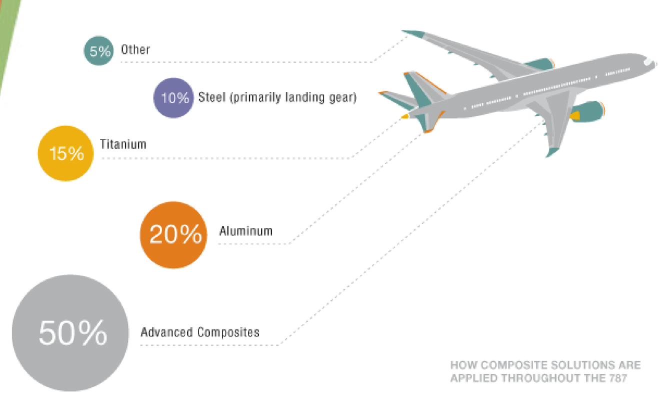
Forming simulations of continuous fibre composite reinforcement at the macroscale

Doctoral student: Bruno Cotrim
Supervisors: Olivier Polit, Michele D'Ottavio, Philippe Vidal, Emmanuel Valot

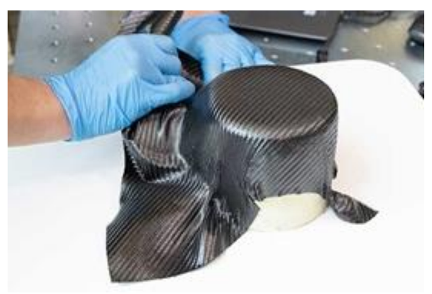
Leme — Laboratoire Énergétique Mécanique Électromagnétisme

Context

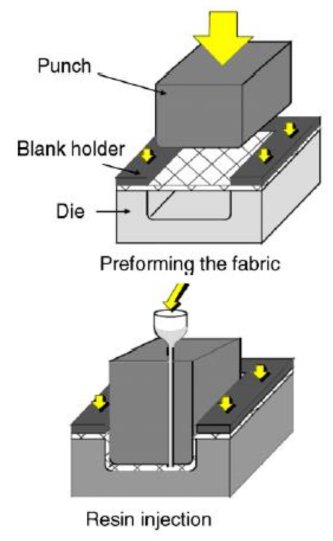
- **Composite materials**: light-weight alternatives to metals (reduced fuel consumption for the same performance – economic)
- **Continuous fibre composite reinforcements**: key component in many composite applications, undergo a specific deformation during the forming process, deformed before resin injection/ hardening
- **Numerical tools**: allows for new designs to be tested without going through real-life expensive experimentation and should retrieve:
  - the material properties after deformation;
  - the final fibre orientation;
  - development of defects (wrinkling, yarn slippage/fracture, etc)



Material composition of a Boeing 787 [1]

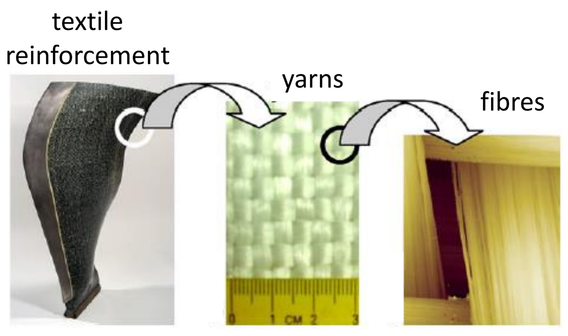


Draping of a carbon-fibre reinforcement [2]

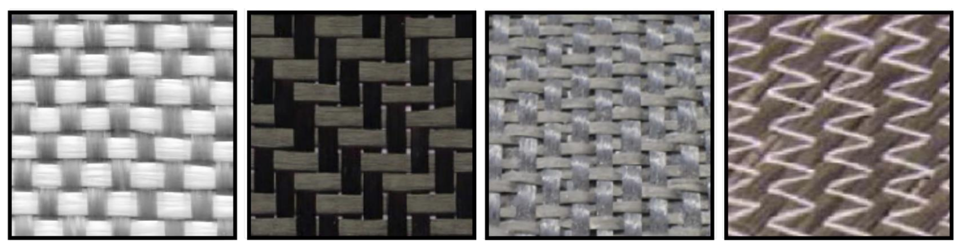


Resin transfer moulding [3]

