Non Destructive Testing:
3D simulation of Inductive Thermography
On Carbon Fiber Reinforced Polymers

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University of Nantes, FRANCE

Outline

Introduction

Composite lifecycle and induction

Multi-scale Modeling

SIBC + Voltage-constrained FEM

Some Applications

Conclusion

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Introduction

http://www.a350xwb.com/

53% Composite

Airbus A350 XWB

Applications

- Cars, Aeronautics, …
- ↗ 10%/year

Performances

- No corrosion
- High ratio resistance/weight

In France (2016)

- Composites : ~**0,5M** tons/ an
- Metal : ~**18M** tons/an

Large scale development

- Manufacturing Methods
- Material health evaluation (SHM- NDT)

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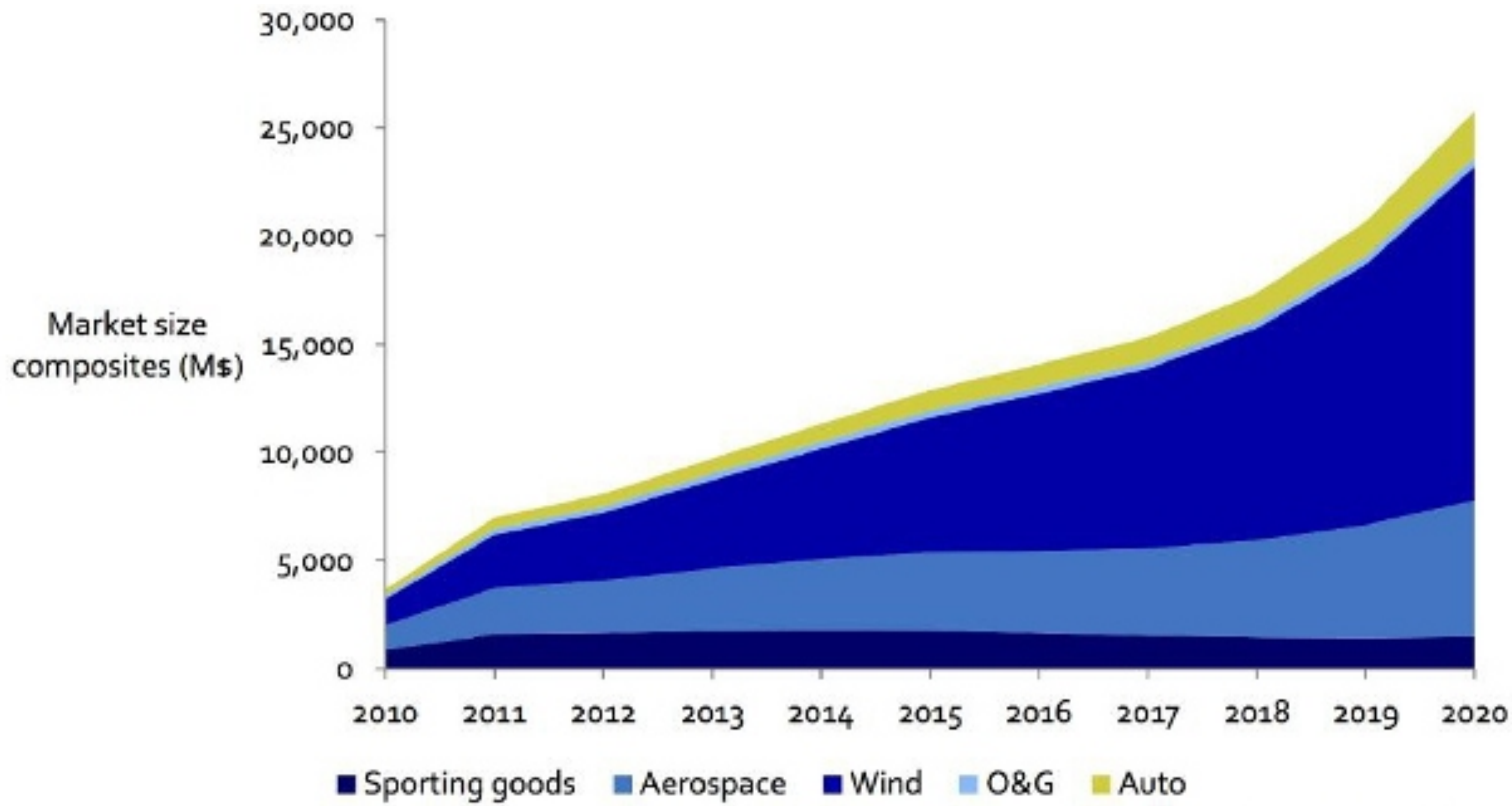
Composite materials: sectors and growth

- Transport (cars or railways), buildings and aeronautics represent 62% of the production of composites.
- The arrival of composites in the new planes (Boeing 787 and Airbus 350) allowed to the aeronautics and aerospace to pass before petroleum sector.
- The growth potential is estimated around 10% by year between 2016 and 2021.

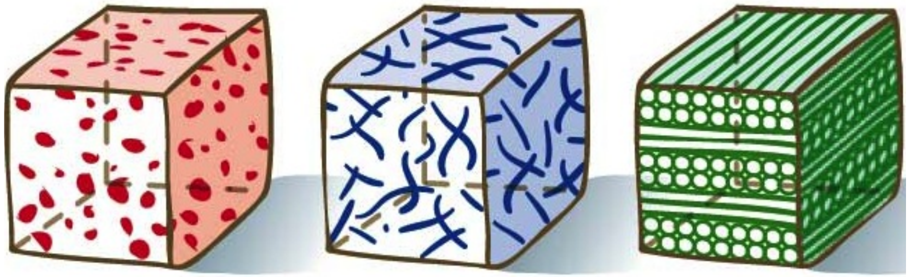


Composite material:

Reinforcements
- Support mechanical stress

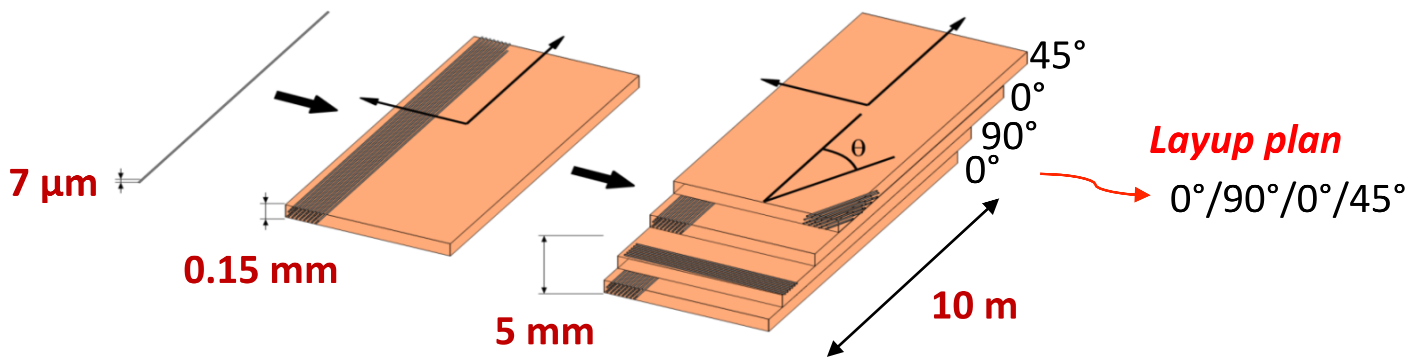
Resine
- Maintaining of the reinforcements
- Repartition of the efforts

Particles | Short fibers | **Long fibers**



Stratified composites (CFRP : Carbon Fiber Reinforced Polymer)

Carbon Fiber | Unidirectionnal Ply | **Stratified** = Plies with different orientations



Characteristics :
- **Multi-plies**
- **Anisotropic**

Interests :
- High performance
- Flexibility of design

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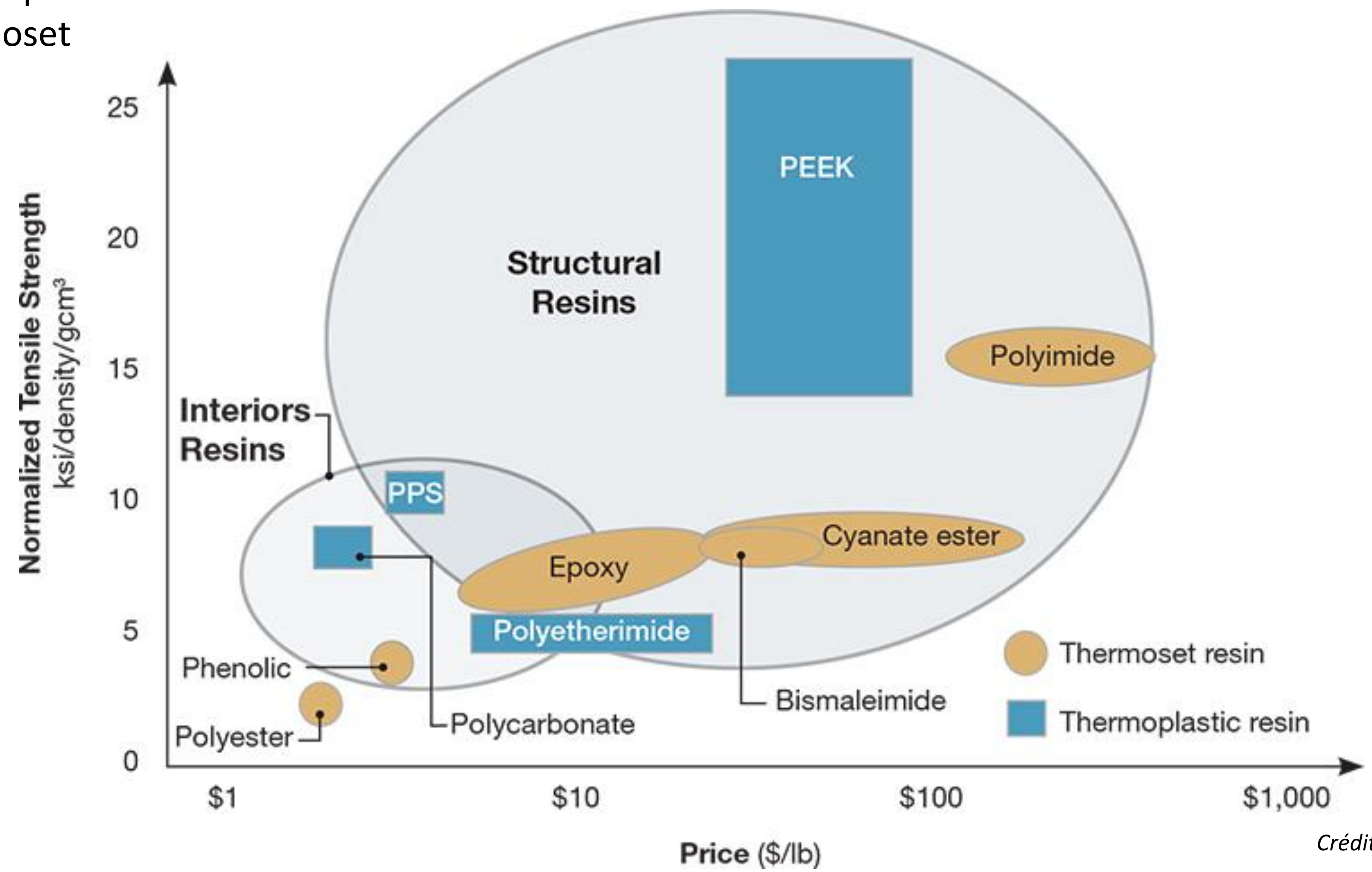
Two families of composites

- Thermoplastic
- Thermoset



Crédit: Lucintel

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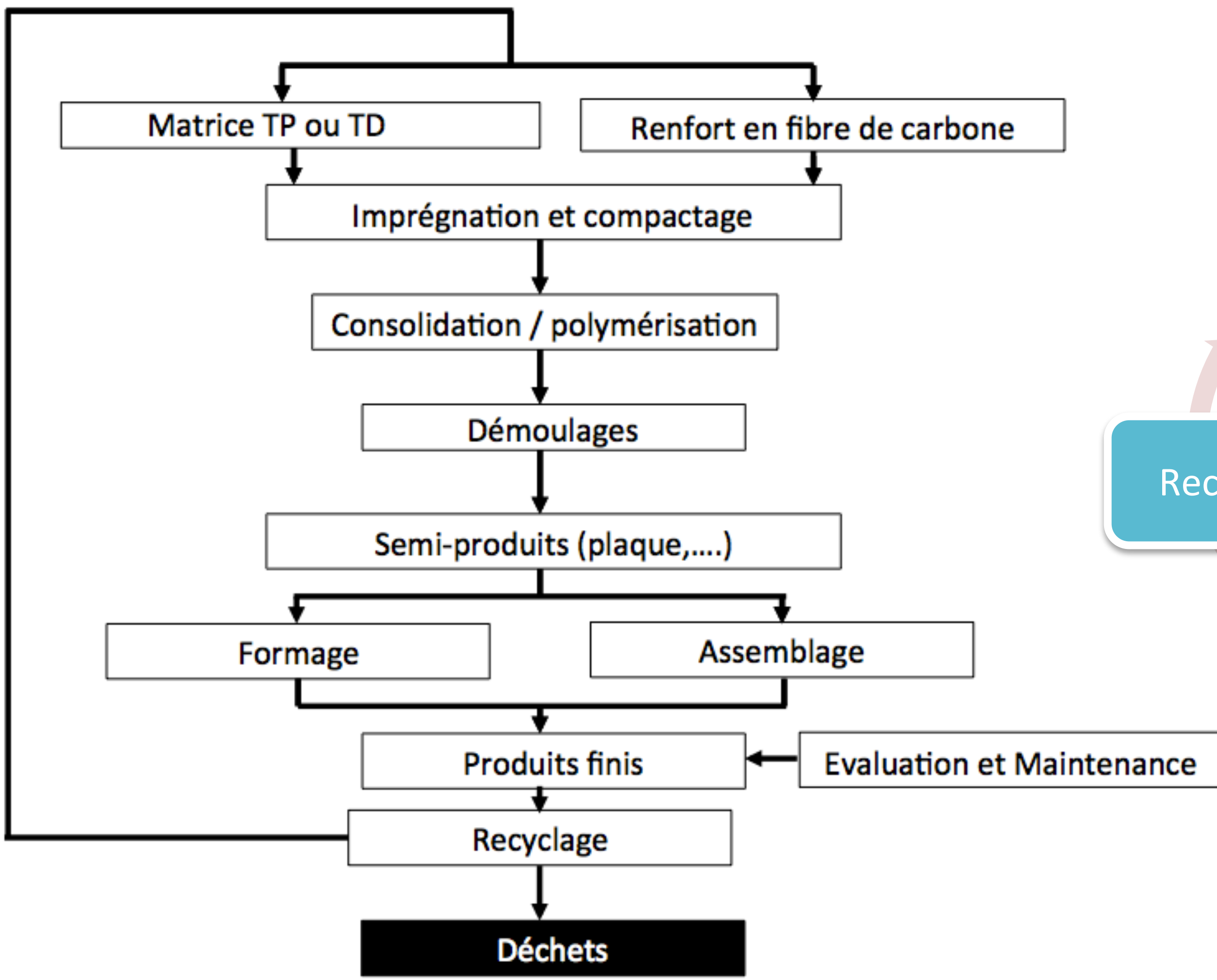
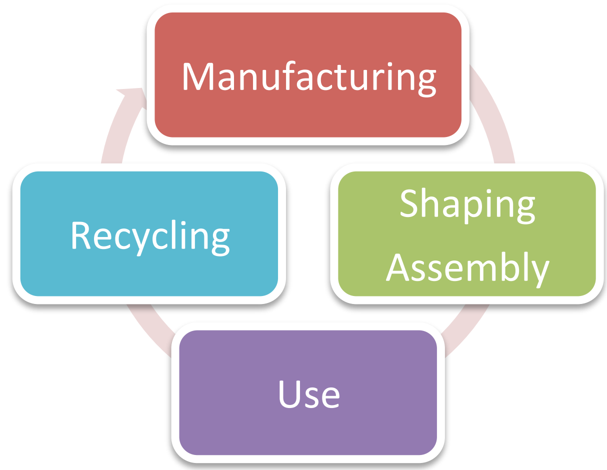
Composite lifecycle and induction

