ACCOUNTING FOR MATERIAL NON-LINEAR BEHAVIOR IN MULTISCALE ANALYSES

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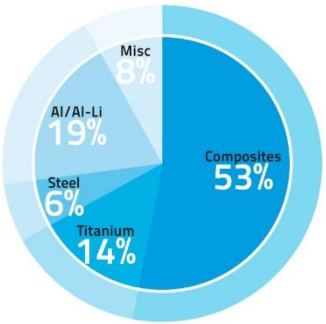
ICCS20
Paris September 5th 2017

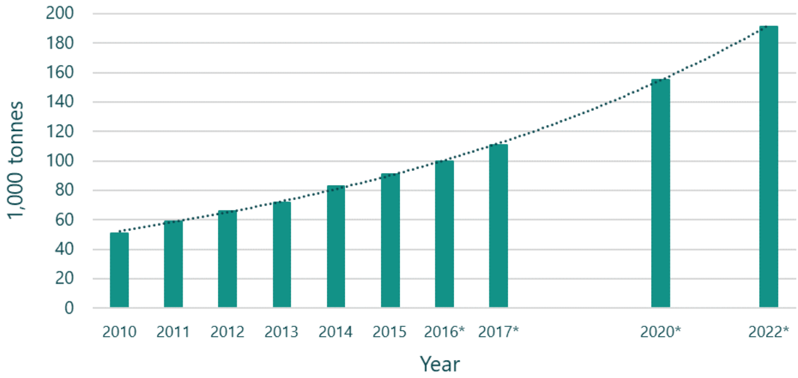
This project has received funding from:
- The European Union’s Horizon 2020 research and innovation programme under grant agreement No 690638
- The Ministry for Industry and Information Technology (MIIT) of China Special Research Plan on Civil Aircraft under grant No MJ-2015-H—G-103

COMPOSITES IN AEROSPACE

The need to reduce the weight of aero-structures, in order to improve its performance minimizing the energy requirements, has lead to a substantial increase in the amount of composites used.



A350 XWB composite fuselage (Airbus Images)



Evolution and estimation of the global CFR demand (1)

Associated to this increase in the demand, there is also a larger amount of carbon waste.

[1] T. Kraus & M. Kühnel. Composite Market Report 2016. AVK. Germany

ECO-COMPASS PROJECT

The eco-compass project seeks reducing the carbon waste in aeronautical industry by using eco-composites in interior and secondary structures of the aircraft.

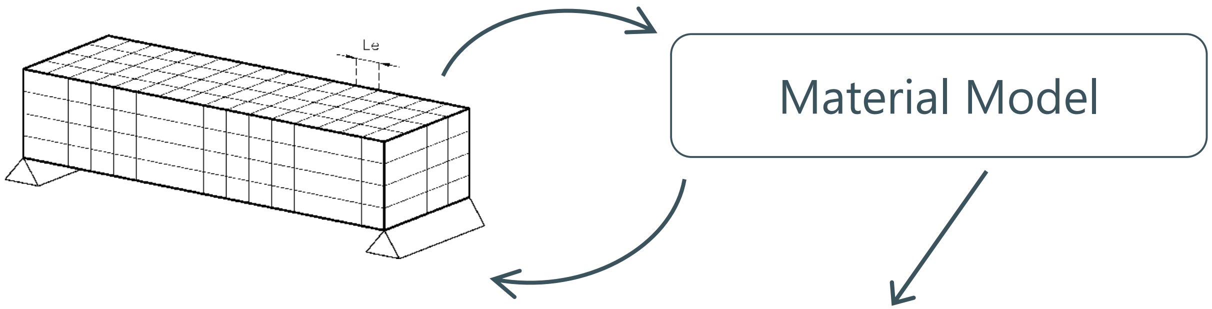
Eco-composites can made of:

- Recycled carbon fibre
- Bio-fibres (ramie, flax, hemp, etc.)
- Bio-resins (rosin, furan, etc.)

STRUCTURAL ANALYSIS

A structural analysis requires of a mathematical model to describe the mechanical response of the material.

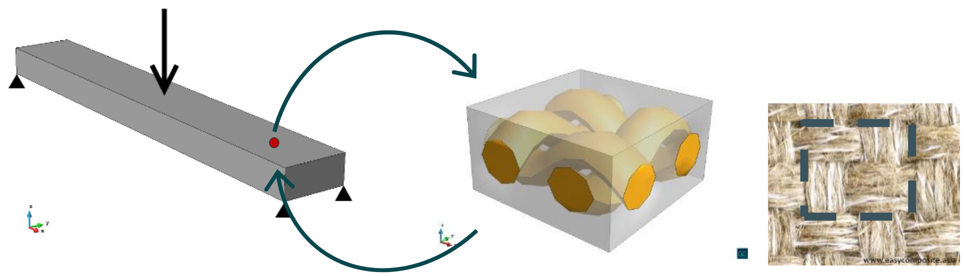
These models vary depending on the complexity of the material response:



- Bulk materials → Constitutive equations
- Composites → Lamination theories
  Serial/parallel mixing theory (const. equation manager)
  Multiscale analyses

MULTISCALE ANALYSES

If the internal structure of the composite is very complex, in order to obtain a good characterization of its mechanical response it is necessary to conduct a multiscale analysis.