- **Multiscale problem**: material behaviour characterised by:
  - Interactions between microscopic fibres that comprise the yarn;
  - Yarn individual properties and processing patterns at mesoscale (weaving pattern, stitching, etc)
  - Geometry of the deformed fabric at the macroscale
- **No globally accepted model exists**:
  - Discrete models better describe the deformation at higher computational cost
  - Continuous models show smaller accuracy but are much cheaper computationally



Continuous fibre reinforcement different scales [3]

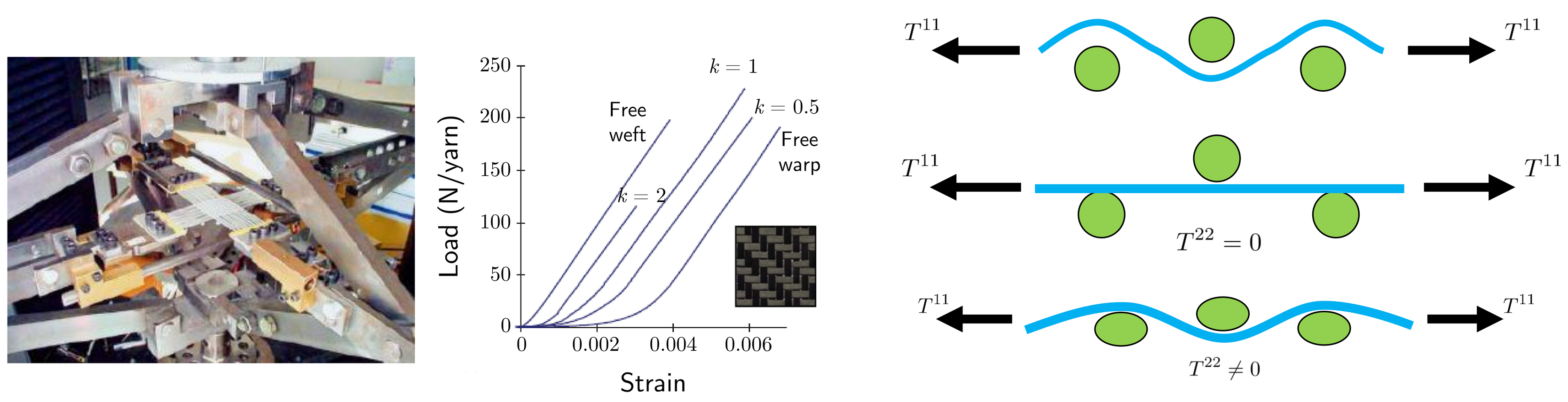


Processing of yarns. From left to right: plain weave, twill weave, interlock, non-crimped fibre [4]

- **Goal**: improve existing numerical tools for draping simulation at the macroscale level
- **Implementation**: In-house finite element code with 3-node elements
- **Programming languages**: Matlab, Java

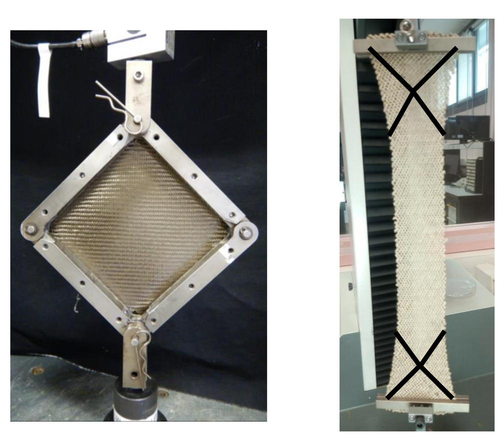
Experimental tests

- Specific tests allows us to characterise different behaviours
- **Tensorial behaviour**: characterised by the biaxial test, assumed linear
  - Stiffness is really high and fibres hardly stretch before breaking (quasi-inextensible fibres)