Need for heat throughout the lifecycle of the **CFRP**





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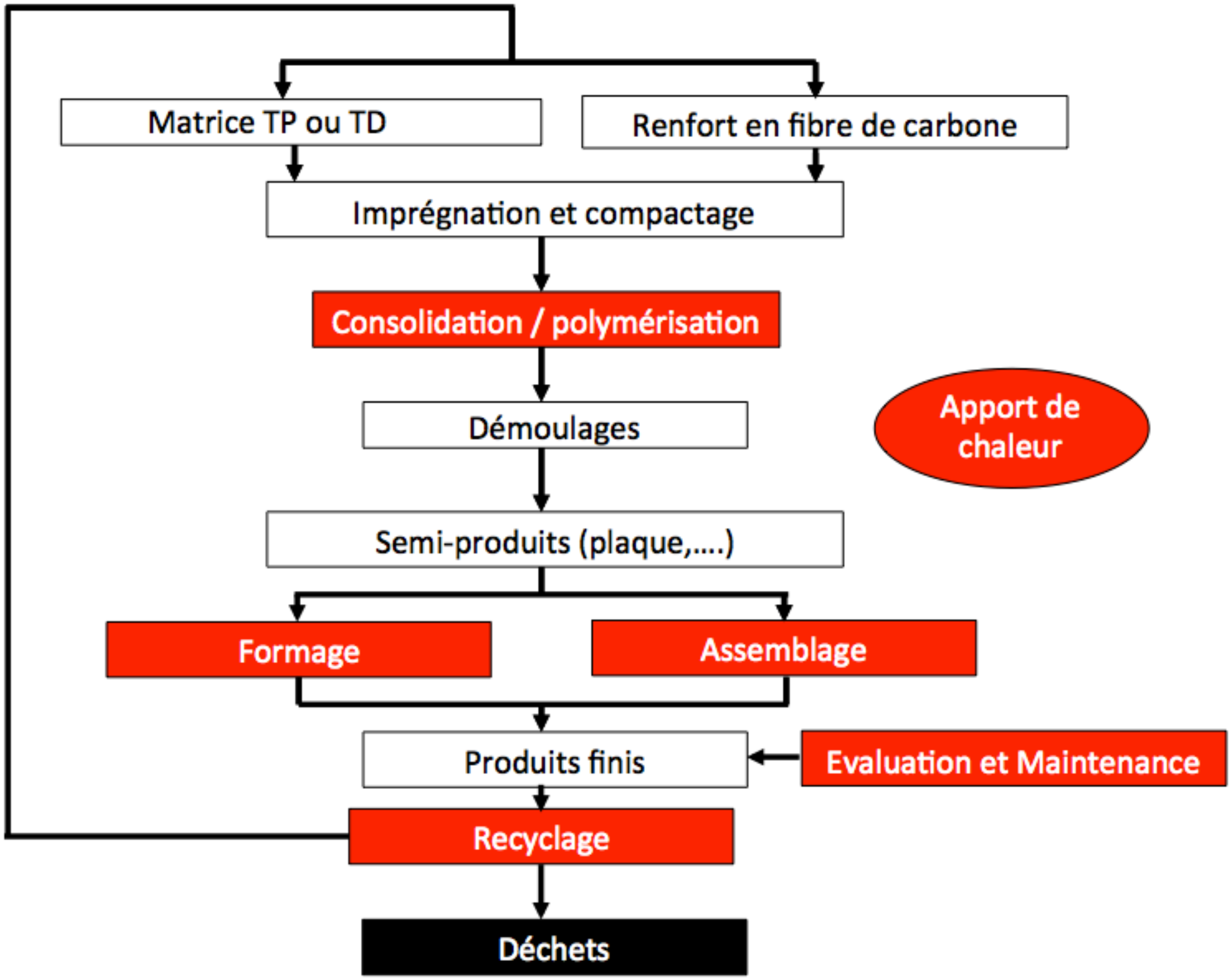
Composite lifecycle and induction



Processes (hot air, heat fluid, electrical resistance, ….)

- Conduction heating
- Autoclave,
- Injection under presure in a mold, …

Limitations :

- Time of cycle,
- Consumption,
- Static processes.

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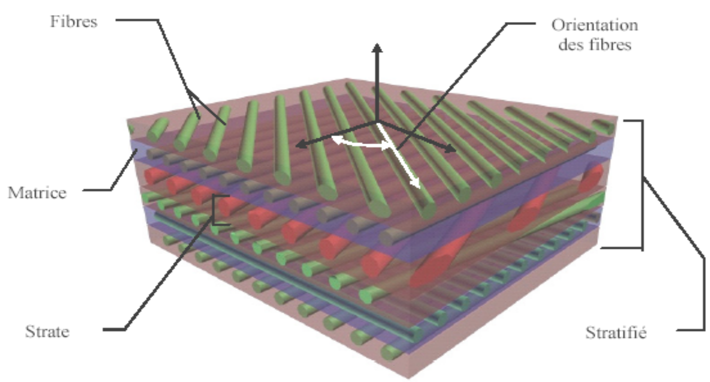
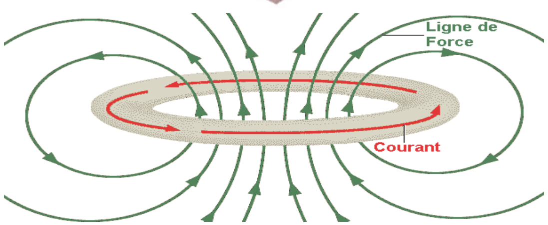
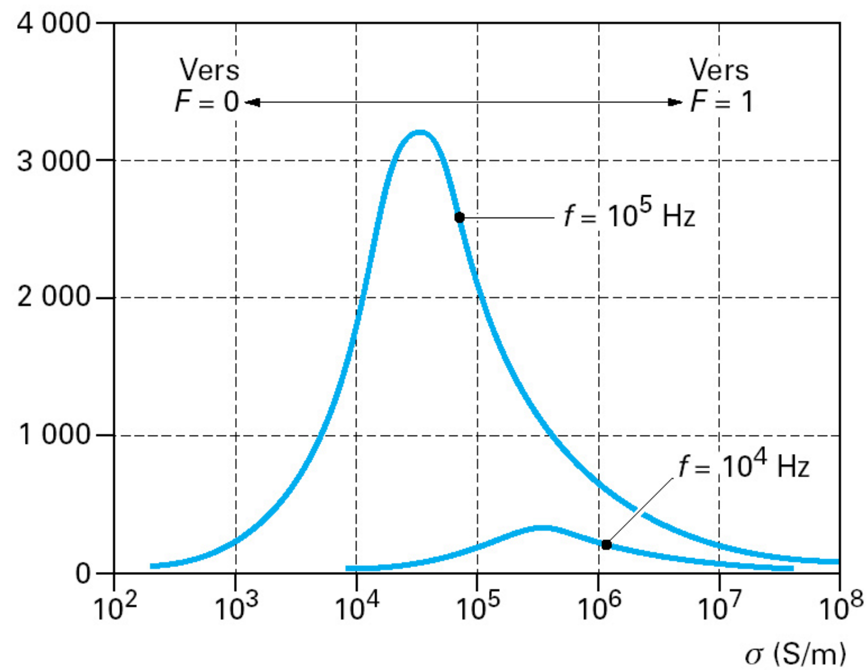
Place of electromagnetic induction?
Numerous advantages and few exploited (for a direct or indirect heating)





Evolution of induction generators



- Contactless,
- Surface or volume power,
- Fast transfert,
- Easy control,
- Repeatable, …

$$Zp = 503.3\sqrt{\frac{1}{\sigma\mu_f f}}; \quad Pch = 2.10^{-3} H_s^2 \sqrt{\frac{1}{\sigma}\mu_r f} SF$$

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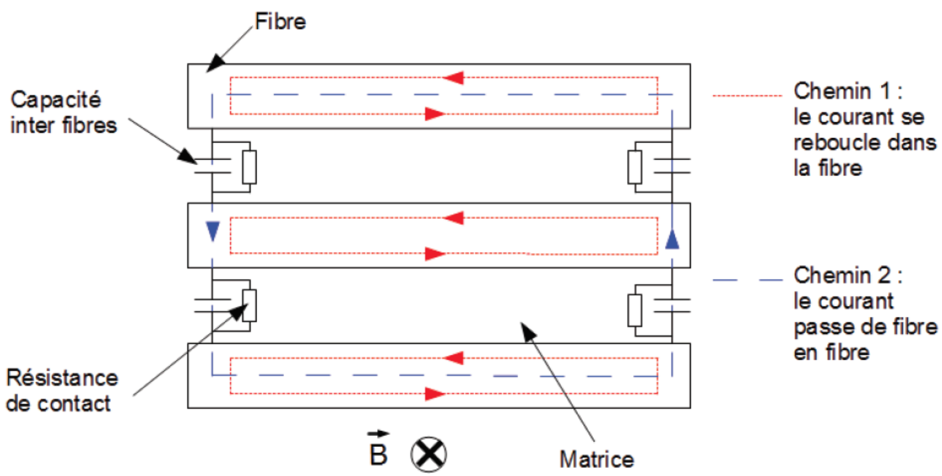
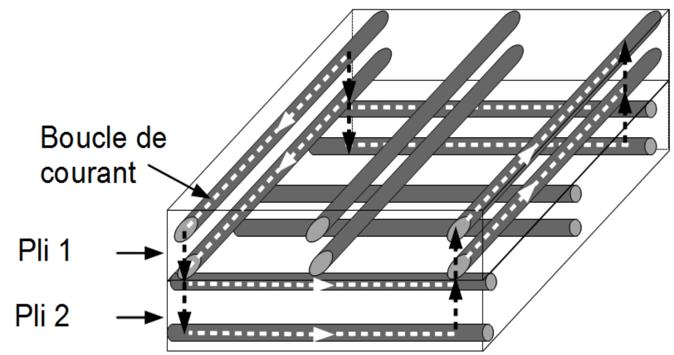
Composite lifecycle and induction

Circulation of eddy currents in composites?

- Frequency <10Mhz => no capacitive effect
- Setting of inductor 0° and 90° lead to very different effects (circulation along z)
- No loop conduction intra-fiber
- Severe thermal contrainsts (delamination, broken fibers, …)





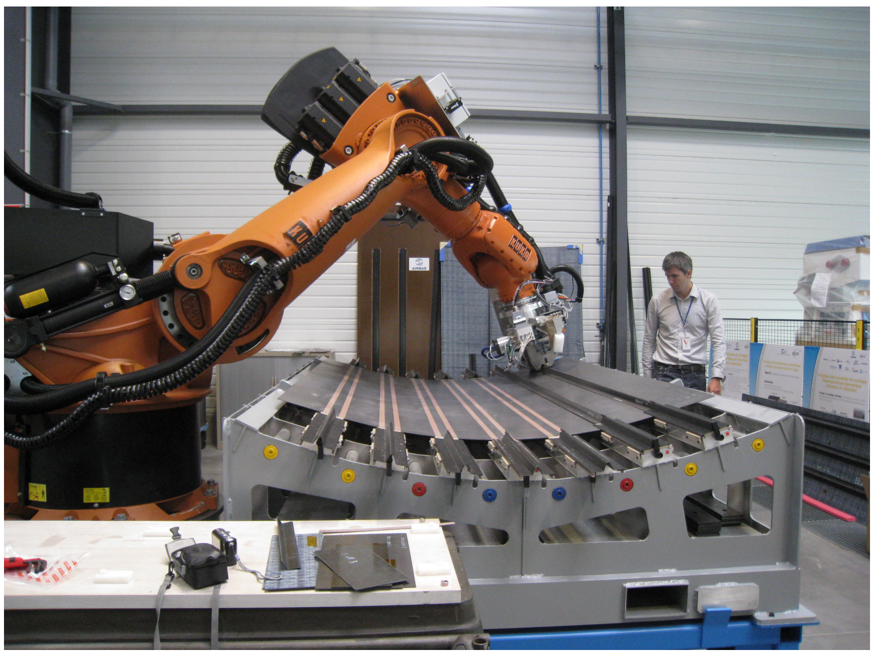
The mastery of the industrial process control of CFRP needs the development of decision-making tools

- Accurate, fast-running with taking into account of movement
- Multi-physic, multi-scale, electrical percolation
- Taking into account of generators for range control

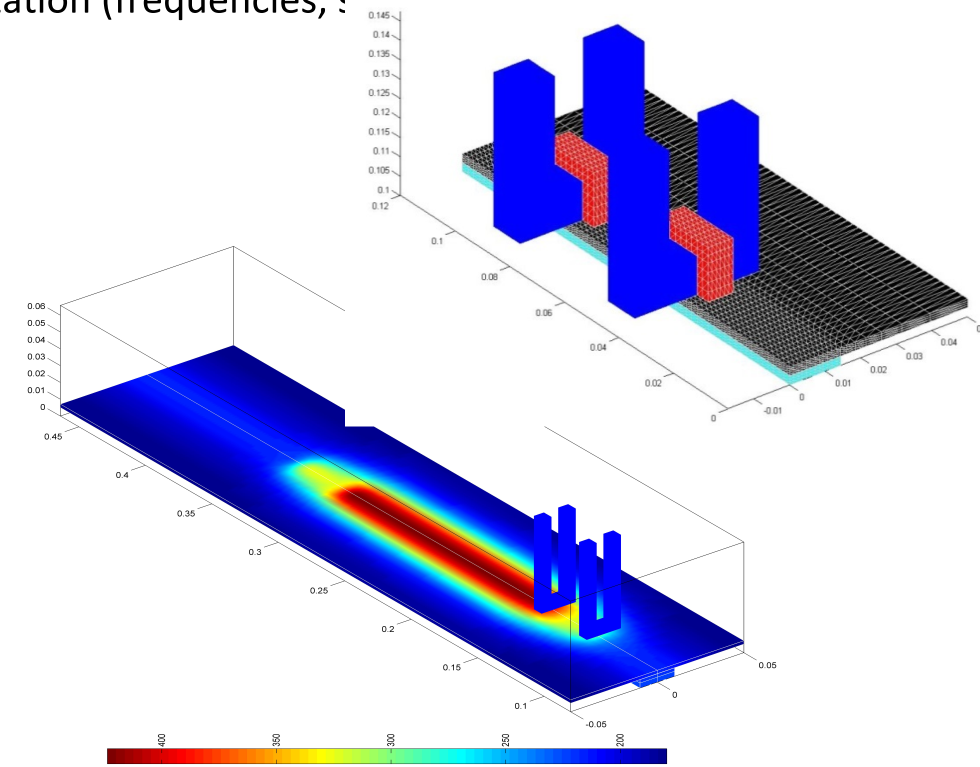
Induction heating for welding

- Elaboration method (**Welding**)
- Material Health Assessment (**Non Destructive Testing** and **Evaluation**)

Modeling tools: for physical phenomena behavior understanding
for inductor design
for welding parameters optimization (frequencies, s



