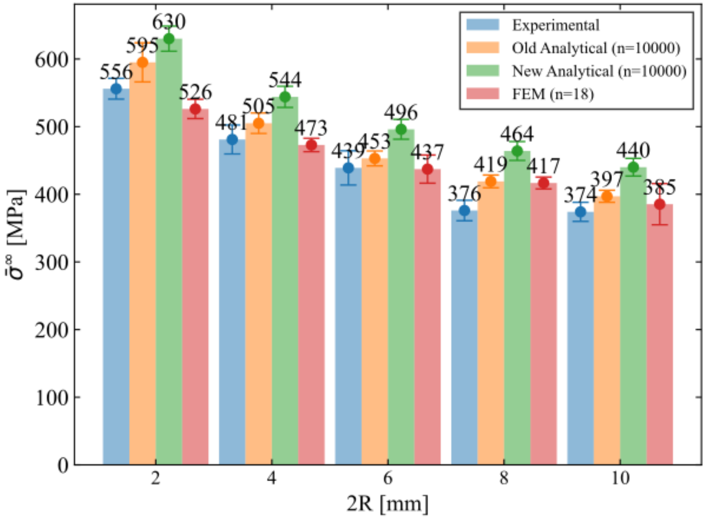
- B-value
- Knock-down factor
- ...

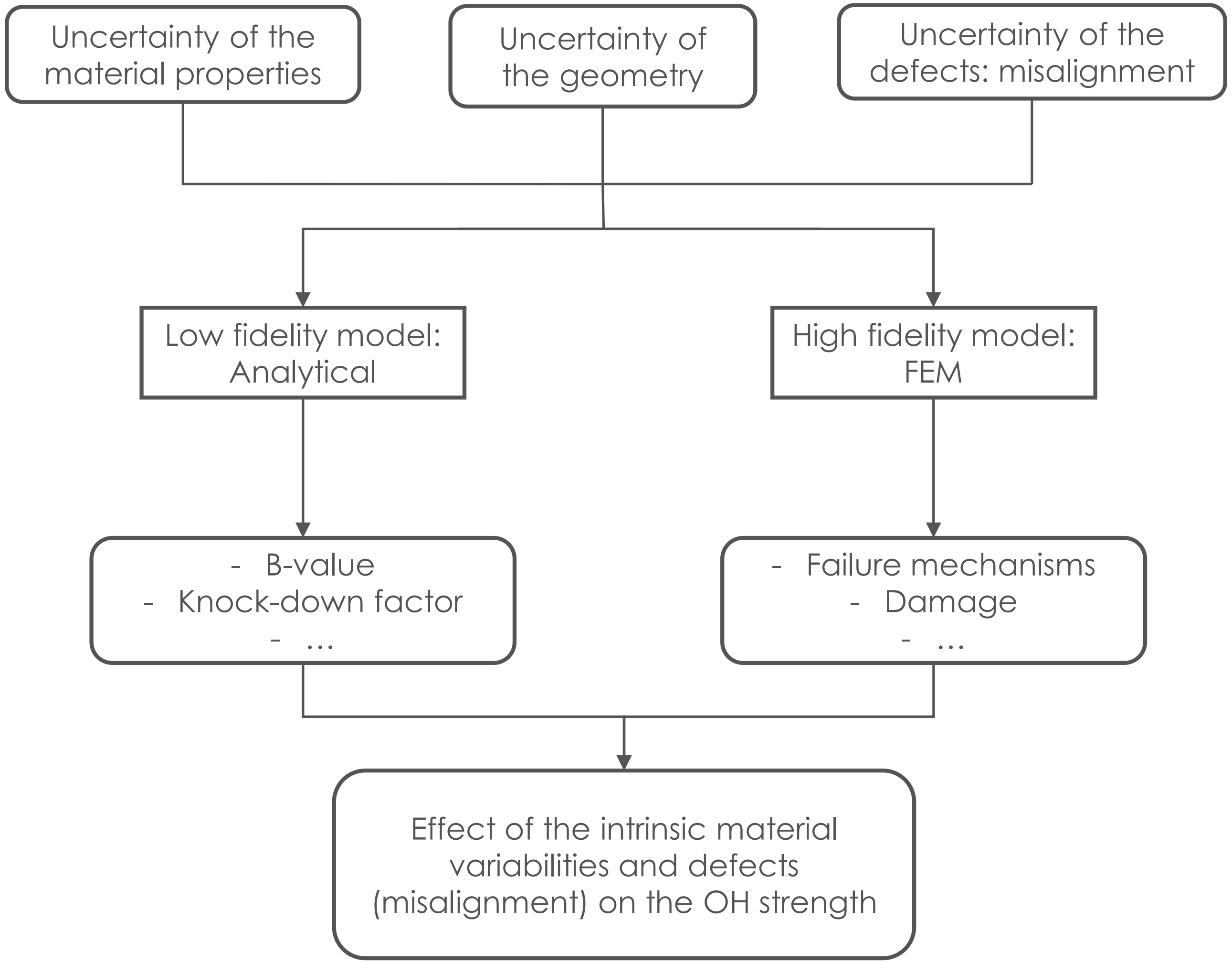
High fidelity model: FEM

- Failure mechanisms
- Damage
- ...