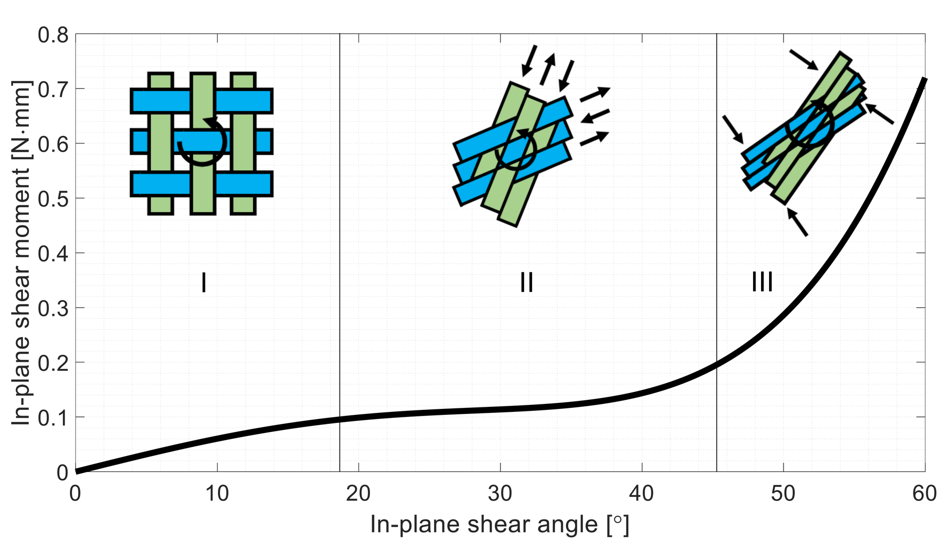


Biaxial test on a cross-shaped specimen and load-strain curve for carbon twill weave ($k=\varepsilon_{warp}/\varepsilon_{weft}$) [5]

- **In-plane shear behaviour**: characterised by the picture frame and the bias extension tests, non-linear behaviour

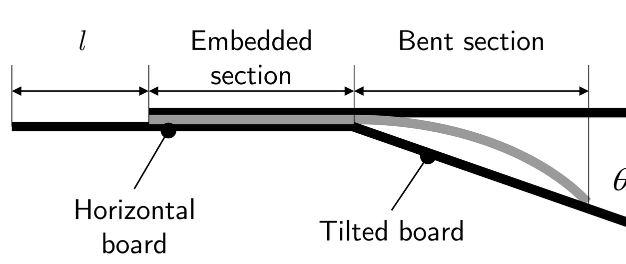


Picture frame and bias extension tests [3]

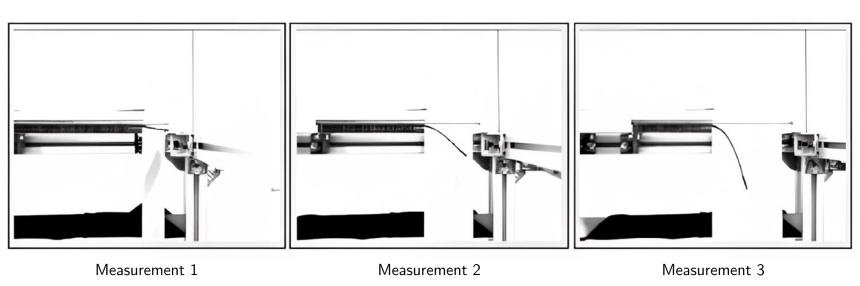


Constitutive law for Hexcel 1151

- **Bending behaviour**: characterised by different tests with different models proposed, assumed linear
  - stiffness is very low, included to better predict wrinkling [4]

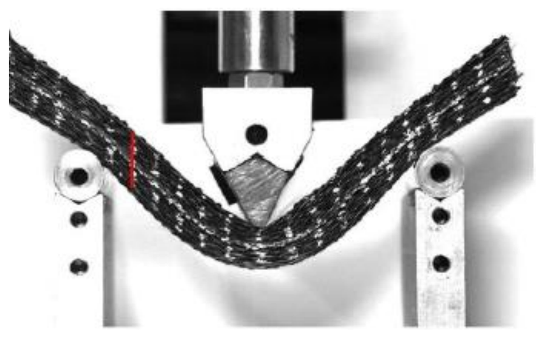


Pierce cantilever test [6]