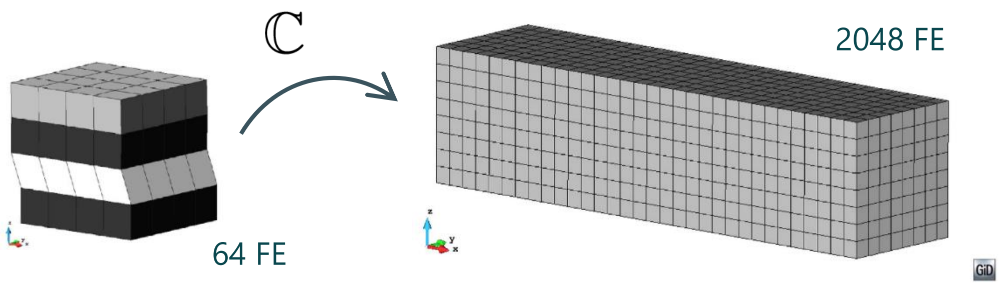


The main drawback of a analysing a structure with a multiscale procedure, specially in its non-linear range, is that it is extremely expensive in terms of COMPUTATION TIME and MEMORY

MULTISCALE ANALYSES

In linear-elastic conditions the mechanical performance of the composite does not vary during the analysis.

In this case it is possible to obtain the stiffness matrix from the RVE and, afterwards, analyse the macro-structure without increasing the computational cost.



[2]

	Micro-model	Multiscale linear	Multiscale FE2
CPU Time [mm:ss]	8:44	0:03	9:31
Memory [Mb]	2690.0	7.5	7.5
Reaction force	236.1	224.7	224.7

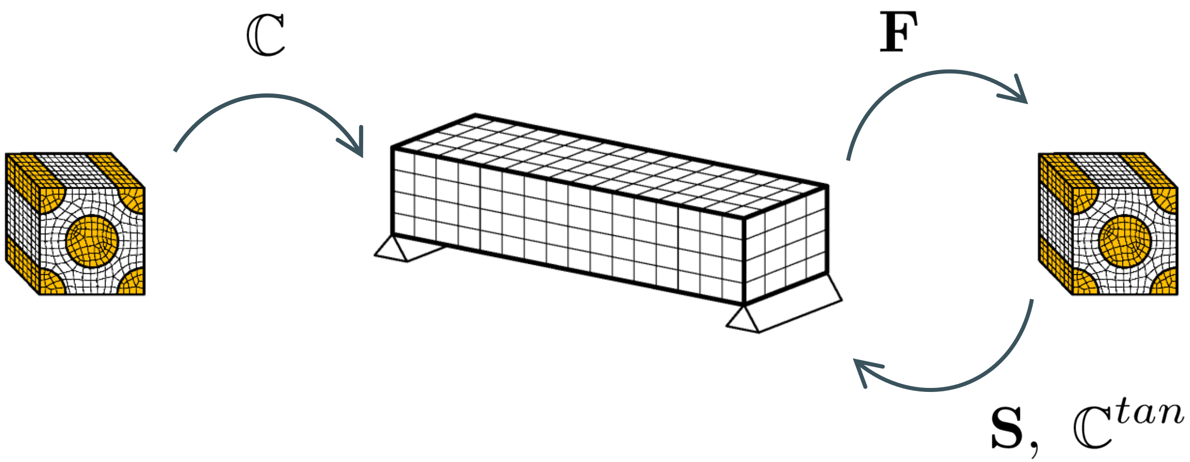
196,608 FE

To be competitive, multiscale analyses need strategies to reduce their computational cost

[2] F. Otero et al. *Computers and Structures*. DOI: 10.1016/j.compstruct.2014.11.041

Approach 1:
FULL MULTISCALE

A FE2 consists on using the RVE as a constitutive equation, without applying any strategy to minimize the times in which it is solved. The RVE is solved at each load step, for each gauss point.