Double curvature 3D structure welding bench



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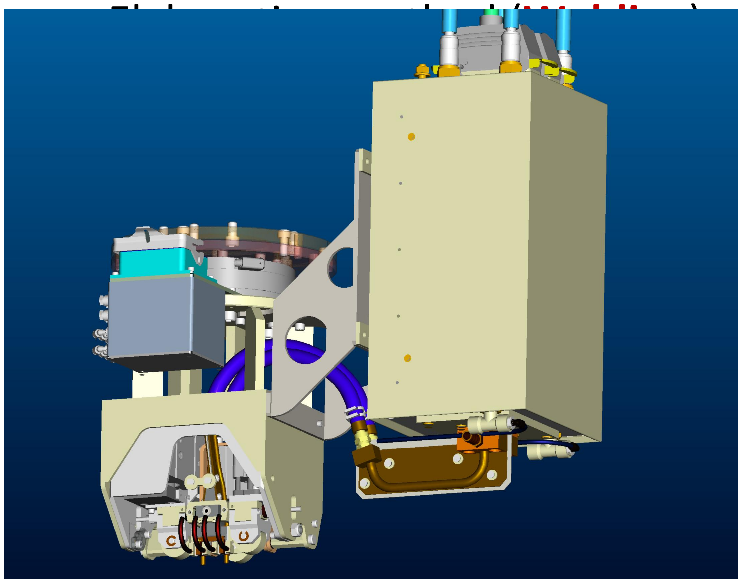
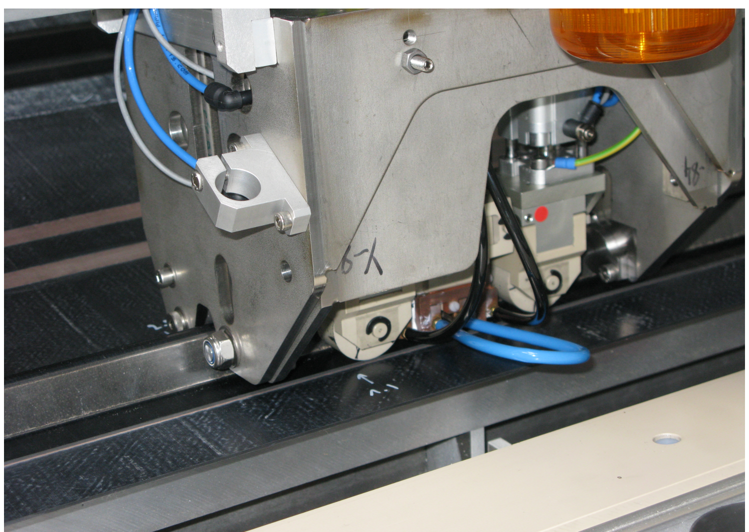
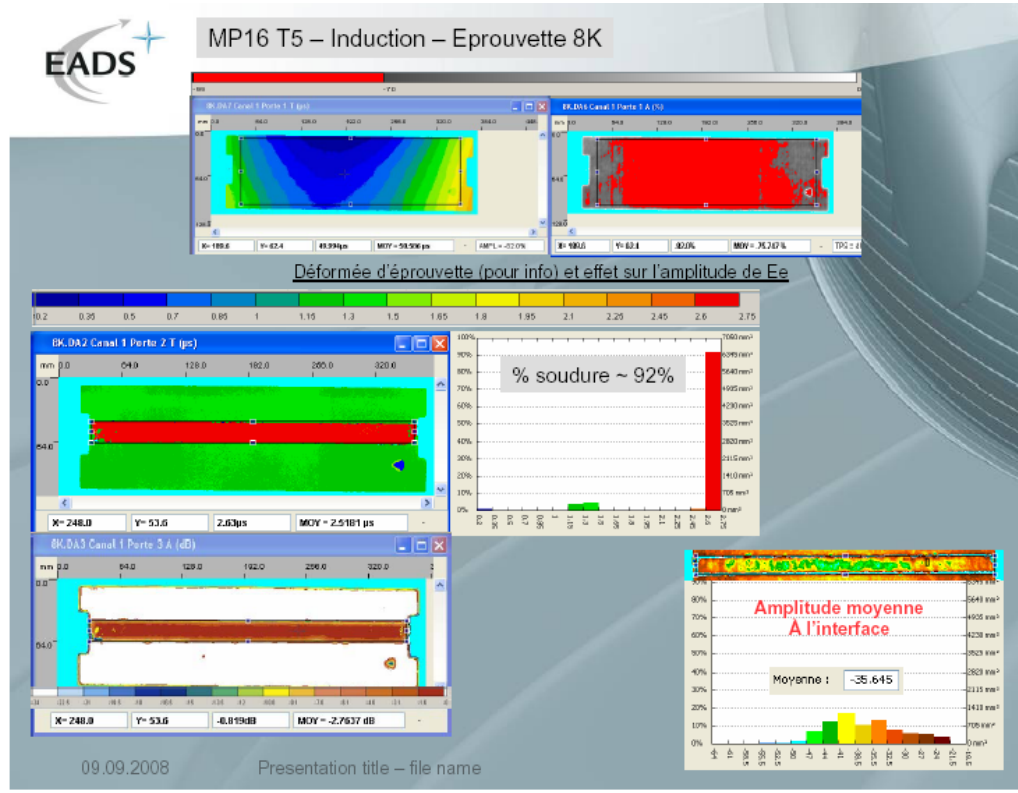
Induction heating for welding







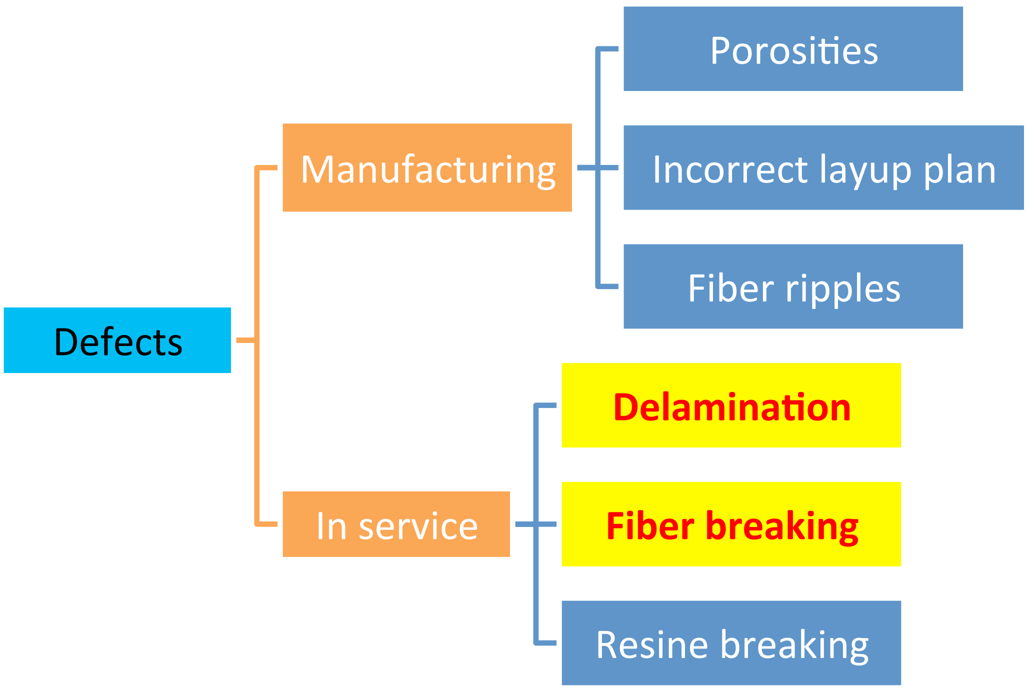
Welding bench

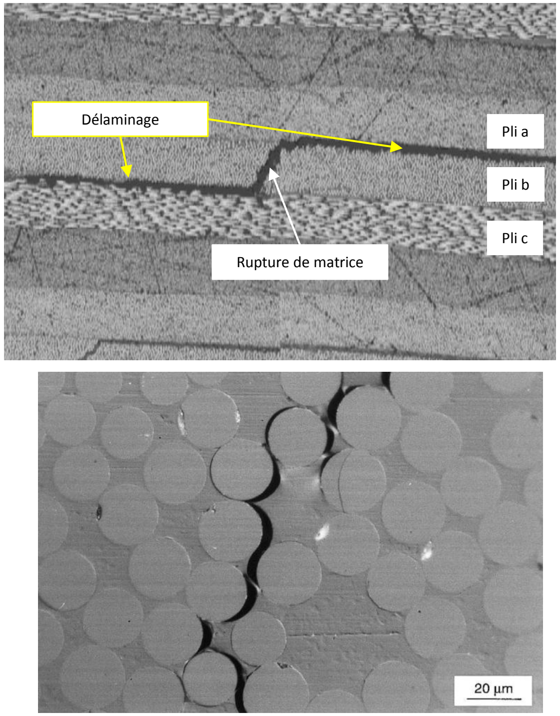
NDT of welding

Feasability dmonstrated:

- Technologic ontrainsts of induction (materials, adaptation box, …)
- Limitations => large thicknesses, focusing, dynamics, …

Defects in stratified



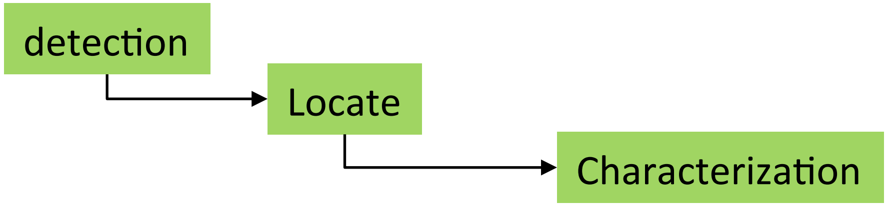


Defects examples

- Dimensions from some µm → some mm

NDT methods

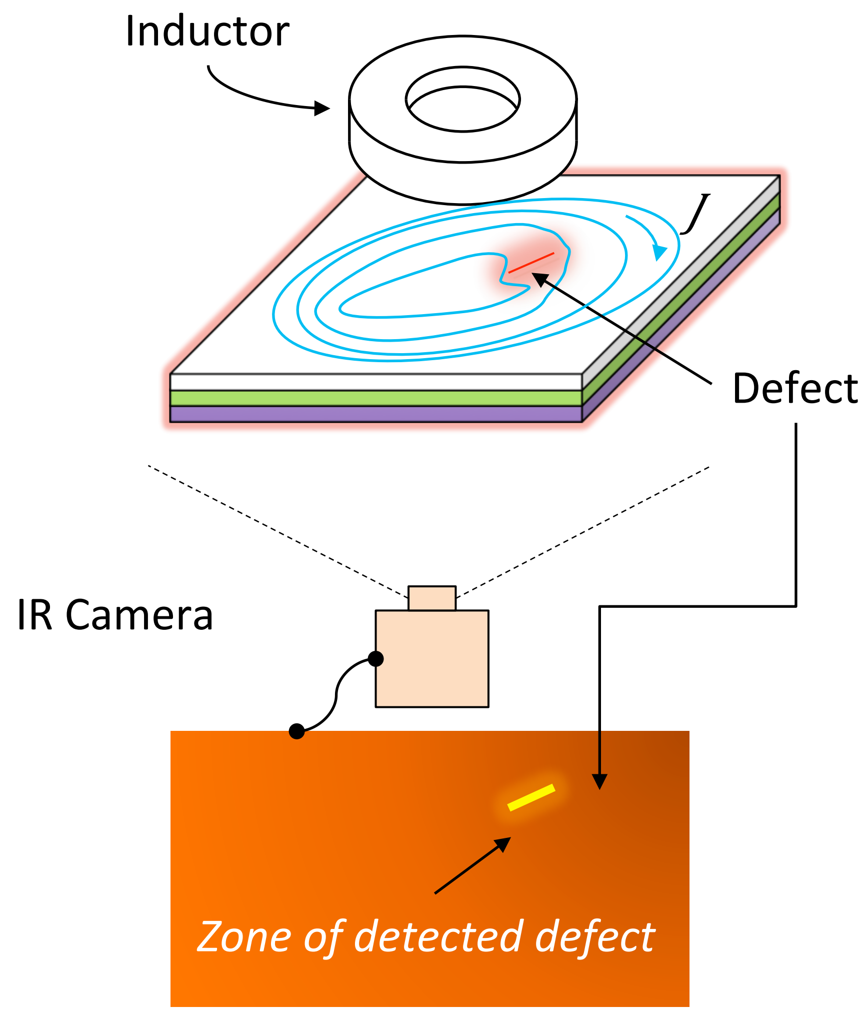
- Ultrasonic
- Eddy current
- Thermography
- Inductive thermography



Composite lifecycle and induction

Inductive Thermography

- **Double mechanism of detection**
  - Perturbation of eddy currents
  - Perturbation of thermal diffusion
- **Global measurement**
  - IR Camera



Thermal Image of the surface of composite

Objectifs recherchés

- **Développement d'un outil de simulation**
- **Investigation de la capacité de détection de défaut par la méthode thermo-inductive**

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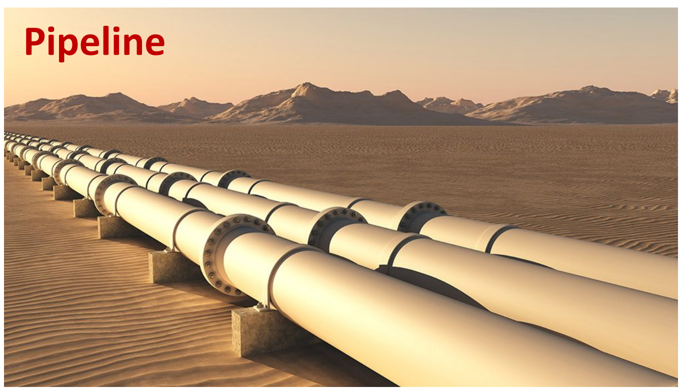
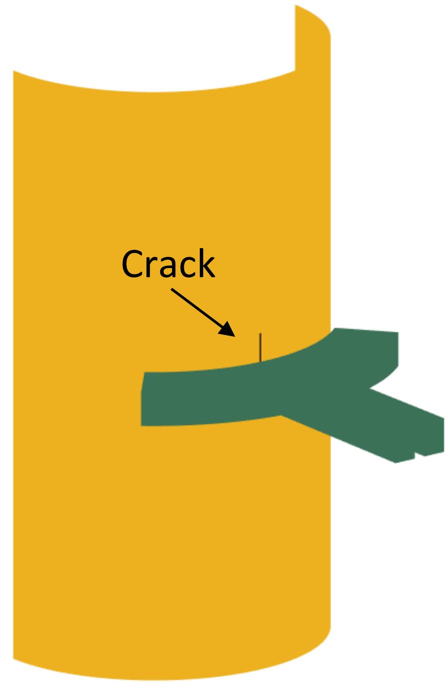
Induction heating for non destructive testing

- Elaboration method (**Welding**)
- Material Health Assessment (**Non Destructive Testing** and **Evaluation**)