Design allowables: presence of defects







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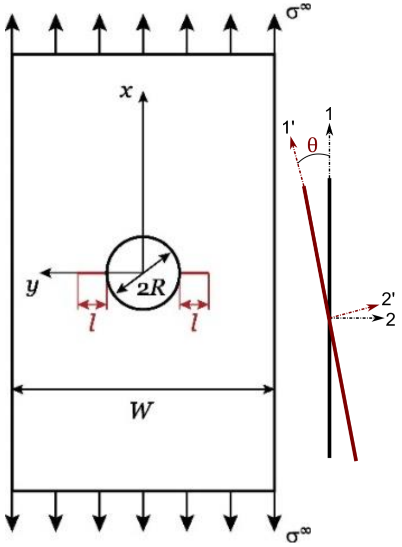
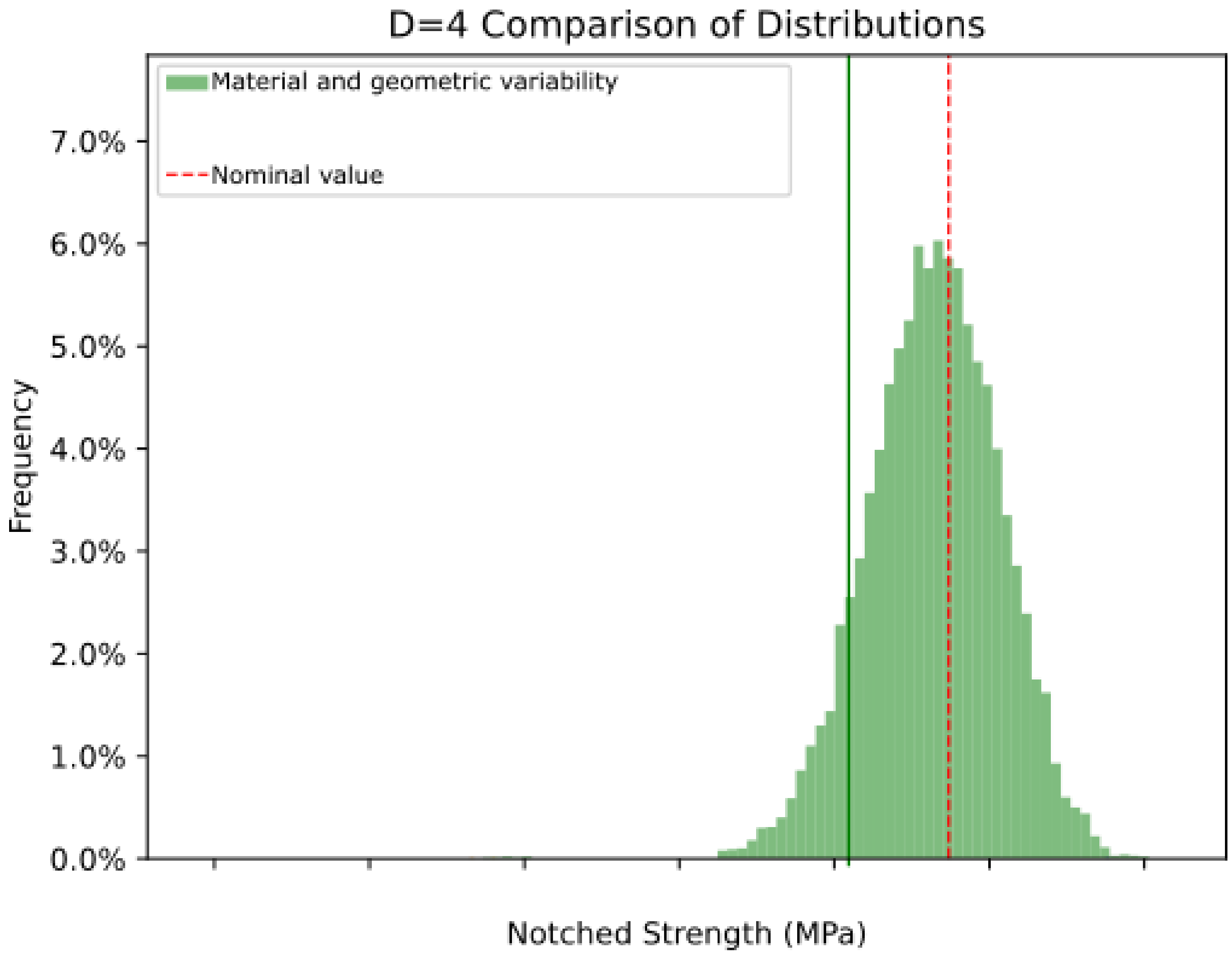
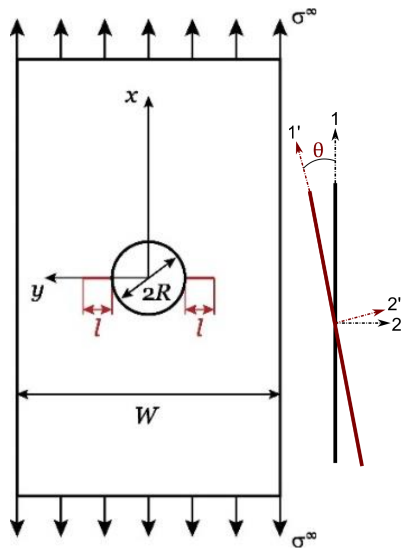