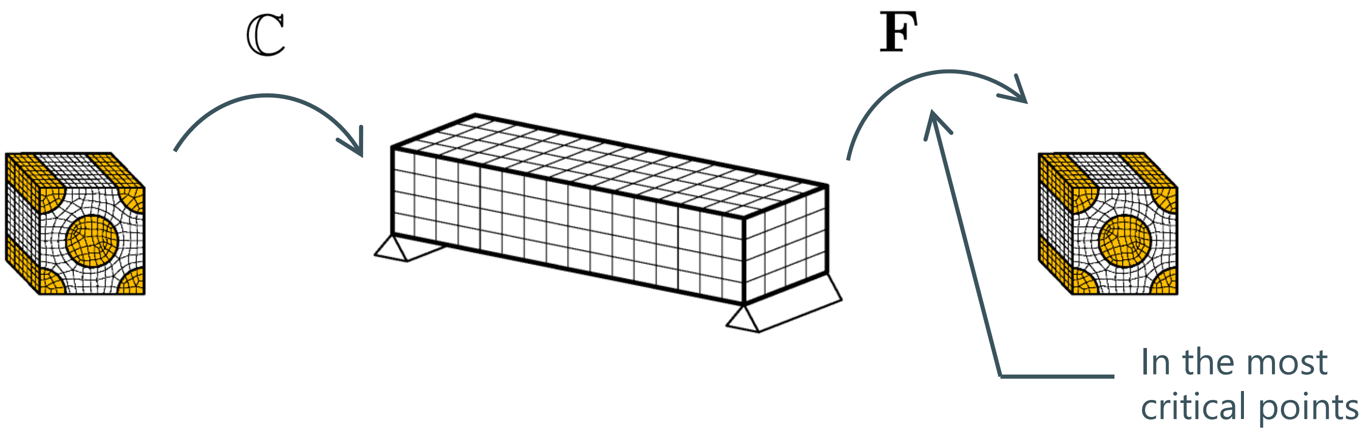


Advantage: It is the most accurate method

Drawback: Extremely large computational cost

Approach 2:
SIMULATION TO FAILURE

A failure characterization procedure consist on analyzing, after completing the macro-analysis, the most critical RVEs with the exact strain values obtained from the macro-analysis, increasing them until failure.

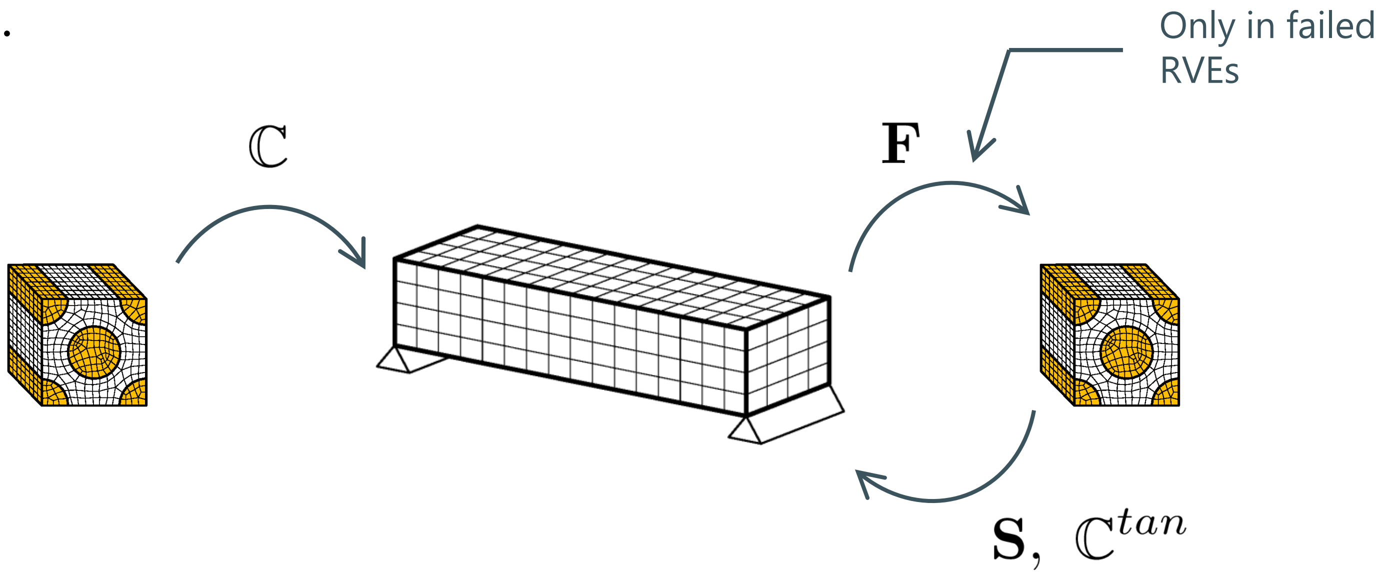


Advantage: With an affordable computational cost it provides the safety factor in the macro-structure and the failure mode in the RVE.

Drawback: Difficult to know with certainty which is the most critical RVE

Approach 3:
NON-LINEAR ACTIVATION FUNCTION [3]

The Non-Linear Activation Function provides a strategy to know if the material is close to failure. Only the RVEs of these points will be analysed.

