Study of fiber waviness in composite structures supported by simulation

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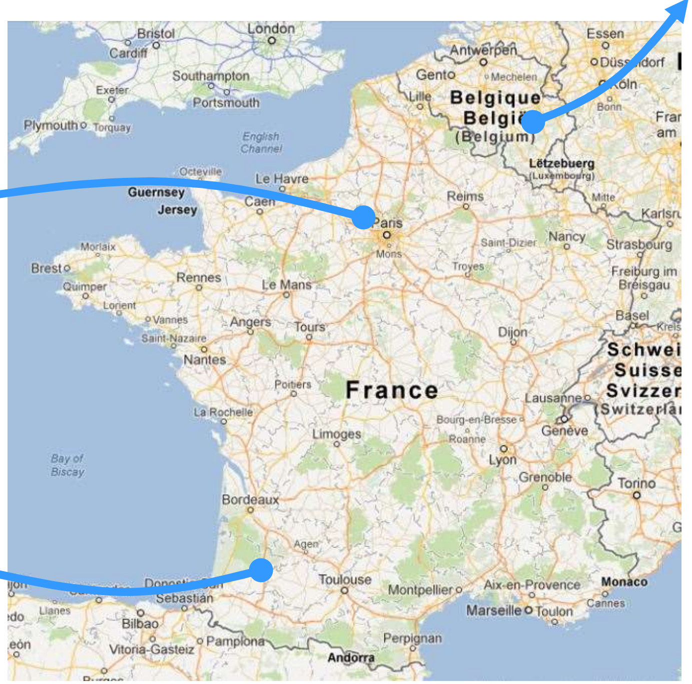
International Conference on Composites
October 2-3, 2018, Liège, Belgium

About GDTech

- Engineering Service company
- Founded in 1991
- Locations
  - Belgium: Liège area
  - France: Paris area and Pau
- More than 200 employees
  - Bachelors, engineers, PhDs