- Input parameters of the case study:
  - Material: IM7-8552
  - Different diameters (D) are considered: 2, 4, 6, 8 and 10 mm
  - Same diameter-width ratio: $\frac{D}{W} = \frac{1}{6}$
  - Misalignment is considered as:
    - Uniform distribution: $\theta º = uniform\{-3º, 3º\}$
    - Normal distribution: $\theta º = normal\{\mu = 0º, s = 3º\}$

Design allowables: presence of defects

- Results:





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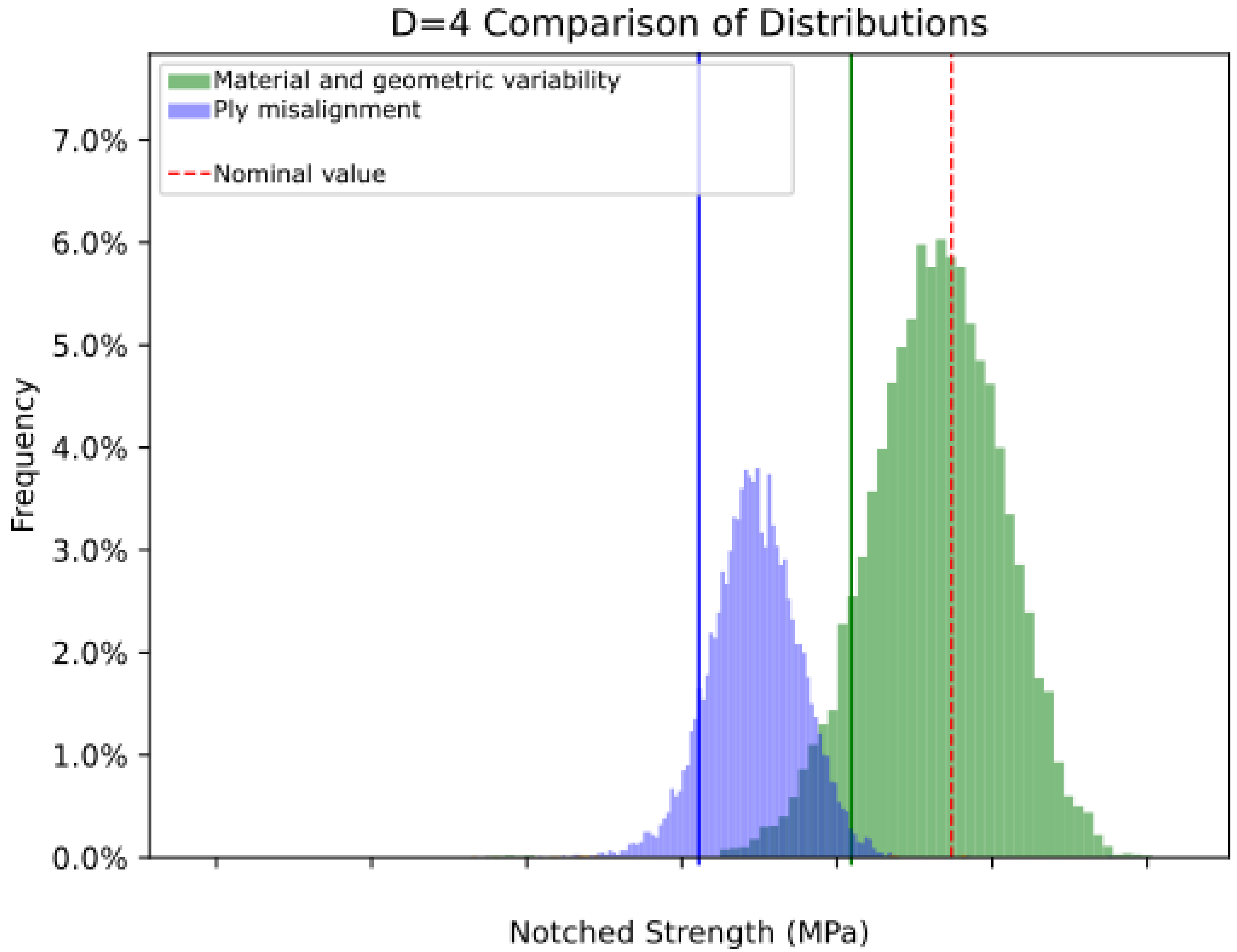