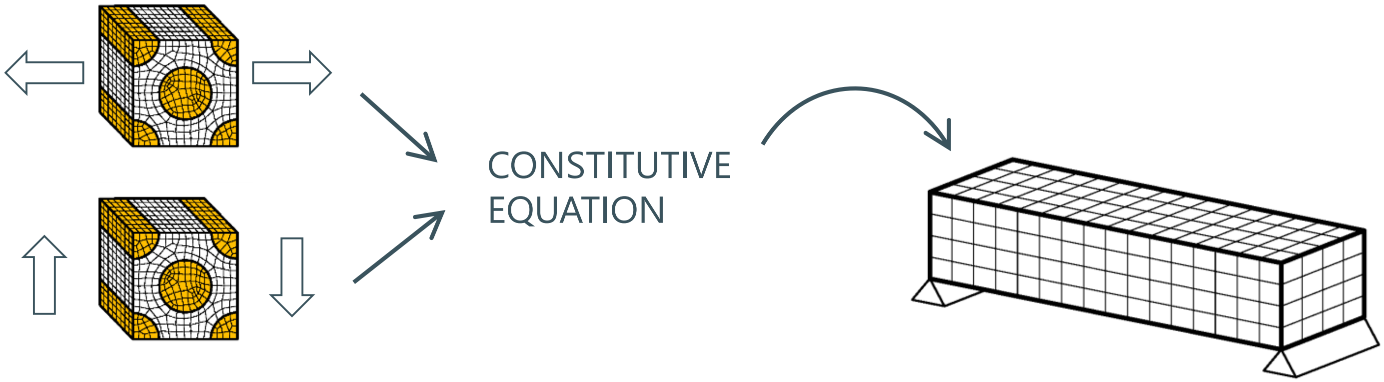


Advantage: It reduces enormously the computational cost compared to a FE^2 method.

Drawback: It is still expensive, specially when failure occurs.

Approach 4:
MULTISCALE CONSTITUTIVE DATABASE

The RVE can be used as an experimental sample. It is numerically tested to define a discrete multiscale constitutive database, which can be used in further macro-analyses.

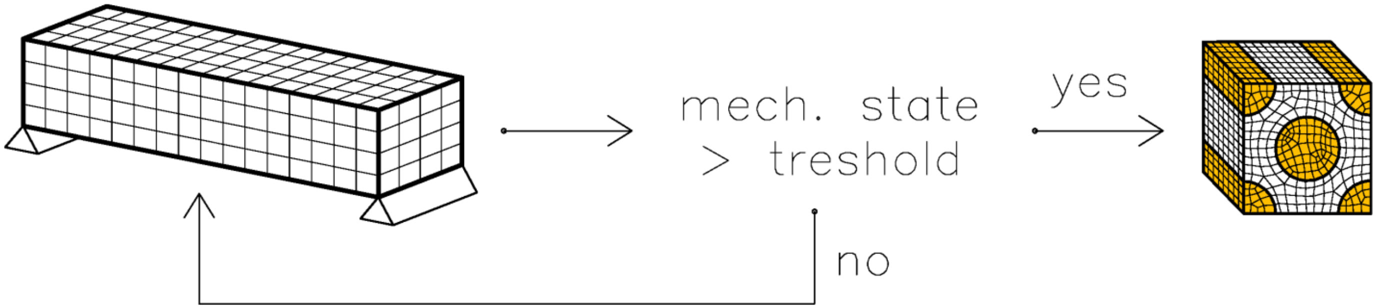


Advantage: Computational cost reduction, specially if the RVE has to be used in several simulations. Possibility to create a material database.

Drawback: The definition of the RVE constitutive equation is very expensive.

NON-LINEAR ACTIVATION FUNCTION

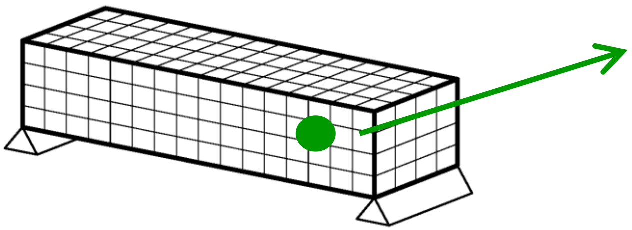
The objective of the NLAF is to have a threshold in the macro-model that tells when the micro-model will become non-linear. And, therefore, if it is necessary to calculate it.



NLAF must be calculated in the macro-model and must depend on damage activation of the micro-model.

NON-LINEAR ACTIVATION FUNCTION

The NLAF is defined using the elastic energy density of the material:



For each integration point,
we can calculate: $\Psi_e = \frac{1}{2}\sigma : \varepsilon$

Each integration point is represented by an RVE, which has a maximum elastic energy density of: Ψ_e^{Lim}

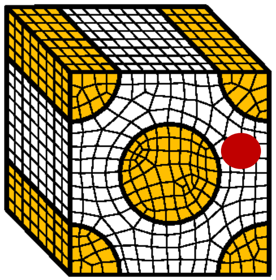
The threshold function is defined as: $\Psi_e - \Psi_e^{Lim} \leq 0$

In order to calculate the limit elastic energy density in the macro model, Ψ_e^{Lim}, the following assumption is made:

NON-LINEAR ACTIVATION FUNCTION

The material becomes no-linear when the first material point of the RVE becomes non-linear.