Induction thermography



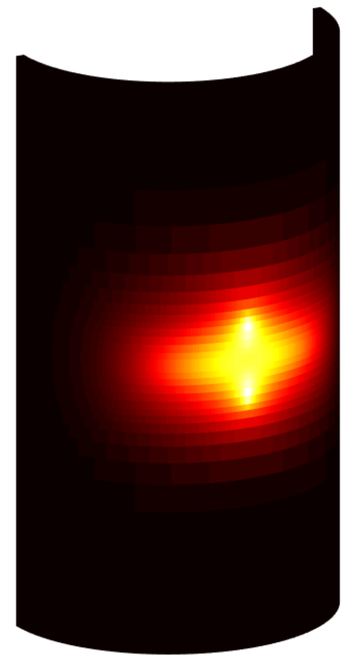


Image by Infrared camera

Induction heating for non destructive testing

- Elaboration method (**Welding**)
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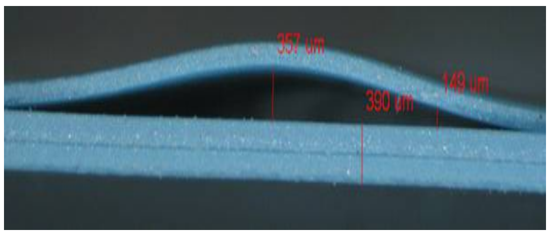
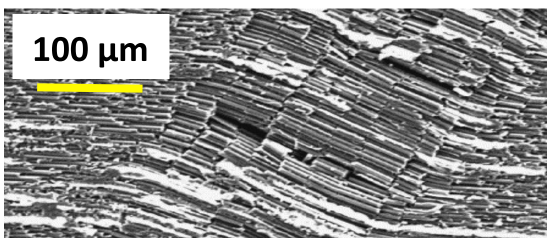
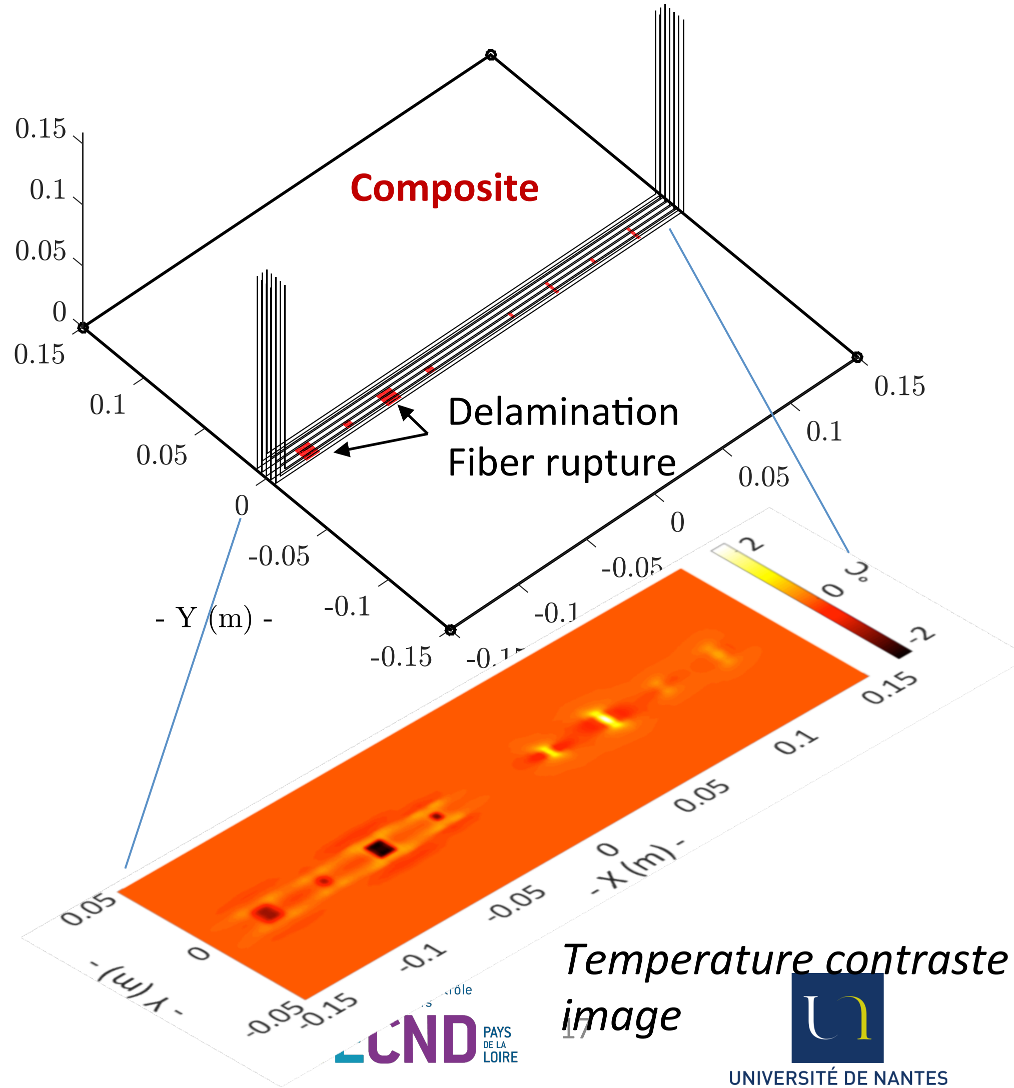


***Delamination* between plies**



***Fibers rupture* in a ply**



Temperature contraste image

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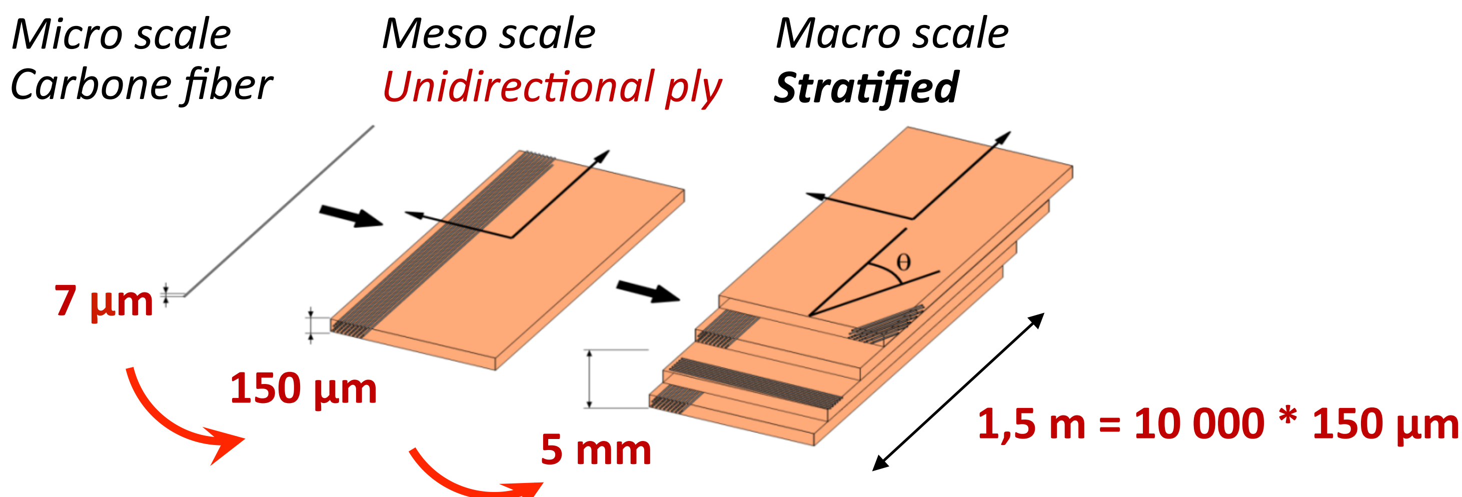
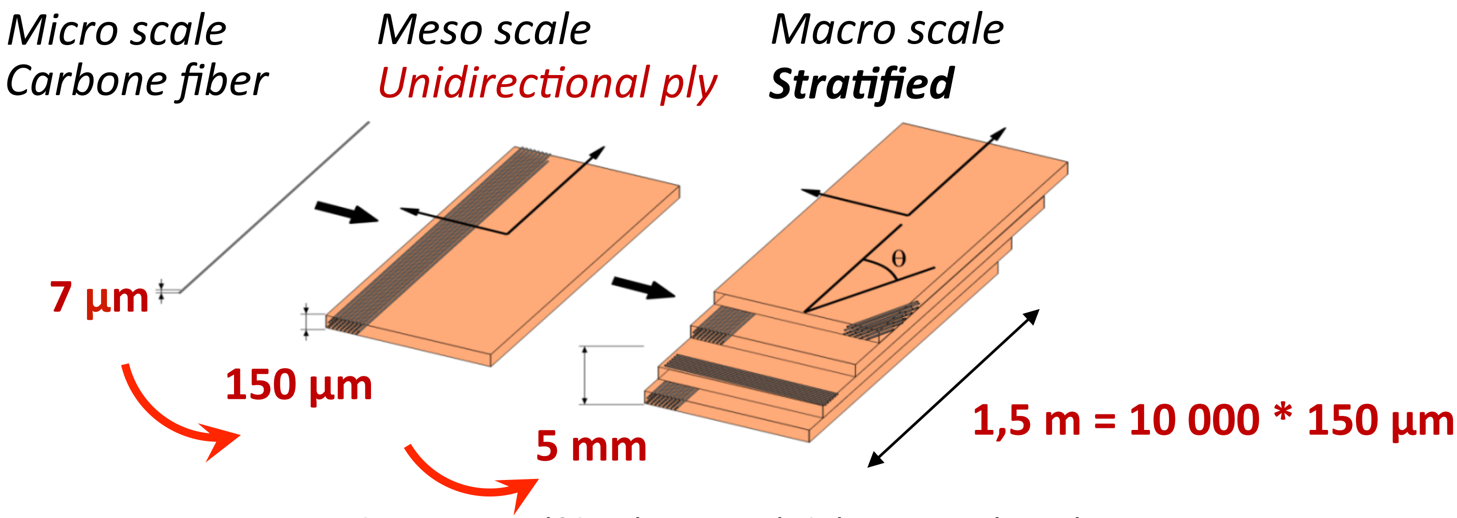
Modelling Issues



3 scales: micro (fiber), meso (ply), macro (part)

Modelling Issues



3 scales: micro (fiber), meso (ply), macro (part)

Micro-scale

- Random behavior
- High anisotropy
- Apparition of contacts
- Numerical omplexity

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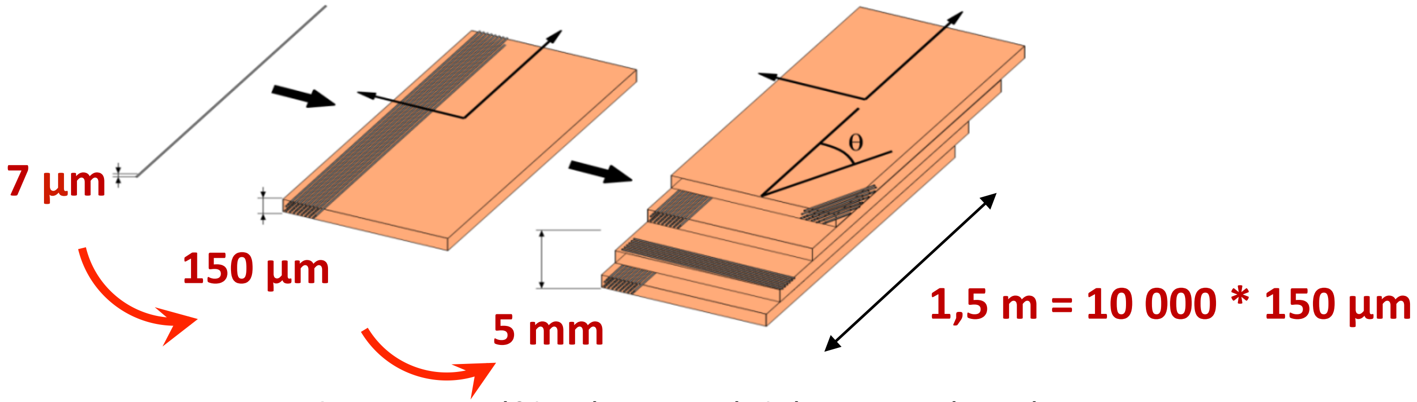
Modelling Issues

Micro scale
Carbone fiber

Meso scale
Unidirectional ply

Macro scale
Stratified



3 scales: micro (fiber), meso (ply), macro (part)

Micro-scale

- Random behavior
- High anisotropy
- Apparition of contacts
- Numerical omplexity

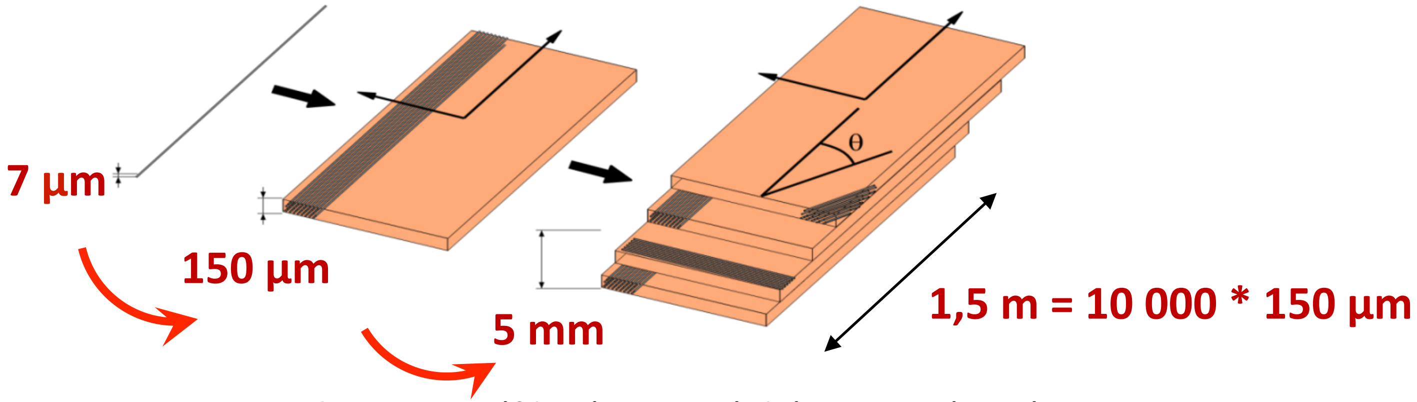
Meso-scale

- Scale Factor
- Anisotropy by layer

Model of homogeneization with taking into account of electrical percolation

Modelling Issues

Micro scale	*Meso scale*	*Macro scale*
Carbone fiber	*Unidirectional ply*	***Stratified***



3 scales: micro (fiber), meso (ply), macro (part)

Micro-scale

- Random behavior
- High anisotropy
- Apparition of contacts
- Numerical omplexity

Meso-scale

- Scale Factor
- Anisotropy by layer

Macro-scale

- Nonlinear Multi-physics
- Taking into account of the movement
- Taking into account of the generator

Model of homogeneization with taking into account of electrical percolation

Use of « shell » elements, multilayer and anisotropic

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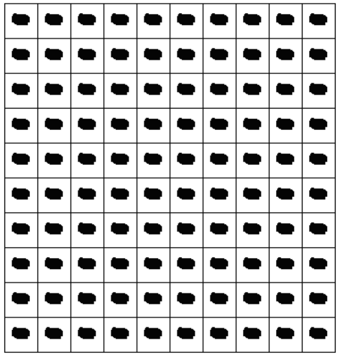
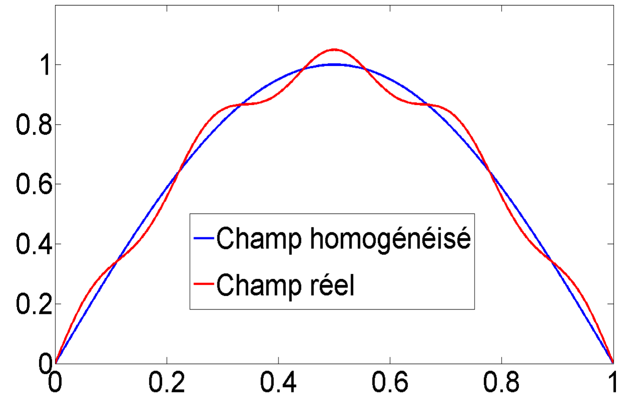
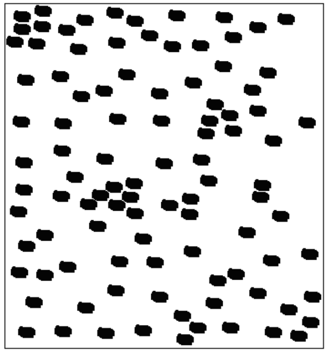
From microscopic to mesoscopic (homogeneization)

Homogeneization approach

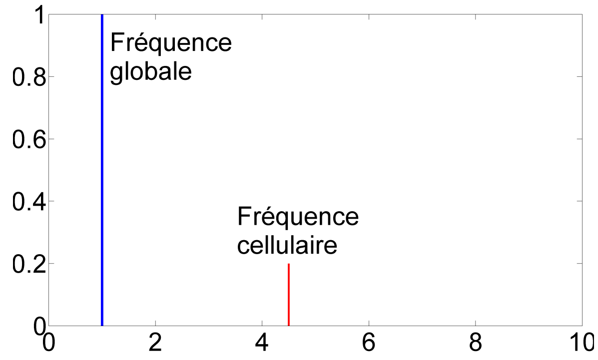
Homogeneization: keep information at global scale