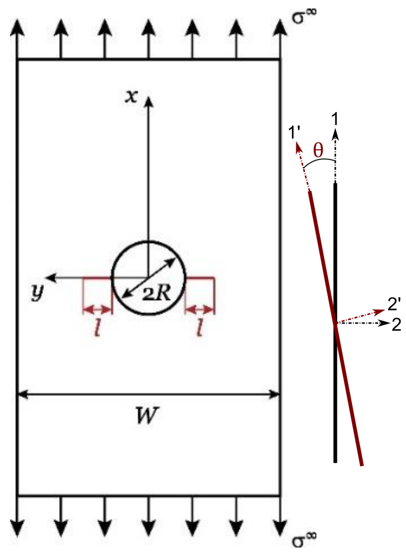

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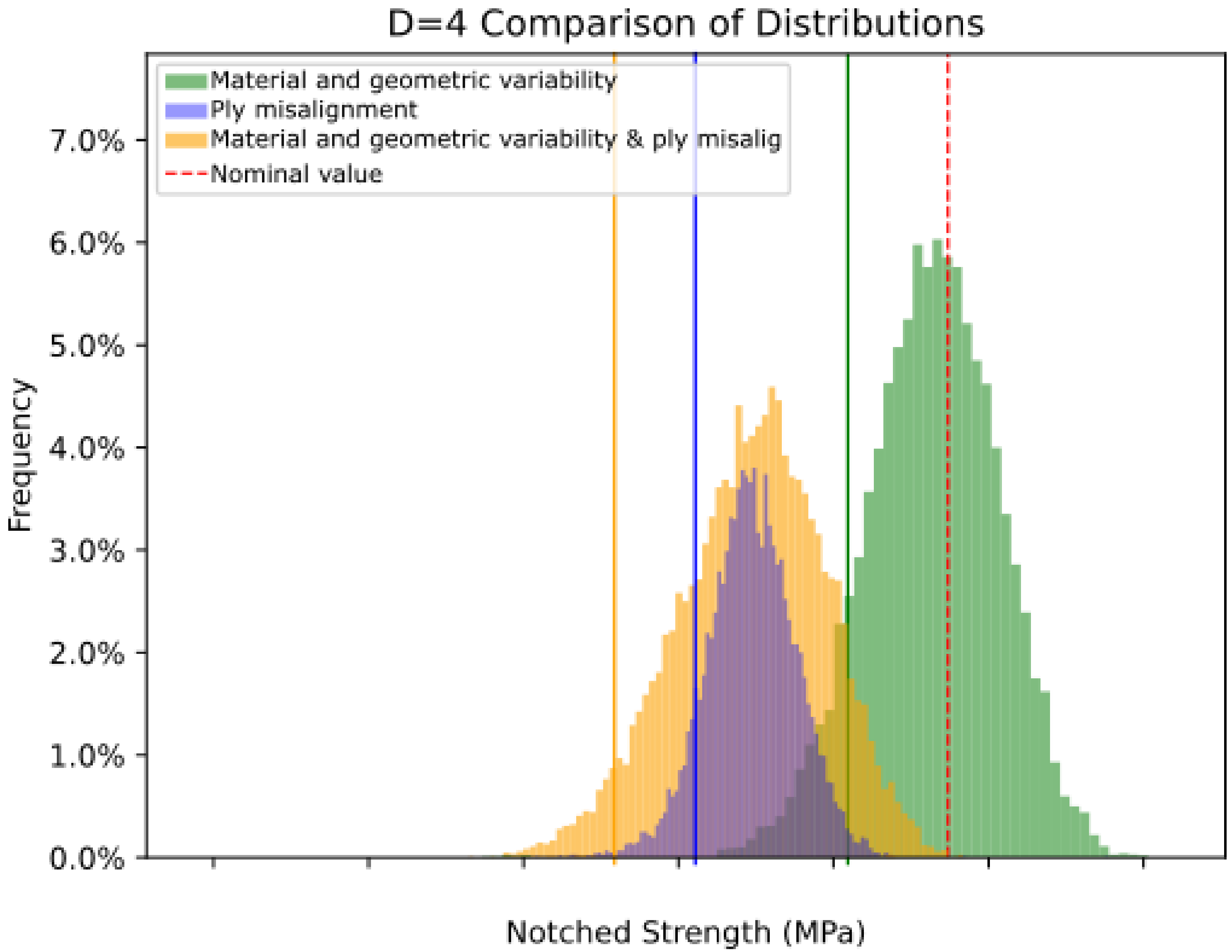