For a given strain-stress state we can calculate, in the RVE, for each integration point (k):



$$\Psi_{e_k} = \frac{1}{2}\sigma_k : \varepsilon_k$$

$$\Psi_{e\ k}^{Lim} = \frac{1}{2}\sigma^{Lim}{}_k : \varepsilon^{Lim}{}_k$$

We can define a function f that relates how close is any integration point of the RVE to its elastic energy threshold:

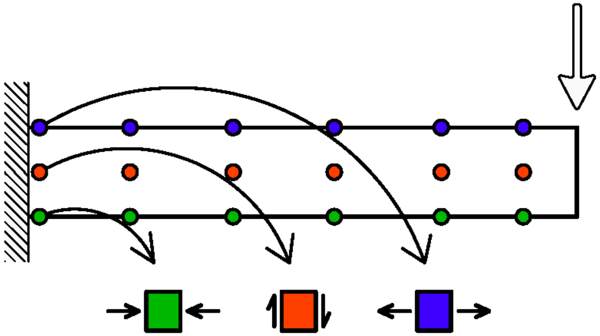
$$f_k = \frac{\Psi_{e_k}}{\Psi_{e\ k}^{Lim}} \xrightarrow{\text{Extrapolation to macro-model}} f = \max\{ f_k \}$$

Therefore: $$\boxed{\Psi_e^{Lim} = \frac{\Psi_e}{f}}$$

NON-LINEAR ACTIVATION FUNCTION

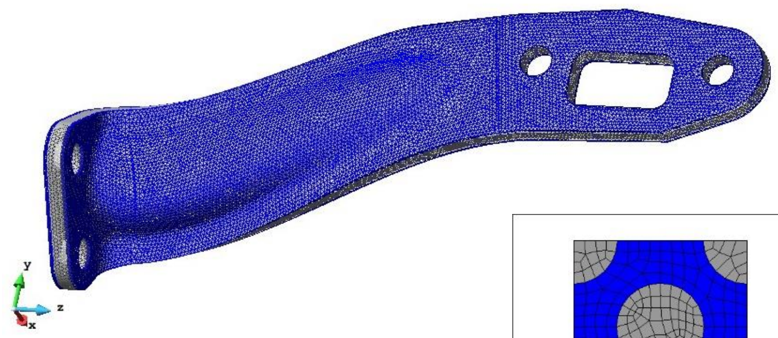
The proposed procedure requires analyzing the RVE of each integration point in the first load step, in order to calculate Ψ_e^{Lim}

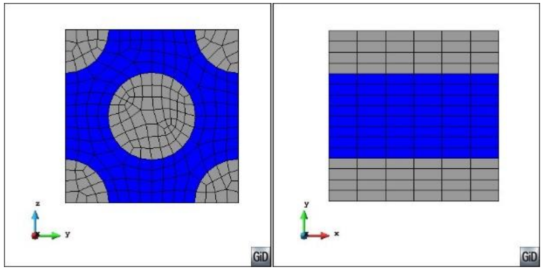
However, in many simulations, there are many strain-stress states that are proportional from the very beginning:

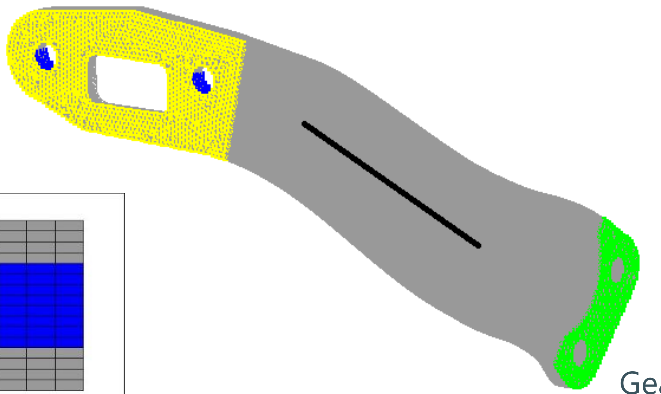


It is possible to define a *Smart First Step* that minimizes the number of RVEs that must be analyzed to obtain the elastic energy limit of all integration points.