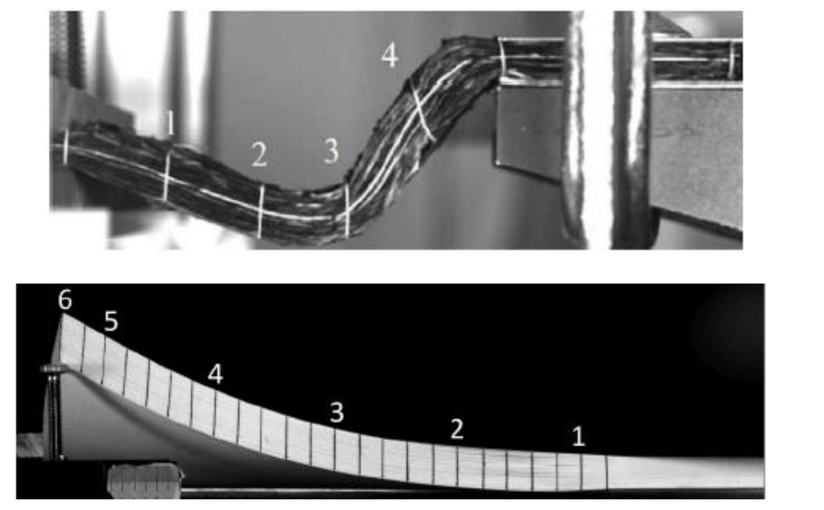


De Bilbao cantilever test [7]

- **Continuous fibre reinforcement stacks**:
  - Lines initially normal to the mid surface do not remain normal after deformation as layers can slip and fibres cannot extend
  - Thickness varies during deformation



3-point bending of a laminate stack [8]



Deformation of multi-layered reinforcements [8]

Modelling

- The tissue reinforcements are considered a continuous medium
- The equilibrium equations are obtained with the virtual work method, with each deformation mode being uncoupled from each other [5, 9]

$$\delta W_{acc} = \delta W_{ext} - \delta W_{int}, \quad \delta W_{int} = \delta W_t + \delta W_{is} + \delta W_{ob} + \delta W_{ts} + \delta W_c + \delta W_{ib} \quad (1)$$

- The finite element method is used to approximate the equilibrium equations

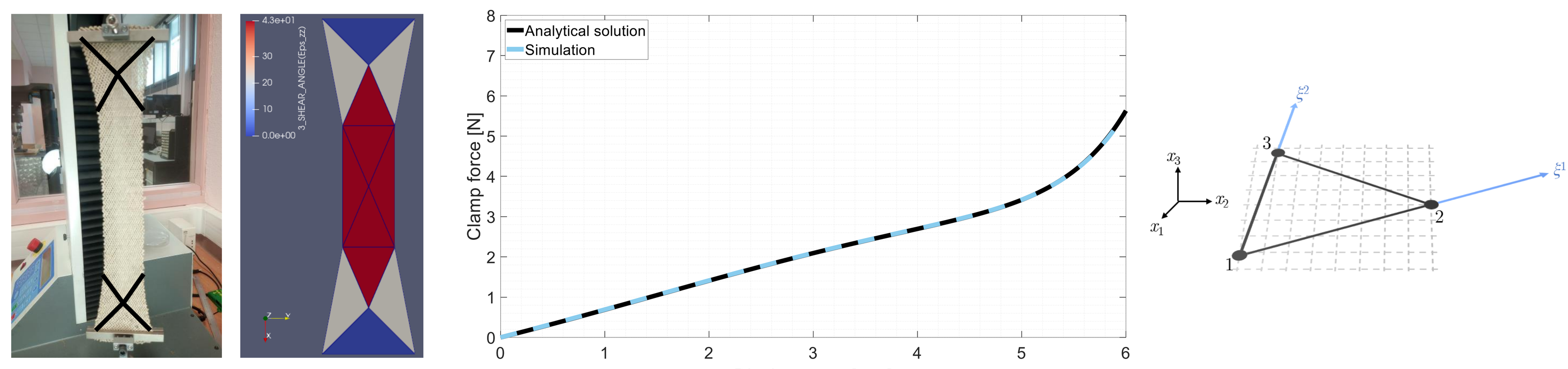
$$\underline{\underline{M}}\,\ddot{\underline{u}} + \underline{\underline{C}}\,\dot{\underline{u}} = \underline{f}_{ext} - \underline{f}_{int} \quad (2)$$

- The equations are solved with a central difference scheme

$$\underline{u}^{n+1} = \underline{u}^{n} + \Delta t^{n} \dot{\underline{u}}^{n+1/2}, \quad \Delta t^{n} = t^{n+1} - t^{n} \quad (3a)$$