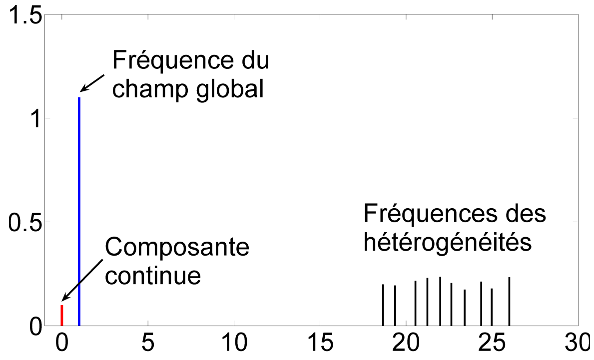






Non periodic structure material





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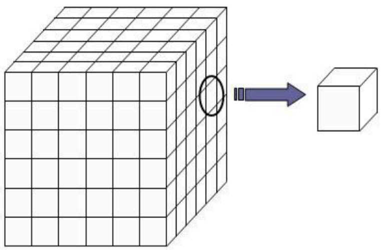
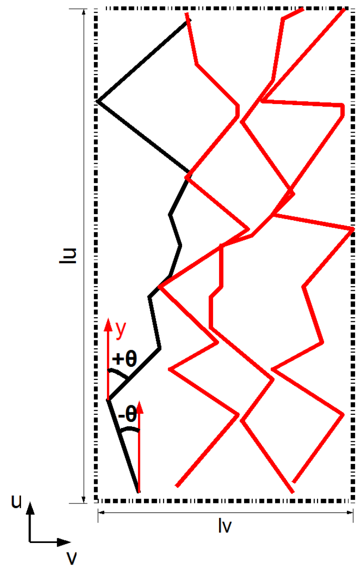
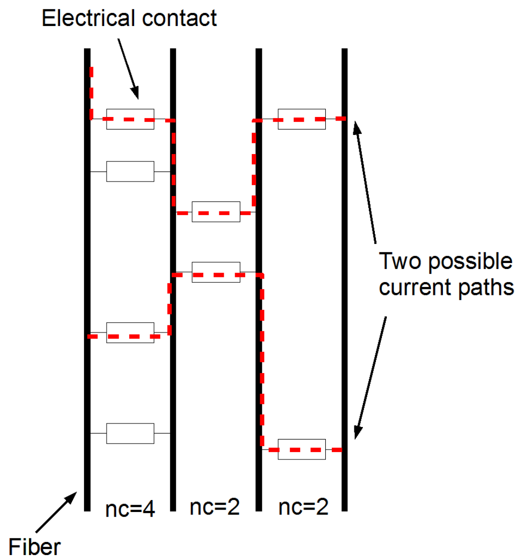
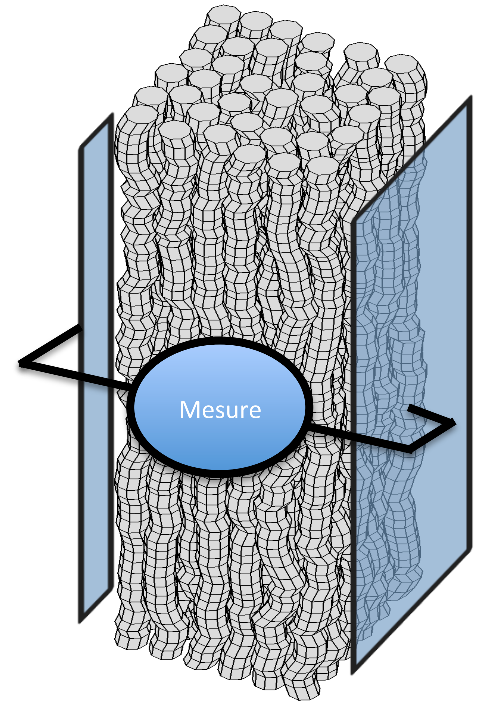
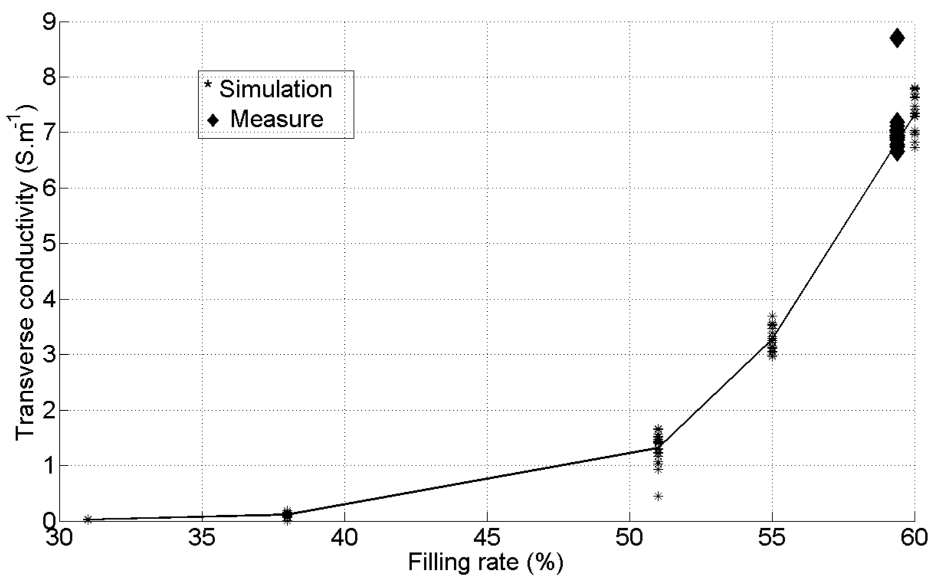
From mesoscopic to macroscopic











$$[\sigma] = \begin{pmatrix} \sigma_{xx} = 44000 & 0 & 0 \\ 0 & \sigma_{yy} = 7.2 & 0 \\ 0 & 0 & \sigma_{zz} = 7.2 \end{pmatrix} [S.m^{-1}]$$

G. Wasselynck, D. Trichet, and J. Fouladgar, "**Determination of the Electrical Conductivity Tensor of a CFRP Composite Using a 3-D Percolation Model,**" IEEE Trans. Magn., vol. 49, no. 5, pp. 1825–1828, May 2013

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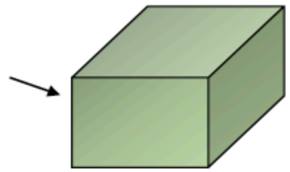
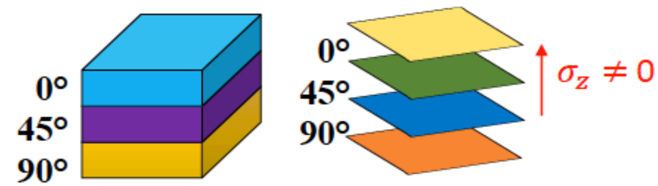
From mesoscopic to macroscopic

homogenized in the global scale

$$\begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}$$



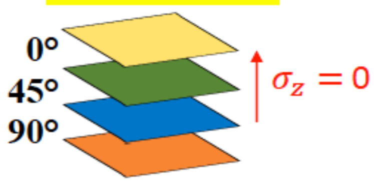
Meshed



Meshed ***Not meshed***

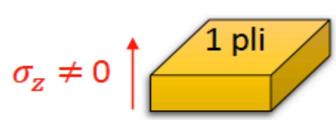
Stratified composite

Not meshed



- Generalization of shell element
- *Multi-layer anisotropic materials*

- *3D homogenization model*
- *Random distribution of fibers*



$$\begin{bmatrix} \sigma_{||} & 0 & 0 \\ 0 & \sigma_{\perp} & 0 \\ 0 & 0 & \sigma_z \end{bmatrix}$$

- *Circulation of eddy-current along the thickness*
- *Effect of stacking sequence*

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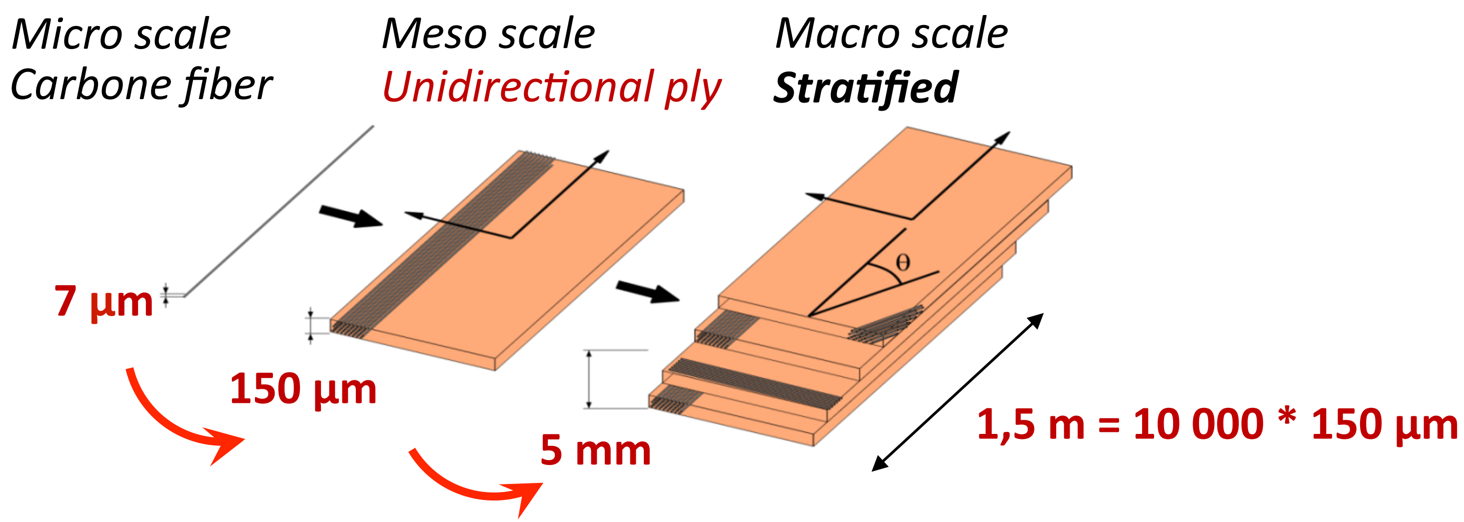
Modelling Issues



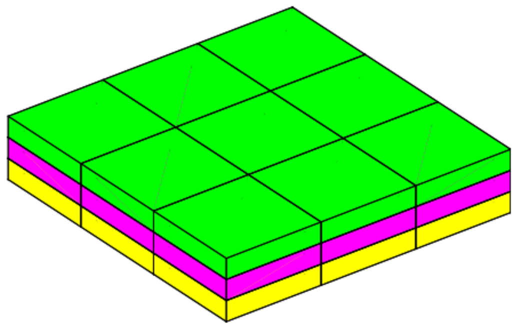
- Multi-scale structure
- Strong scale factor

→ Multi-scale modelling approach

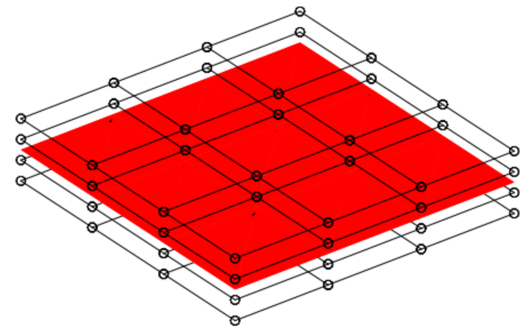
- Very thin layers and strong anisotropic material

→ Degenerated Edge Finite Element

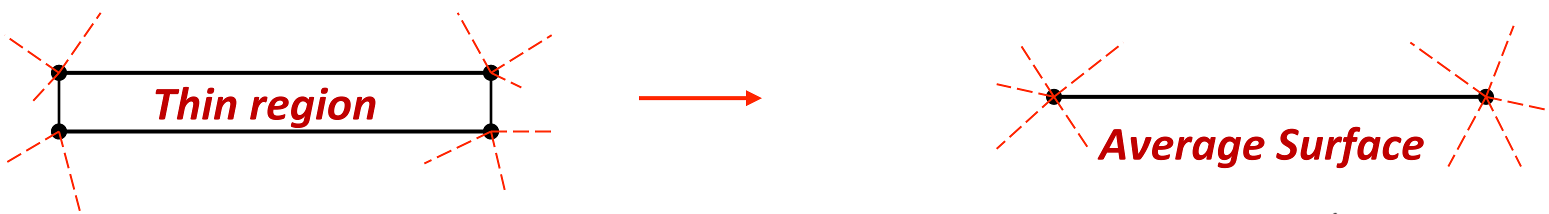
Degenerated Edge Element for Thin and Anisotropic Material



Volume mesh

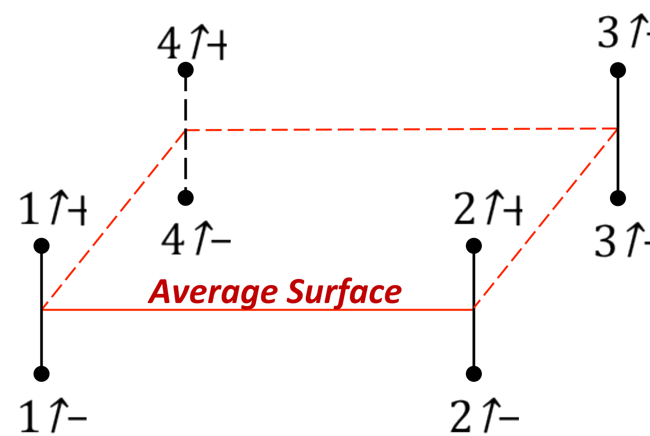


Double-layer surface mesh



Degenerated Edge Finite Element

Vector Potential Function



H. K. Bui, G. Wasselynck, D. Trichet, G. Berthiau, "Degenerated hexahedral Whitney elements for electromagnetic fields computation in multi-layer anisotropic thin regions", IEEE Transactions on Magnetics, vol. 52, no. 3, 2015.

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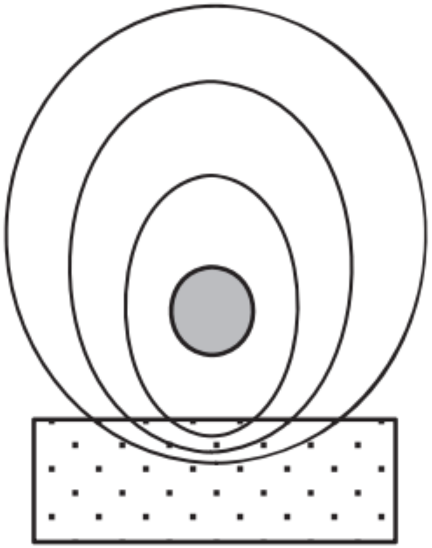

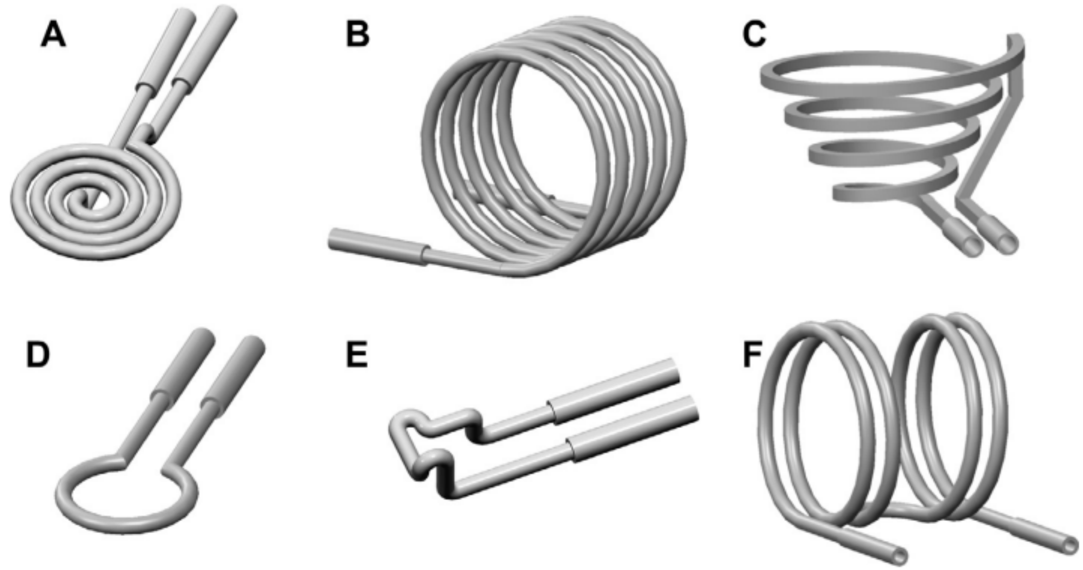

[T. Bayerl et *al.*]

- Massive and complex shape coil (inductor)
- Strong Skin Effect
- Calculation of Impedance

→ Surface Impedance Boundary Condition (SIBC)

+ Voltage-constrained Finite Element Model

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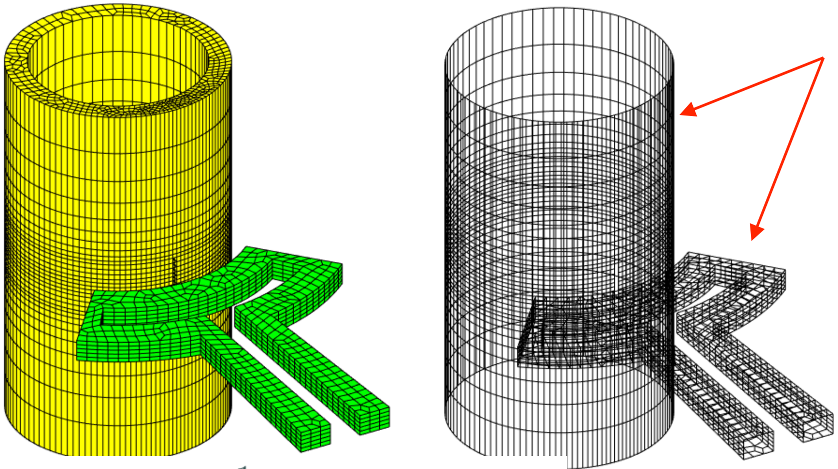
Surface Impedance Boudary Condition (SIBC)