NON-LINEAR ACTIVATION FUNCTION





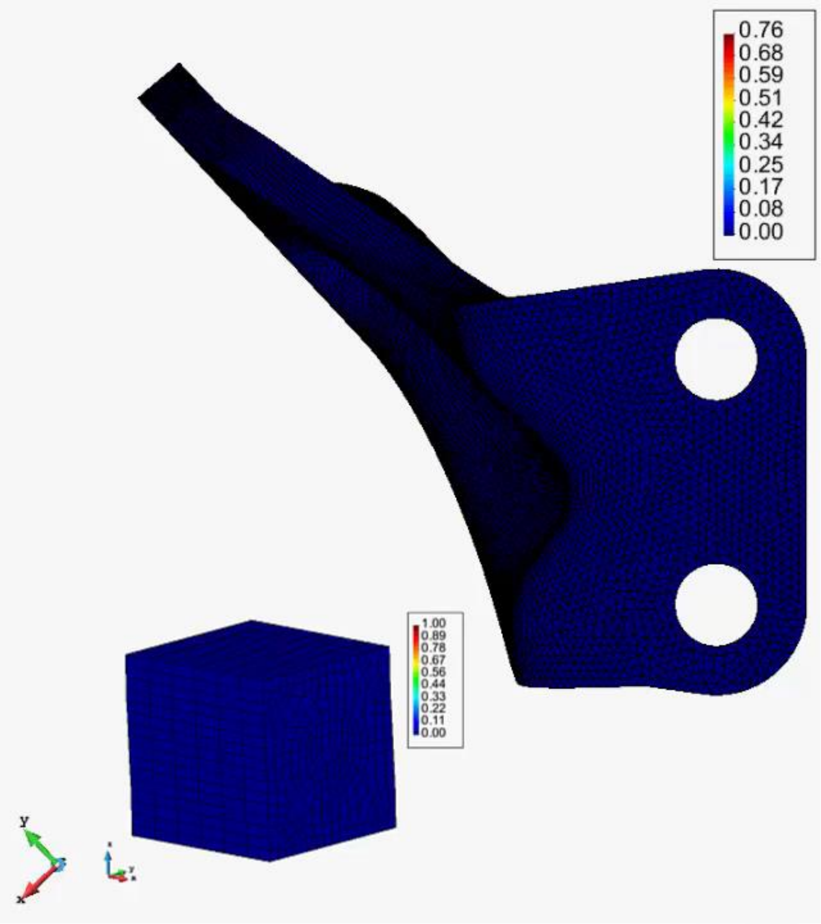


Material	Model	E [GPa]	ν	σ_{lim} [MPa]	Gf [kJ/m^2]
Fibre (Carbon)	Elastic	235	0.21	4410	-
Matrix (Epoxy)	Damage	4.52	0.36	68	780

Material	Model	E1 [GPa]	E2 [GPa]	G [MPa]
TenCate core	Elastic	56.1	55.6	4.5

NON-LINEAR ACTIVATION FUNCTION

Results obtained. Damage parameter

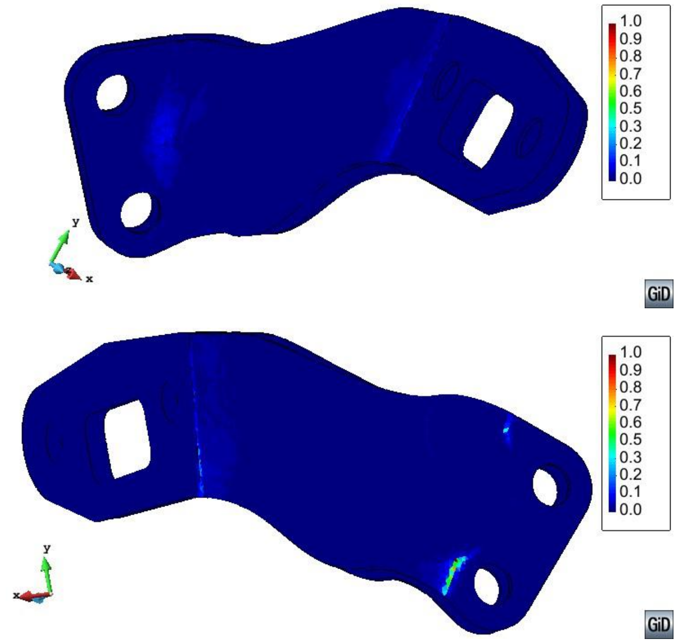


Note: Damage parameter in the macro-model is calculated based on the lost of stiffness of the whole RVE, and not as the integral of the damage over the RVE volume.

NON-LINEAR ACTIVATION FUNCTION

Expected failure regions:

Higher value means lower elastic energy available. Value equal to 1.0 means that all elastic energy has been consumed.



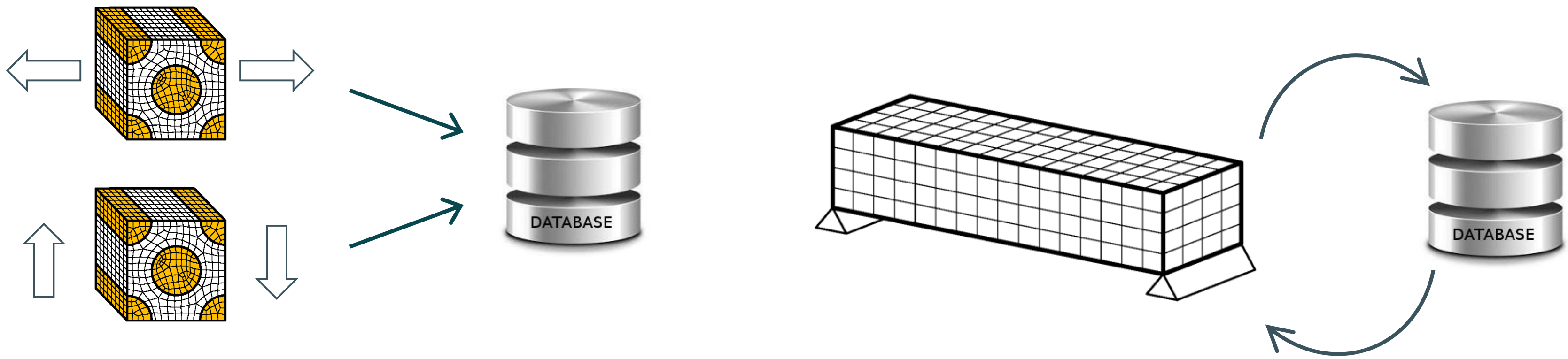
Computational cost:

Model	FE^2	NLS	Speed ratio
Mesh1-Micro1	32d 14h 46′	11h 36′	67.4

98.5 % reduction of the computational cost !