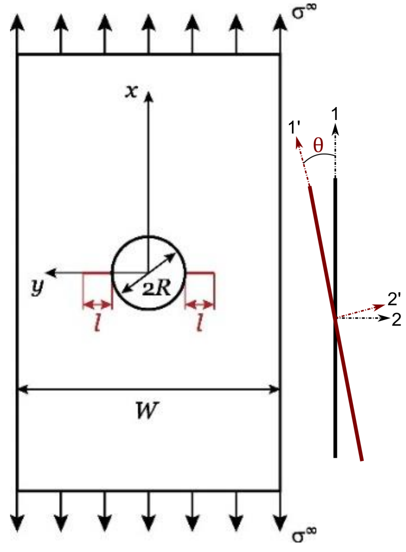

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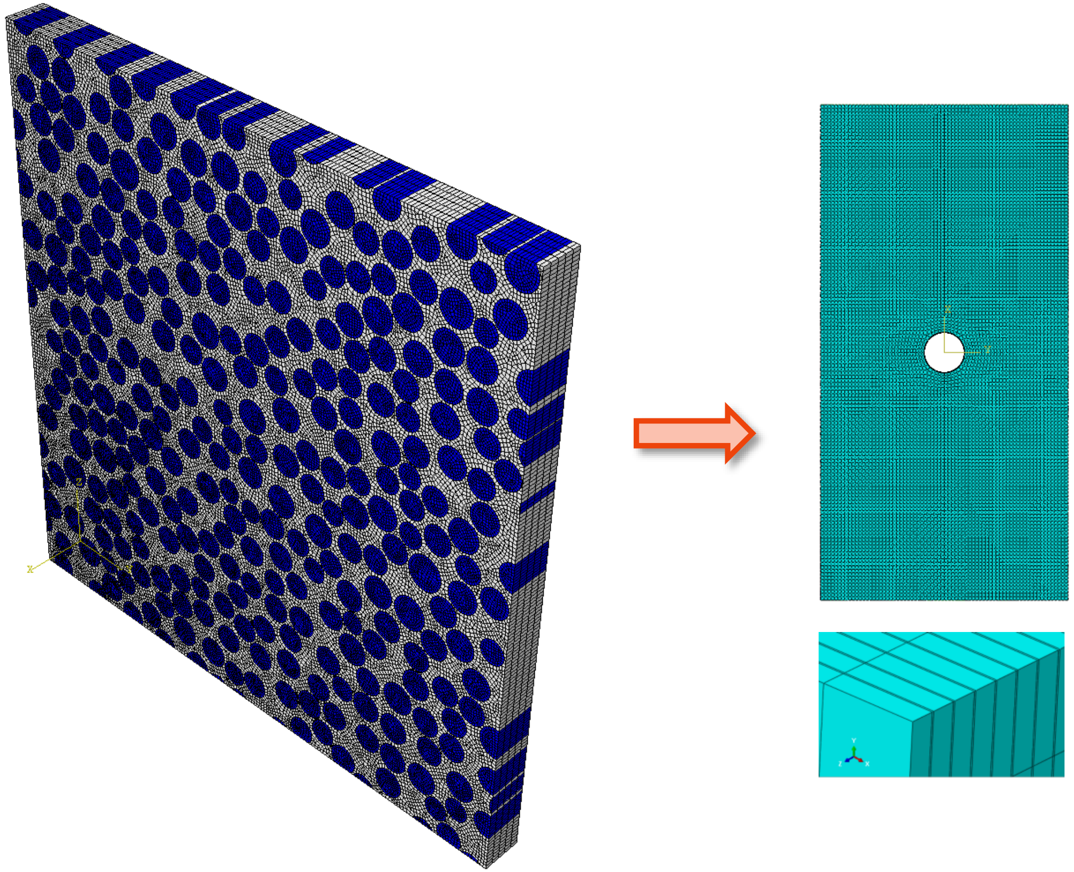
- **Objective 2**: How to determine the material variability with the presence of defects?