SIBC condition:

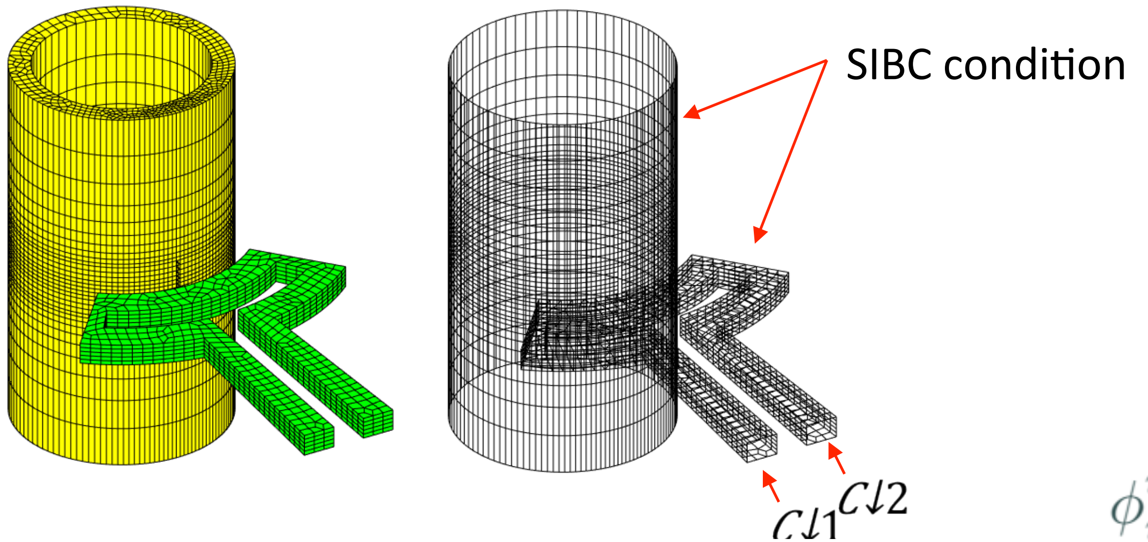
$$\boldsymbol{n} \times \frac{1}{\mu}\boldsymbol{curl}\,\boldsymbol{A}|_{\Gamma^c}$$
$$= \frac{1}{Z_c}\boldsymbol{n} \times (\boldsymbol{n} \times j\omega(\boldsymbol{A} + \boldsymbol{grad}\phi))|_{\Gamma^c}$$
$$Z_c = (1+j)/(\delta\sigma)$$

$$\boldsymbol{curl}\mu^{-1}\boldsymbol{curl}\,\boldsymbol{A} = 0$$

$$\int_\Omega \boldsymbol{curl}\mathbf{w}^e \frac{1}{\mu}\boldsymbol{curl}\,\boldsymbol{A}dv - \int_{\Gamma^c} \mathbf{w}^e(\boldsymbol{n} \times \boldsymbol{H})ds = 0$$

$$\int_{\Gamma^c} \mathbf{w}^e \frac{1}{Z_c}(\boldsymbol{n} \times jw(\boldsymbol{A} + \boldsymbol{grad}\phi)) \times \boldsymbol{n}ds$$

Voltage-constrained FEM



$$\phi_i^{imposed} = 0 \quad on \quad C_1$$

$$\phi_i^{imposed} = \frac{V}{jw} \quad on \quad C_2$$

$$\phi = \sum_{\Gamma^c \backslash (C_1 \cup C_2)} w^{n_i} \phi_i^{free} + \sum_{C_1 \cup C_2} w^{n_i} \phi_i^{imposed}$$

$$\int_\Omega \boldsymbol{curl}\mathbf{w}^e \frac{1}{\mu} \boldsymbol{curl}\boldsymbol{A} dv$$
$$+ \int_{\Gamma^c} (\boldsymbol{n} \times \mathbf{w}^e) \frac{1}{Z_c} (\boldsymbol{n} \times jw\boldsymbol{A}) ds + \int_{\Gamma^c} (\boldsymbol{n} \times \mathbf{w}^e) \frac{1}{Z_c} (\boldsymbol{n} \times jw\boldsymbol{grad}\phi^{free}) ds$$
$$= - \int_{\Gamma^c} (\boldsymbol{n} \times \mathbf{w}^e) \frac{1}{Z_c} (\boldsymbol{n} \times jw\boldsymbol{grad}\alpha\phi^{imposed}) ds$$

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Outline

Introduction

Composite lifecycle and induction

Multi-scale Modeling

SIBC + Voltage-constrained FEM

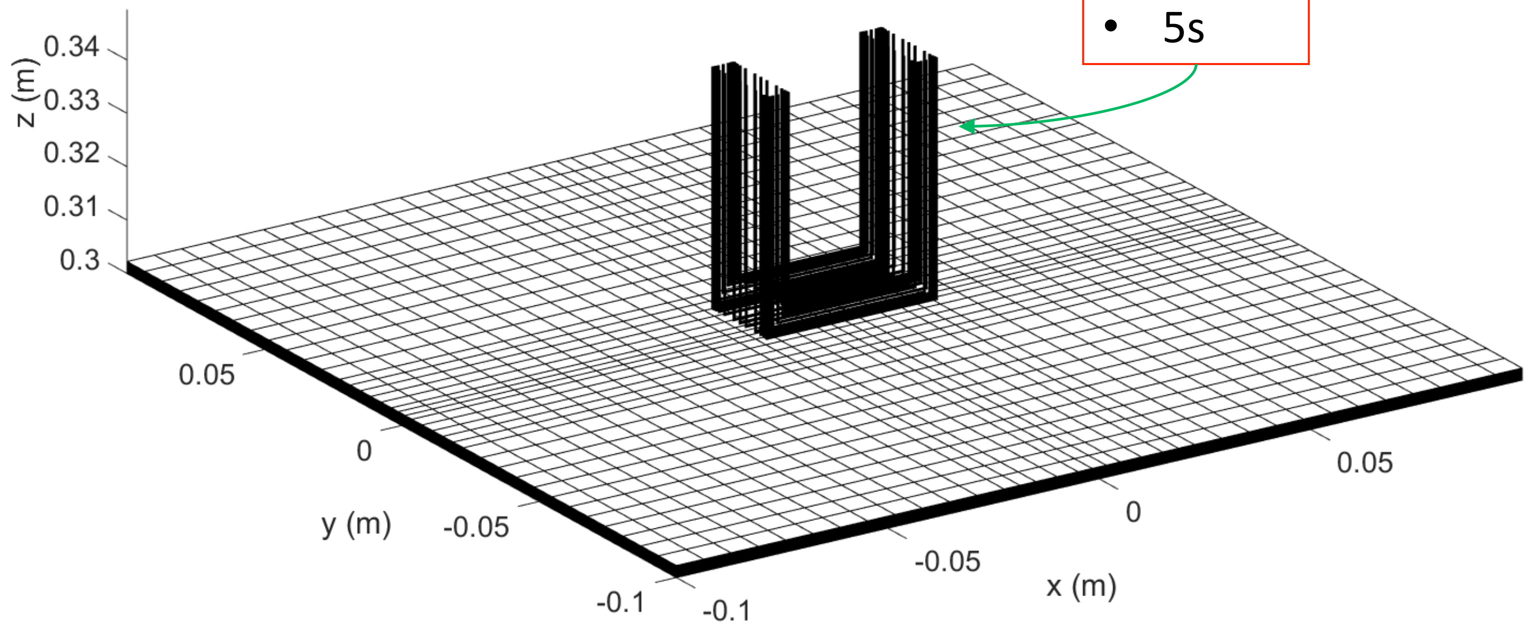
Some Applications

Conclusion

Stratified CFRP Plate

U-shaped Inductor

- 2 MHz
- 200A
- 5s



- 16 plies
- Stacking sequence : [135 90 45 0 135 90 45 0 0 45 90 135 0 45 90 135]

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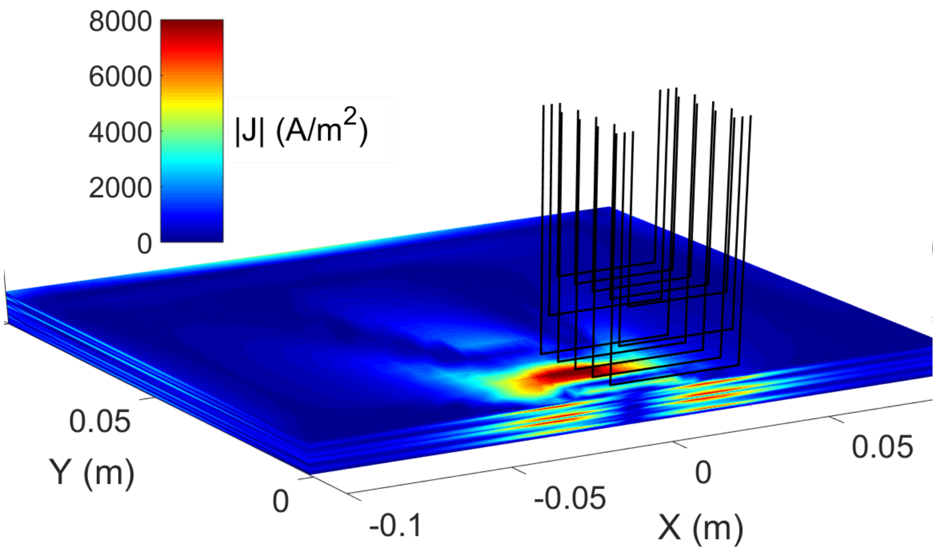
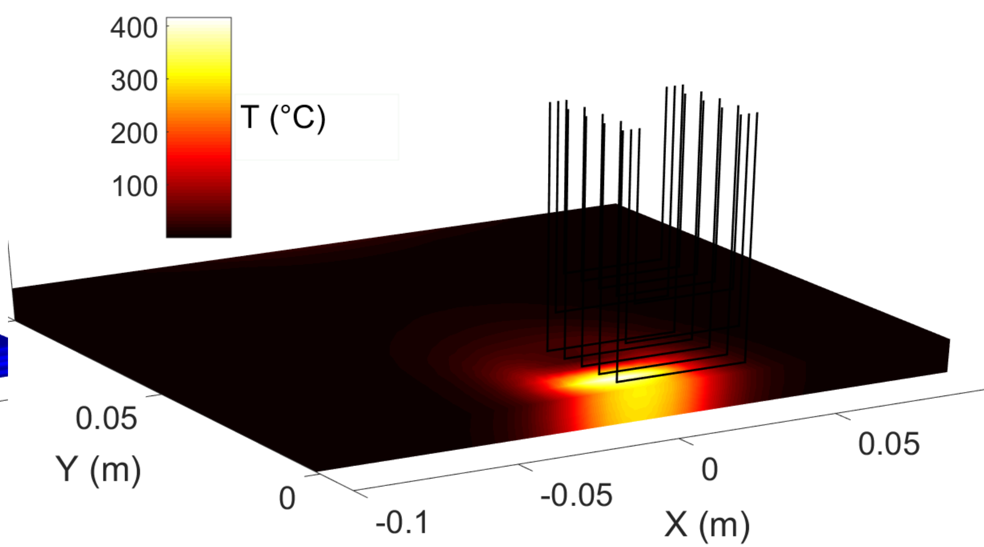
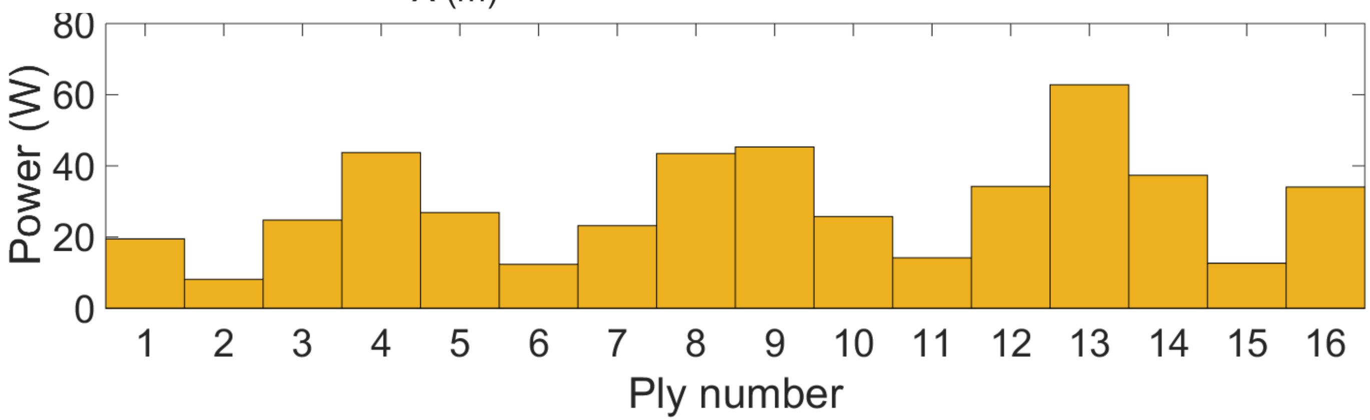
Stratified CFRP Plate