MULTISCALE CONSTITUTIVE DATABASE

With this approach, the RVE is analysed before solving the macro-model. The results of this analysis are stored in a discrete database which is accessed afterwards as a constitutive model.

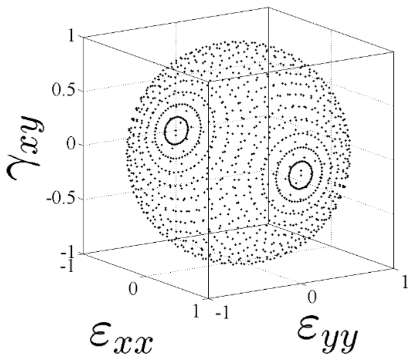


The results included in the database are the threshold values in which composite failure starts and the stiffness evolution of the composite during the failure process.

The composite material performance follows a damage law.

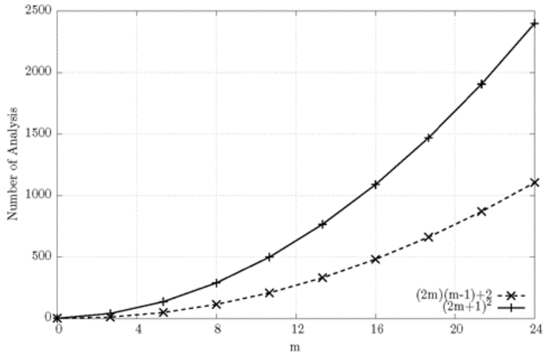
MULTISCALE CONSTITUTIVE DATABASE

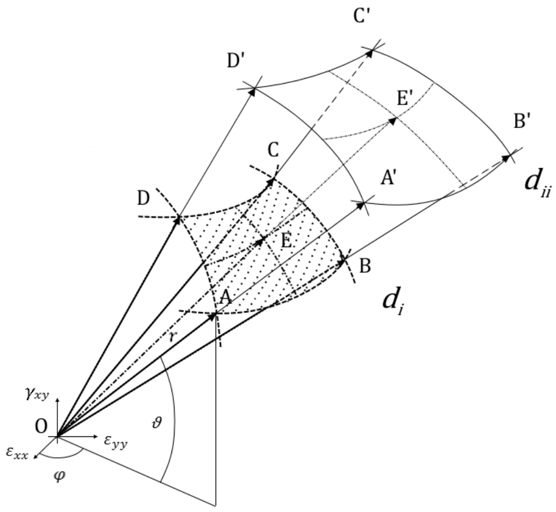
The directions of the deformation imposed to the RVE are defined as equi-spaced points over a sphere where the radius represent the intensity of the applied strain.



$$\begin{cases} \varepsilon_{xx} = r \cdot cos(\theta) \\ \varepsilon_{yy} = r \cdot sin(\theta) \cdot cos(\varphi) \\ \gamma_{xy} = r \cdot sin(\theta) \cdot sin(\varphi) \end{cases}$$

$$r = \sqrt{\varepsilon_{xx}^2 + \varepsilon_{yy}^2 + \gamma_{xy}^2}$$





The total number of analysis increase with the refinement of the strain space

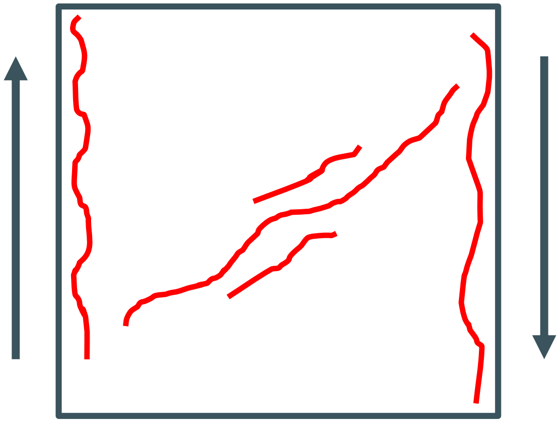
When conducting a numerical analysis, the procedure requires an interpolation to obtain the response of the material for a given stress-strain state (if it has not been computed initially)