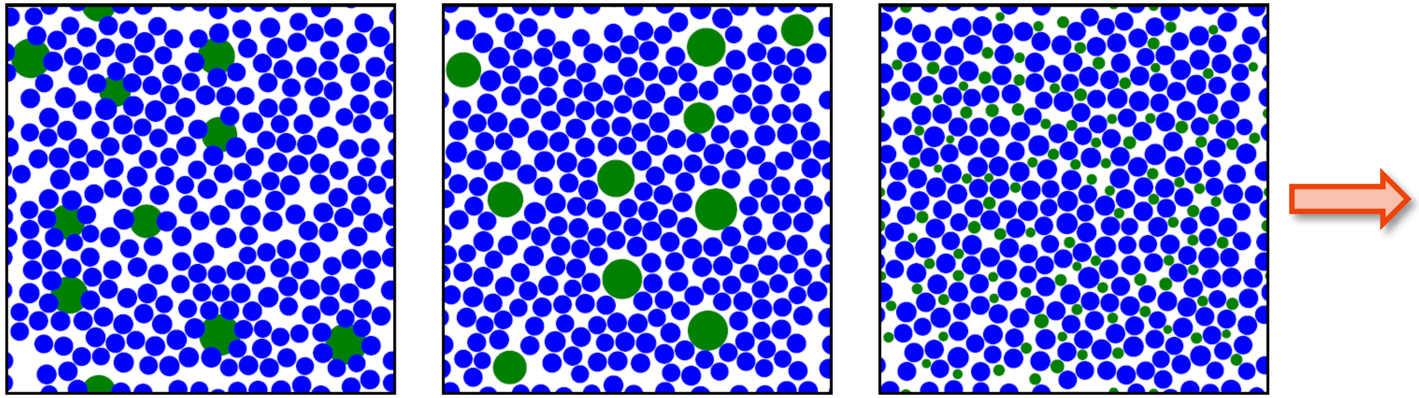
Material uncertainty: microscale analysis

- Microstructural analysis are useful to determine the properties that feed meso-scale models (eg: OH) from the properties of the constituents and their distribution:
  - Fibers
  - Matrix
  - Fiber/matrix interface



Material uncertainty: microscale analysis

- The variability of the constituents, the presence of defects and their random spatial distribution are the main sources of uncertainty:



$E_{11}(mean, STDV)$

$v_{12}(mean)$

$E_{22}(mean, STDV)$

$G_{12}(mean, STDV)$

$G_{23}(mean, STDV)$

$v_{23}(mean)$

Material uncertainty: microscale analysis

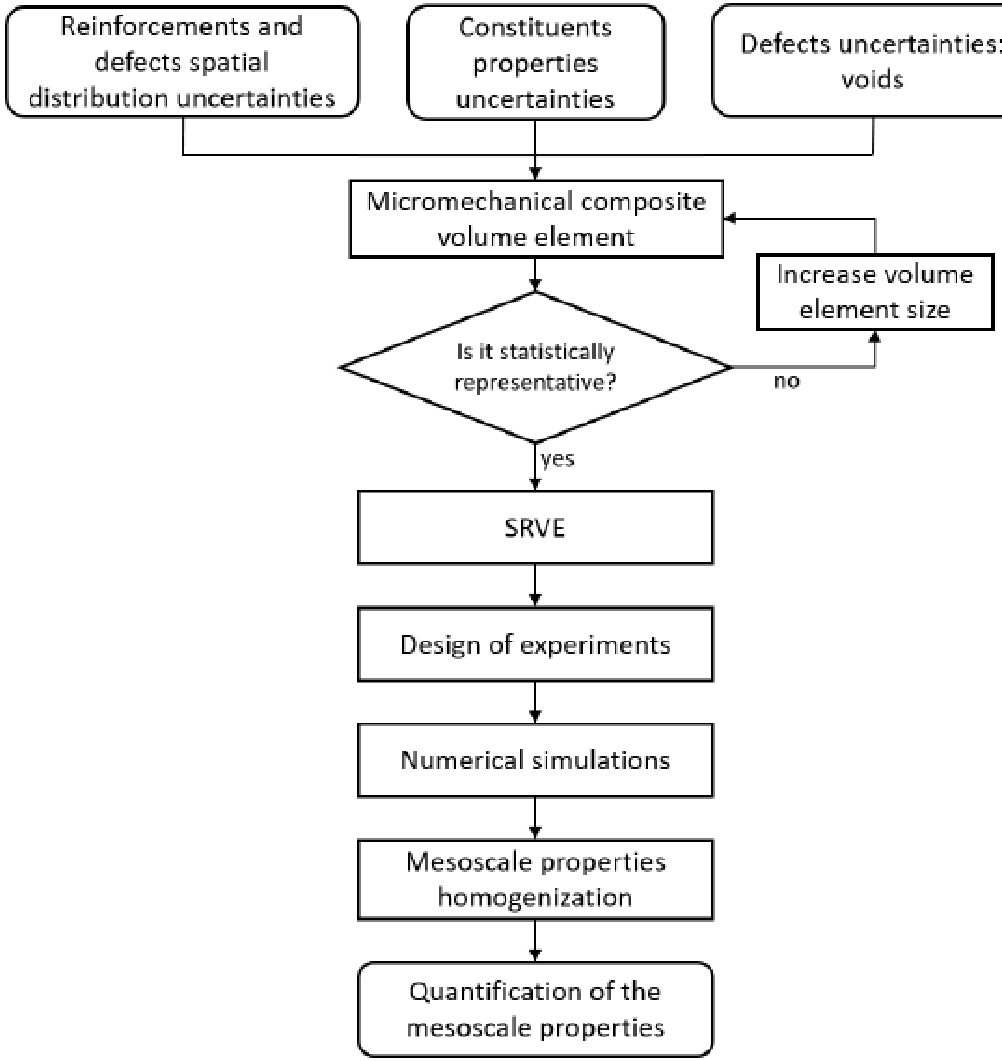
- Input parameters of the case study:

Constituent	E_1 [MPa]		E_2, E_3 [MPa]		ν_{12}, ν_{13}		ν_{23}		G_{12}, G_{13} [MPa]		G_{23} [MPa]	
	Mean	STDV	Mean	STDV	Mean	STDV	Mean	STDV	Mean	STDV	Mean	STDV
Carbon fiber AS4	225 000	11 250	15 000	750	0.2	0.01	0.07	0.0035	15 000	750	7 000	350
Epoxy matrix 3501/6	4 200	210	-	-	0.34	0.017	-	-	1 567	78.35	-	-

Void type	Mean diameter [mm]	STDV diameter [mm]	$k_{fiber-void}$ [-]
Small matrix voids	0.004	0.0004	0.1
Large matrix voids	0.014	0.001	0.1
Inter-fiber voids	0.014	0.001	-0.05

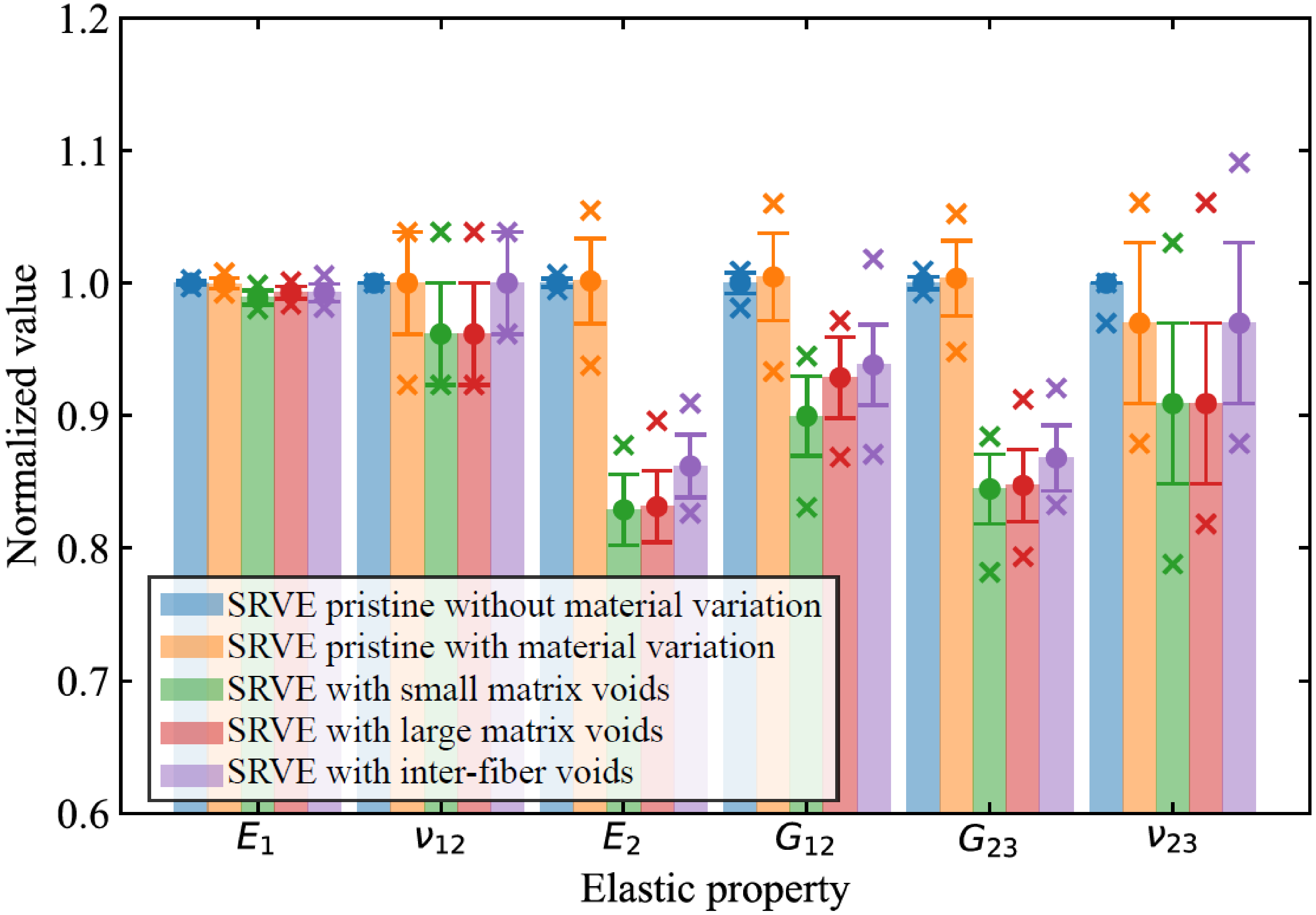
Material uncertainty: microscale analysis