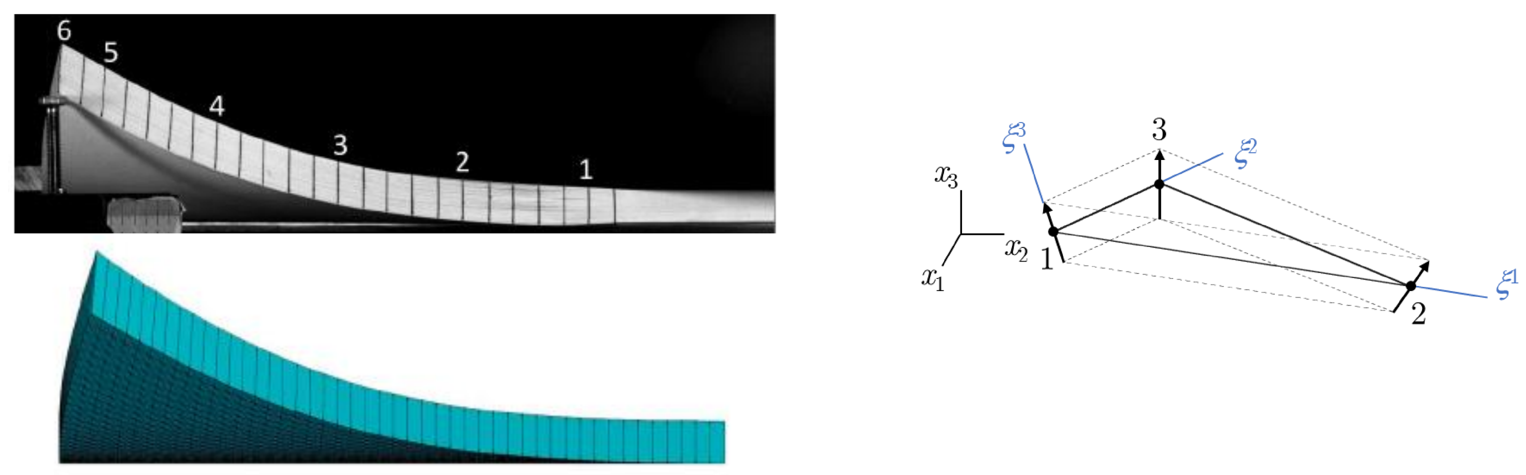
$$\dot{\underline{u}}^{n+1/2} = \dot{\underline{u}}^{n-1/2} + \Delta t^{n-1/2} \ddot{\underline{u}}^{n}, \quad \Delta t^{n} = t^{n+1/2} - t^{n-1/2} \quad (3b)$$

- **Simulation of the bias extension test with a 2D finite element**: hyperelastic model for membrane (δW_t, δW_{is}) [10]



Simulation of a bias extension test

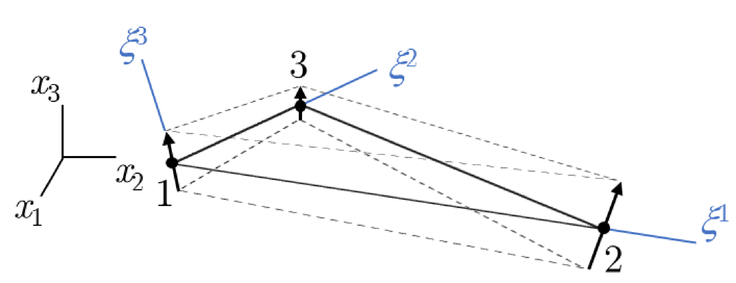
- **Simulation of a multi-layered reinforcement with a constant-thickness 3D finite element**: semi-discrete model for membrane (δW_t, δW_{is}) and a Kirchhoff-Love plate for bending (δW_{ob}) [8]



Simulation of the deformation of a multi-layered reinforcement [8]

Conclusions and on-going work

- 3-node finite elements were implemented in Matlab and Java
- **In development**: ED-1 based finite element for variable thickness with hyperelastic membrane (δW_t, δW_{is}), Kirchhoff-Love plate for bending (δW_{ob}) and 1-D elasticity for compaction



ED-1 based finite element under development

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