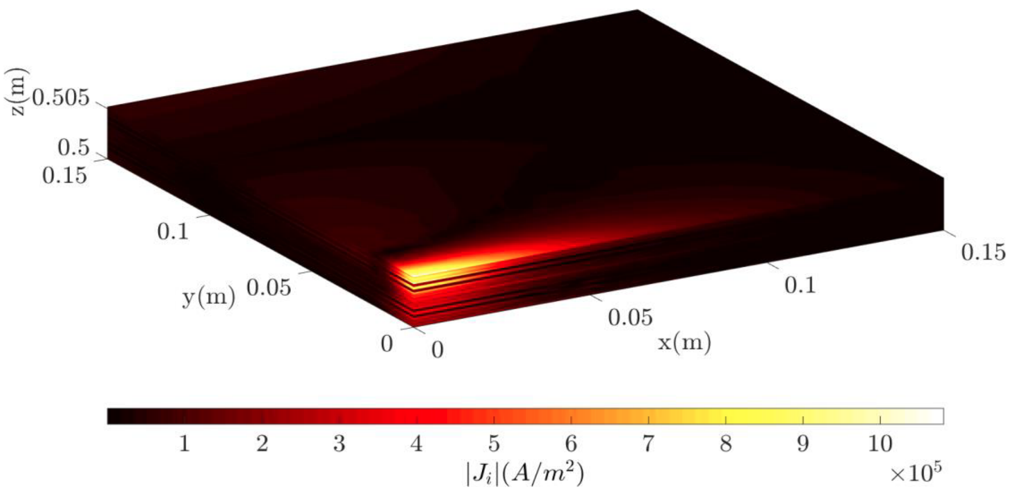


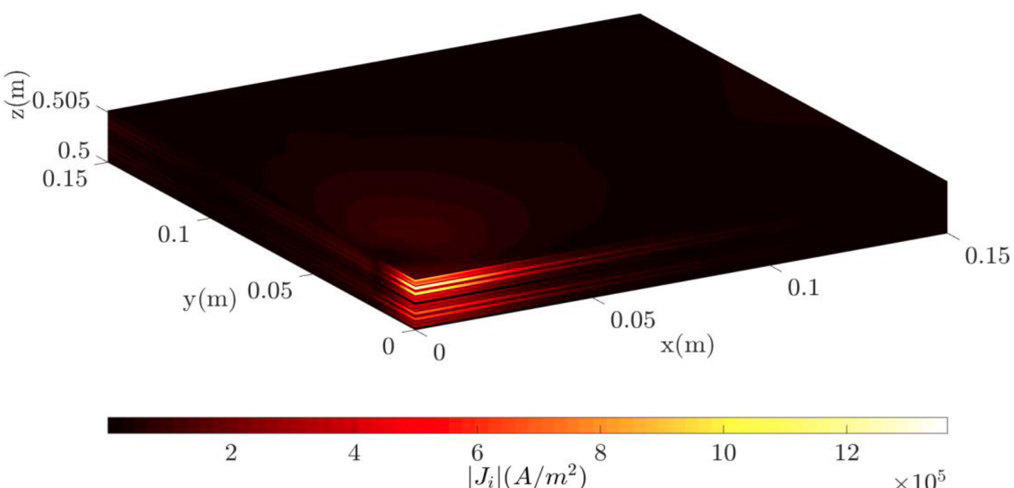


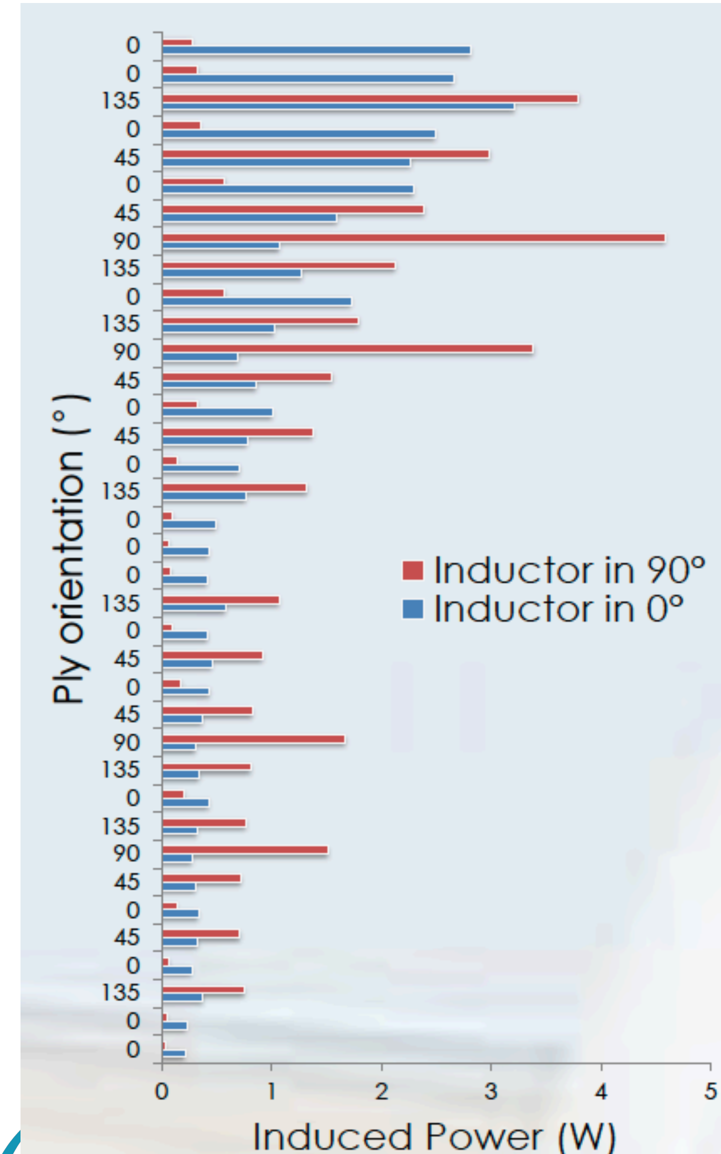
- **Inductor design to focus on interface layers.**

Stratified CFRP Plate

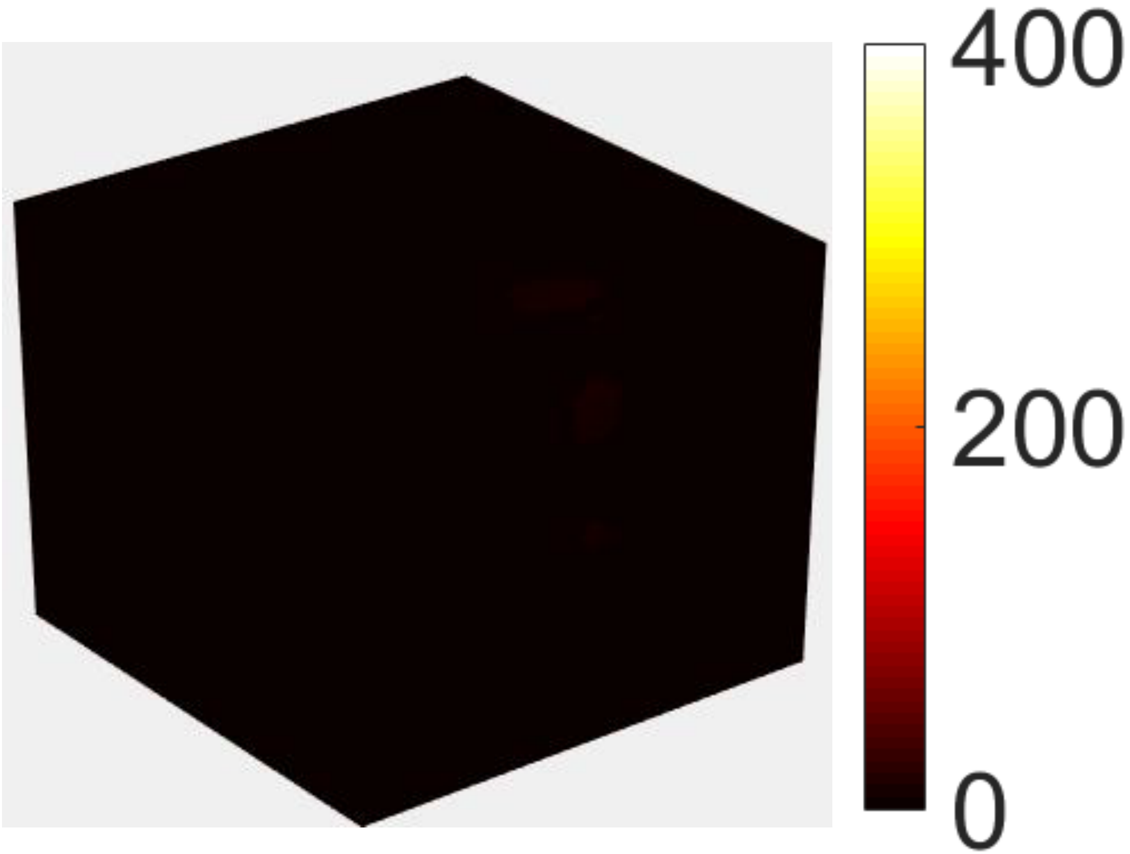
CFRP 37 plis / inducteur U / f=240kHz



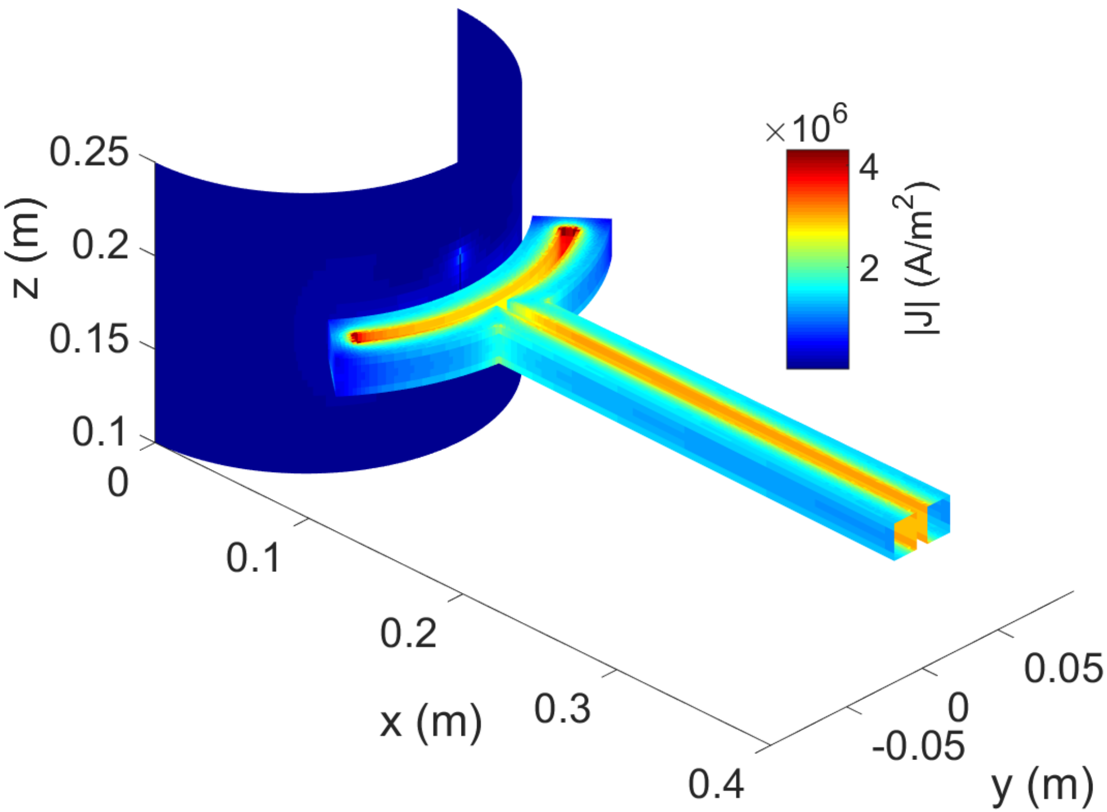


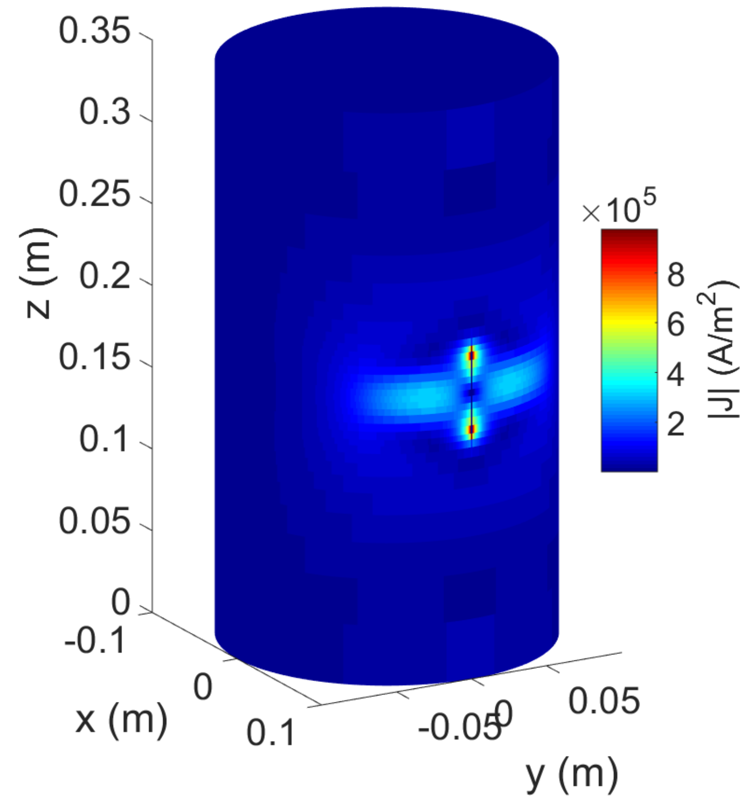


Stratified CFRP Plate



NDT Induction Thermography on Pipe





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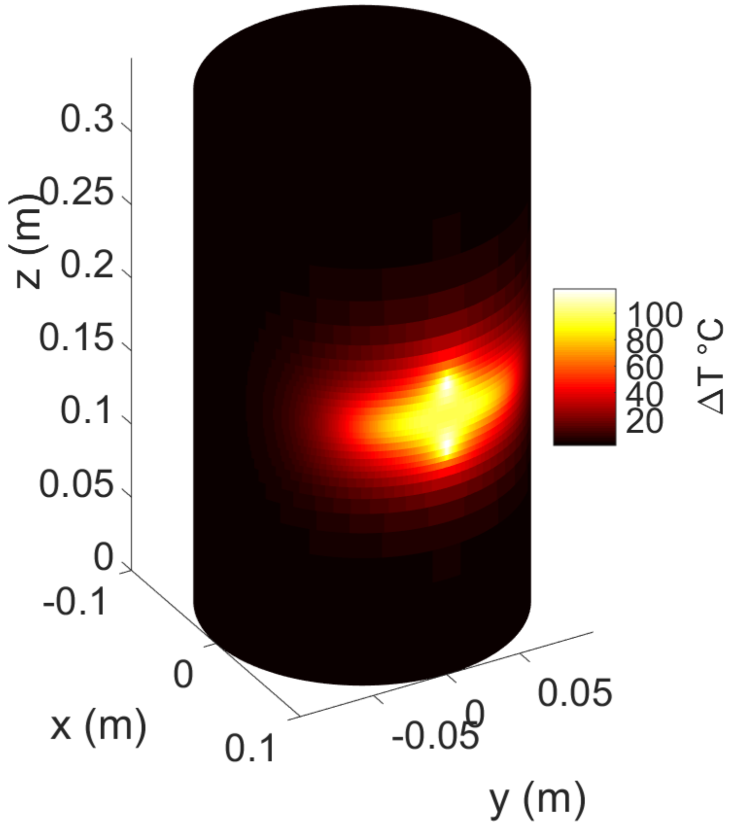
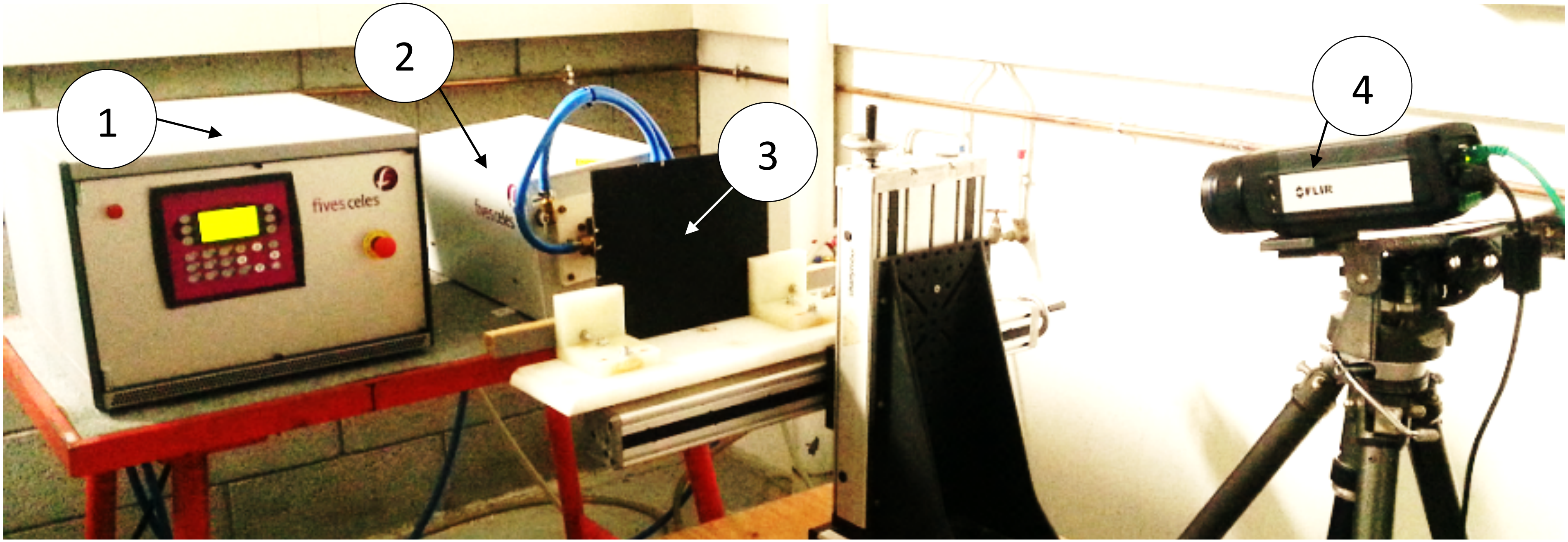
NDT Induction Thermography on Pipe