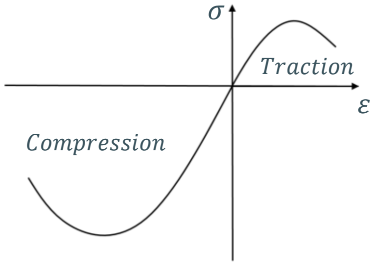
MULTISCALE CONSTITUTIVE DATABASE

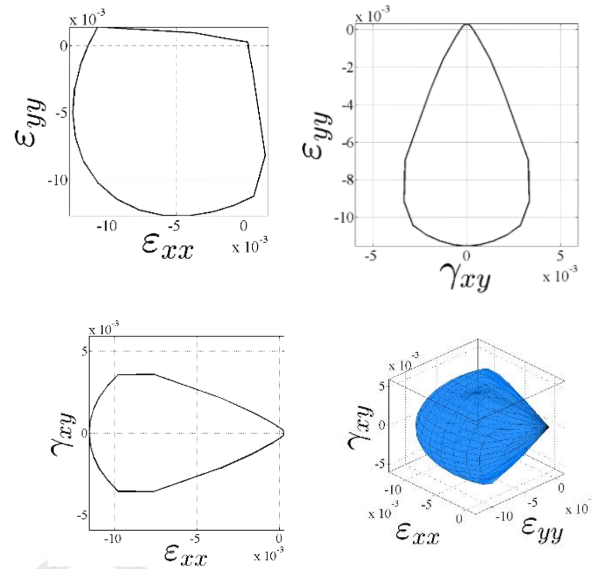
The validation is made using a tension/compression damage material in order to capture the evolution of the stress behaviour for both direction during a shear test applied to a square plate

Damage Traction/Compression Properties

Young Modulus	900	MPa
Poisson Ratio	0.15	
Stress Traction Limit	0.25	MPa
Traction Fracture Energy	0.016	J/mm²
Stress Compression Limit	10.5	MPa
Compression Fracture Energy	40.0	J/mm²

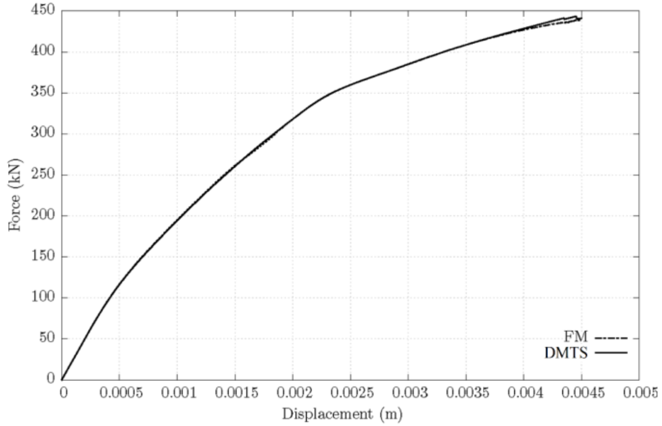






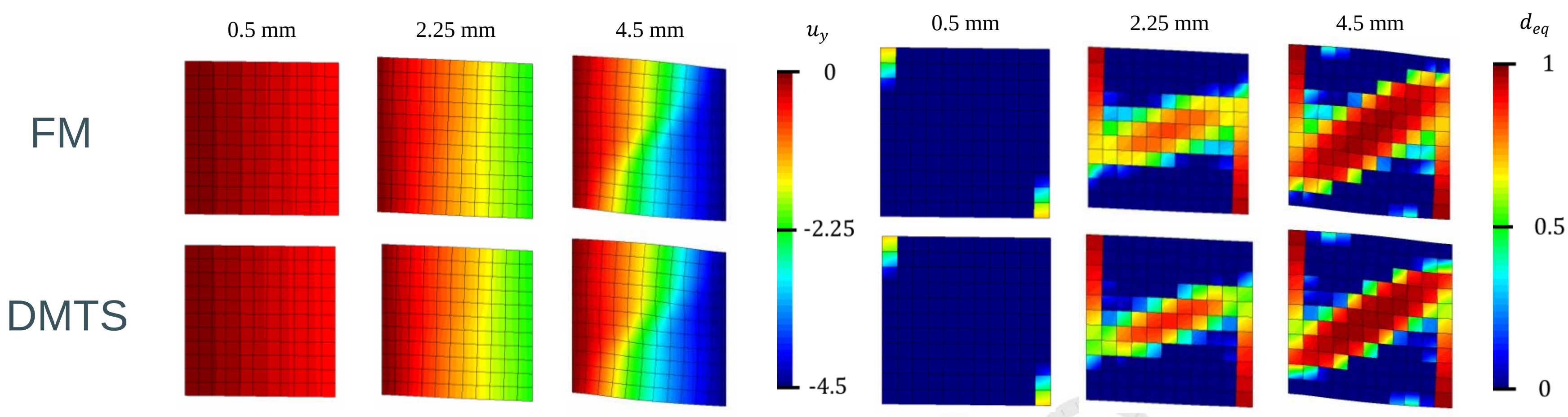
MULTISCALE CONSTITUTIVE DATABASE

Comparison with the results obtained using a full multiscale analysis



Memory and Time comparison

Type	Time [s]	Memory [kB]	Number of Active RVEs	Time Speedup
Full Multiscale	844.72	169788	484/484	-
DMTS	646.39	92140	388/484	1.307



SUMMARY

- Multiscale analyses are very useful when dealing with materials that do not fit into a specific constitutive law to characterize their performance.
- The computational cost of these procedures is extremely high when non-linear effects are considered.
- There are solutions that allow using multiscale procedures in non-linear analyses, with an affordable computational cost.
- The selection of the best solution depends on the type of simulation or the type of problem to be solved.

Acknowledgements: EU EU-H2020 agreement No 690638 (ECO-COMPASS) and Spanish Ministry MAT2014-60647-R (OMMC)

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