- Methodology:



Material uncertainty: microscale analysis

- Results:



Objectives

On the generation of design allowables taking into account the material variability, the presence of defects and the random spatial distribution of FRP

- **Objective 1**: How to determine the design allowables of different stress raisers?
  - Geoemtrical feature: Open Hole
  - Damage: impact on a surface
  - Presence of defects: fiber misalignment

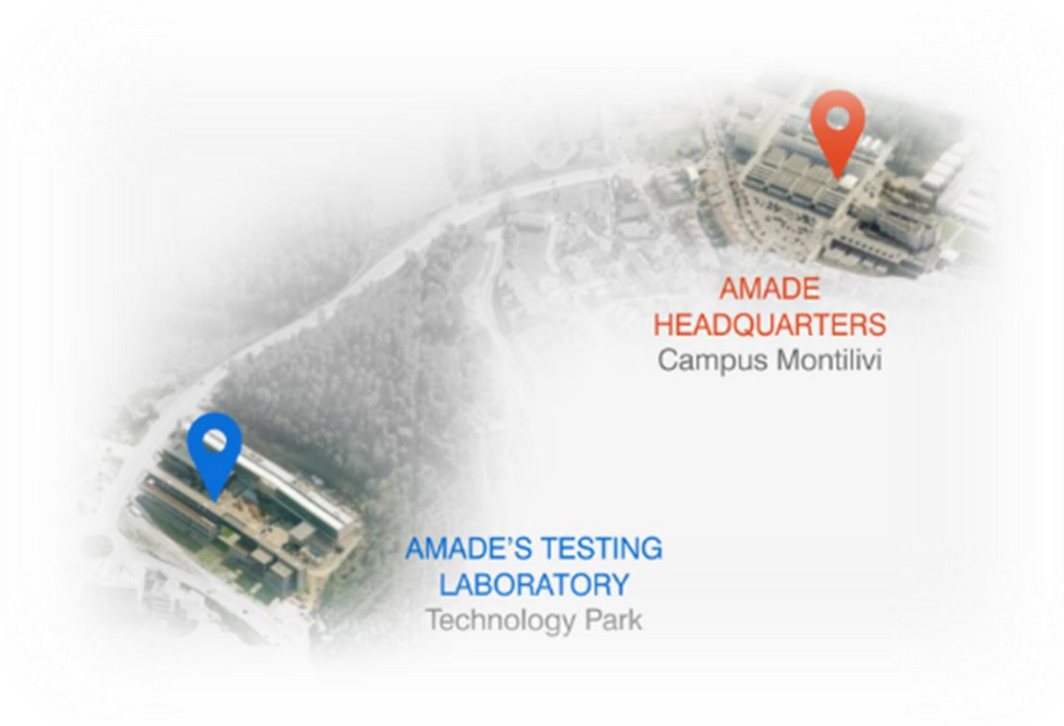
- **Objective 2**: How to determine the material variability with the presence of defects?

Conclusions

On the generation of design allowables taking into account the material variability, the presence of defects and the random spatial distribution of FRP

- A new methodology to calculate design allowables
  - Analytically
  - Numerical (FEM)

- A new methodology to determine the uncertainty on the material properties



Thanks for your attention!

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ANALYSIS AND ADVANCED MATERIALS
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