Experiment benchmark

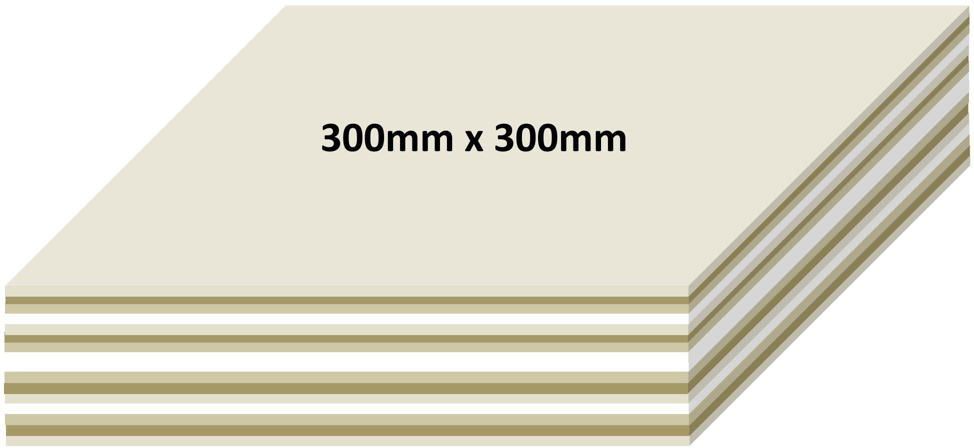


1. ***Induction generator***
2. ***Impedance adaptation box***
3. ***Composite plate***
4. ***IR camera***

Test case: plate with defects

- Fiber breakings
- Dlaminations

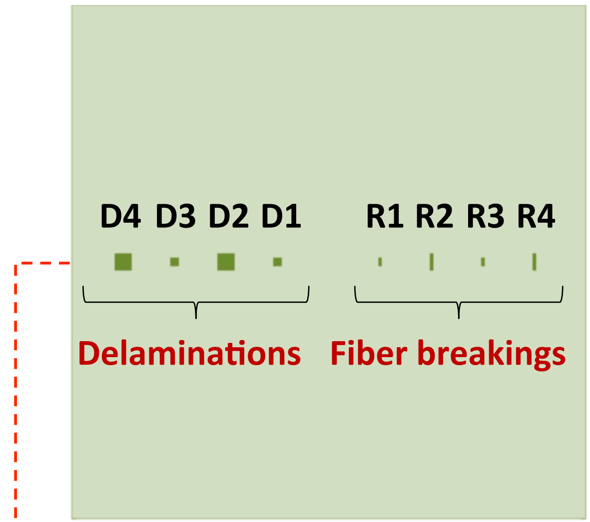
- **3D view**



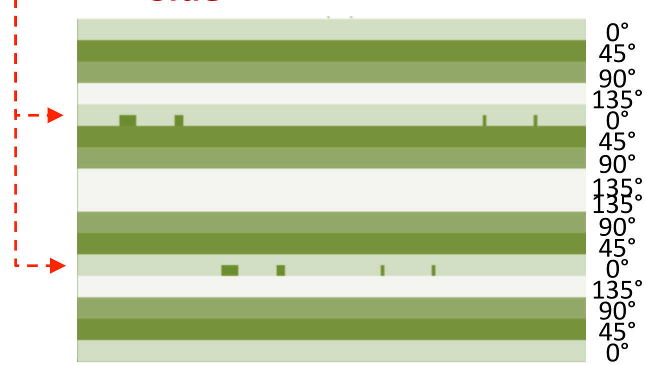
Configuration of control:

- 16 plies
- Quasi-isotropic layup
- 8 defects inside the 0° plies
- Length max 10mm x 10mm
- Thickness of a ply = 136µm
- Same thicknesses of the defects: 68µm ou 34µm

- **Up**



- ***Side***



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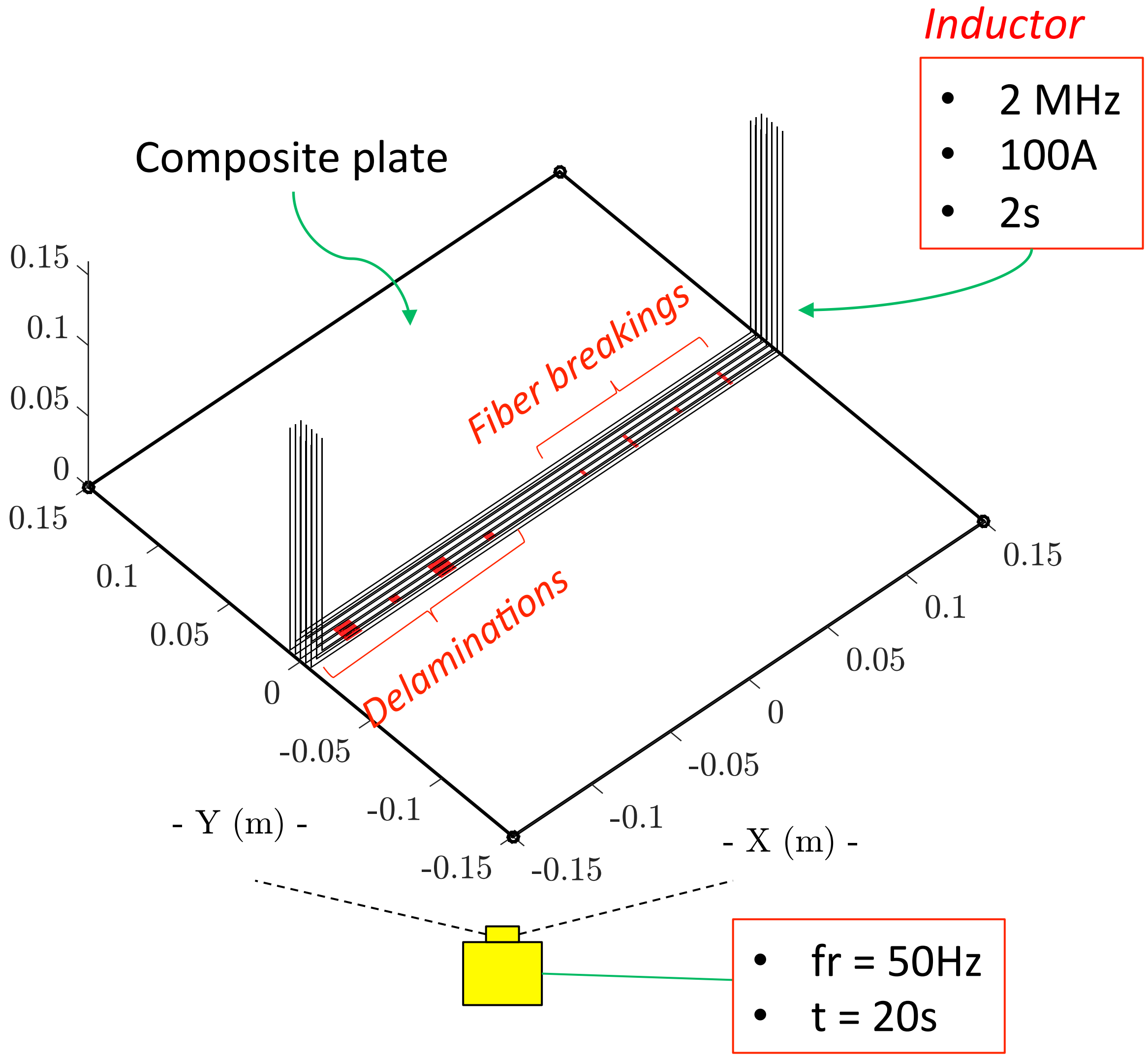
Control configuration



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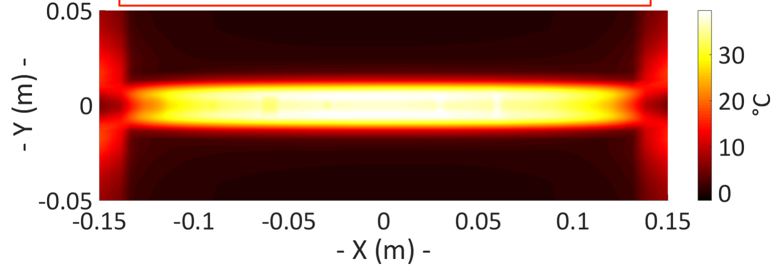
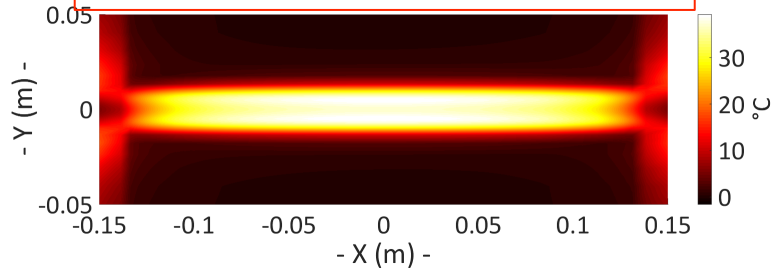
Absolute contrast Ca

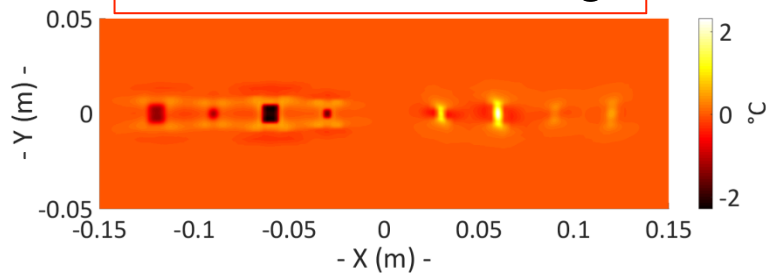
- At , ***WITH defect***



- At , ***WITHOUT defect***



- ***Substraction*** of image



- **Shapes** of defects are revealed
- For the **delaminations**
- For the **fibres breakings**

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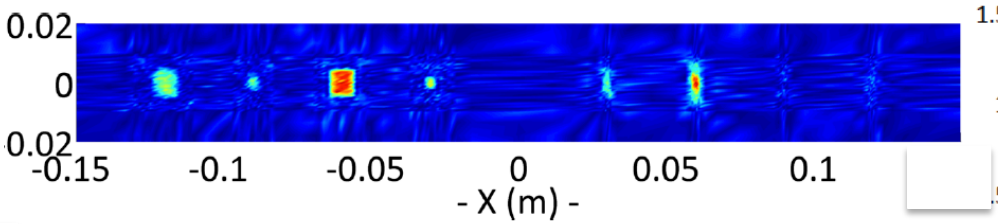
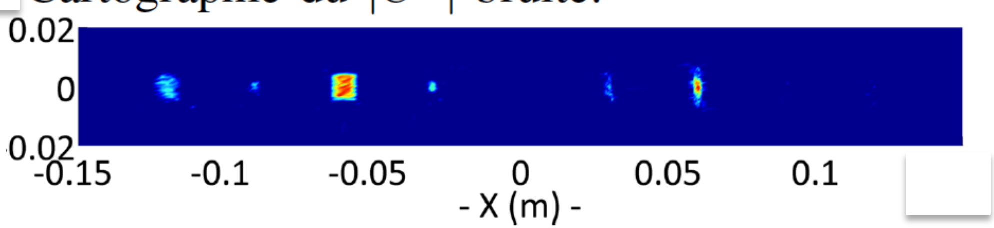
Taken into account of NOISE

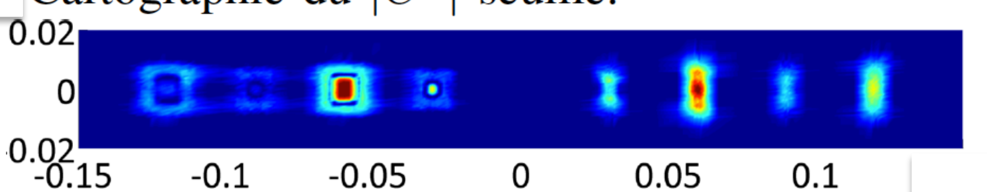
- Accuracy of the IR camera
- Homogeneity of emissivity of material surface
- White noise with standard deviation



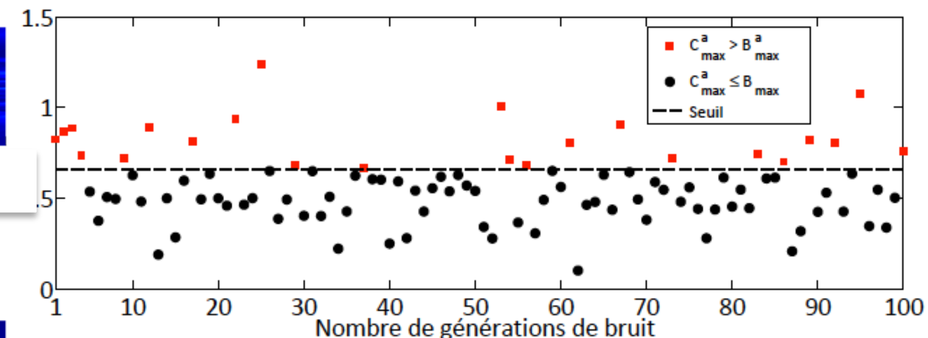
Cartographie du $|C^a|$ bruité.



Cartographie du $|C^a|$ seuillé.



Cartographie du contraste d'amplitude.



	D4	D3	D2	D1	R1	R2	R3	R4
C^a	100	94	100	100	88	100	1	17
C^{Amp}	100	100	100	100	100	100	100	100

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Parameters to be optimized

- Shape and dimensions of the inductor
- Frequency of the generator
- Time of heating
- Intensity of inductor current
- Frequency of the IR caméra
- Acquisition time
- …

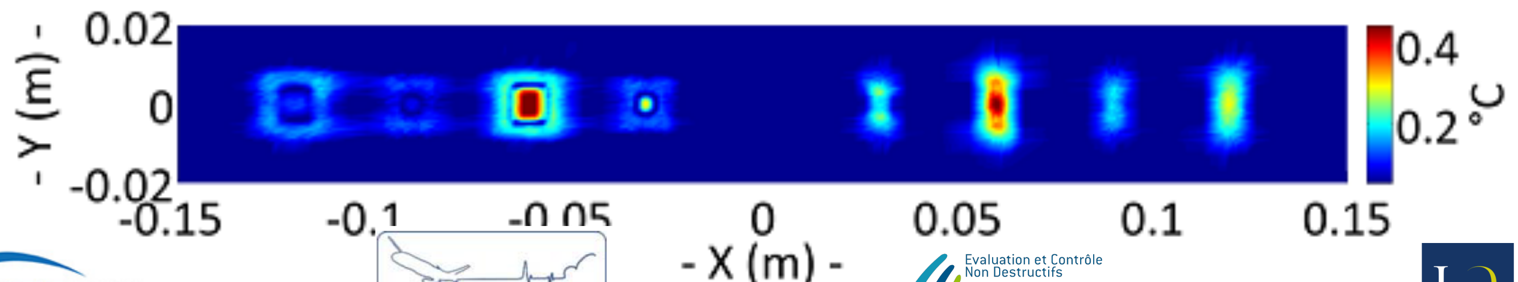
Examples

- ↗

	D4	D3	D2	D1	R1	R2	R3	R4
	100	**100**	**100**	**100**	**100**	**100**	**100**	**100**

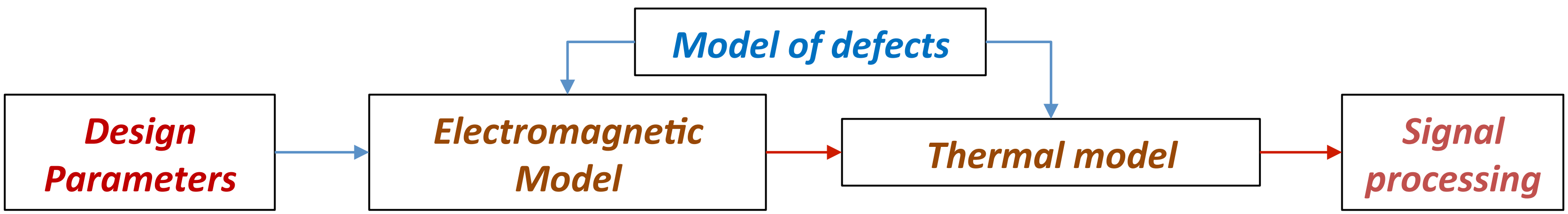
- ↗

	D4	D3	D2	D1	R1	R2	R3	R4
	100	**100**	**100**	**100**	**100**	**100**	**100**	**100**



Conclusion

- Induction is well adaptated to the injection of power without contact in composites
- Need of predictive simulation code for design, dimensioning and optimization



Multi-physic model of stratified composites

Perspectives

Characterization, optimization, … , toward electrical functional materials

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Thank you !

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