GDTeh group headquarter
Liège – Belgium

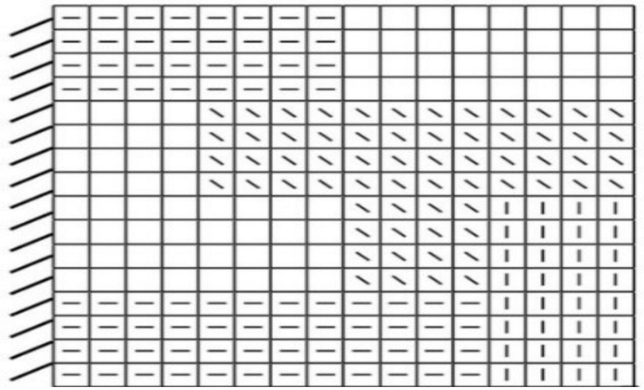


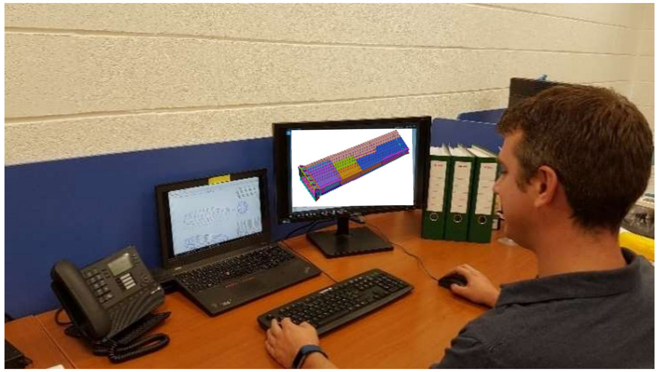
Buchelay – France

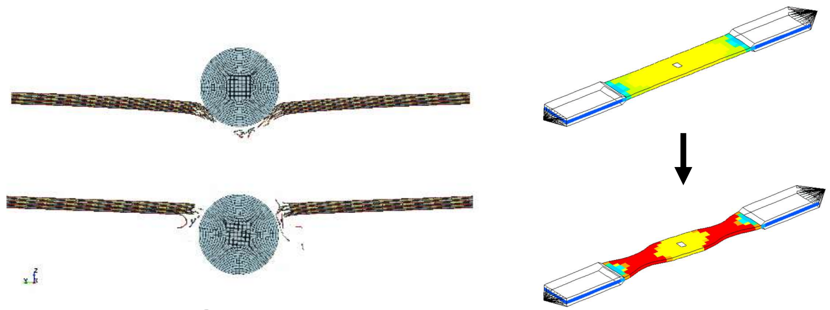
Pau – France

- Different teams
  - R&T team for industrial partners (e.g. SAFRAN)
  - CAD team (Computer Aider Design)
  - CAE team (Computer Aider Engineering)
    - CFD (Computational Fluid Dynamics)
    - CSM (Computational Structural Mechanics)
    - Multi-physics modelling
- R&D essential to provide high value service
  - Walloon & Skywin support (e.g. **TECCOMA project**)
  - European support
- GDTech is member of NAFEMS and is active in the NAFEMS Composite Working group

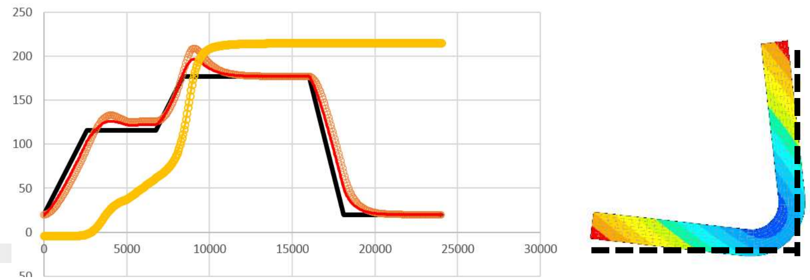
Design, modelling and optimisation







Stress analysis

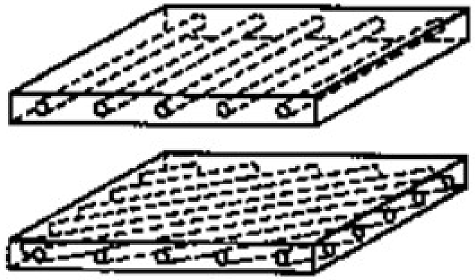


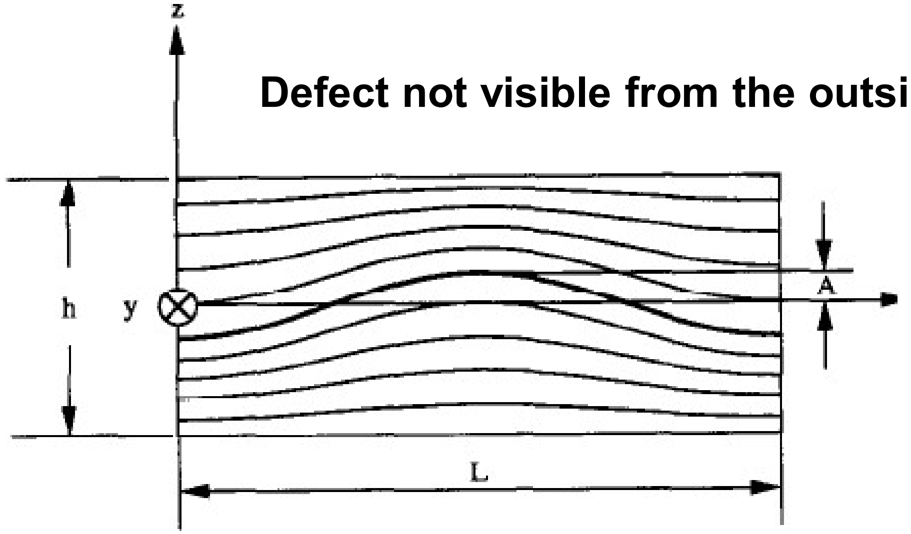
Thermo-set curing simulation

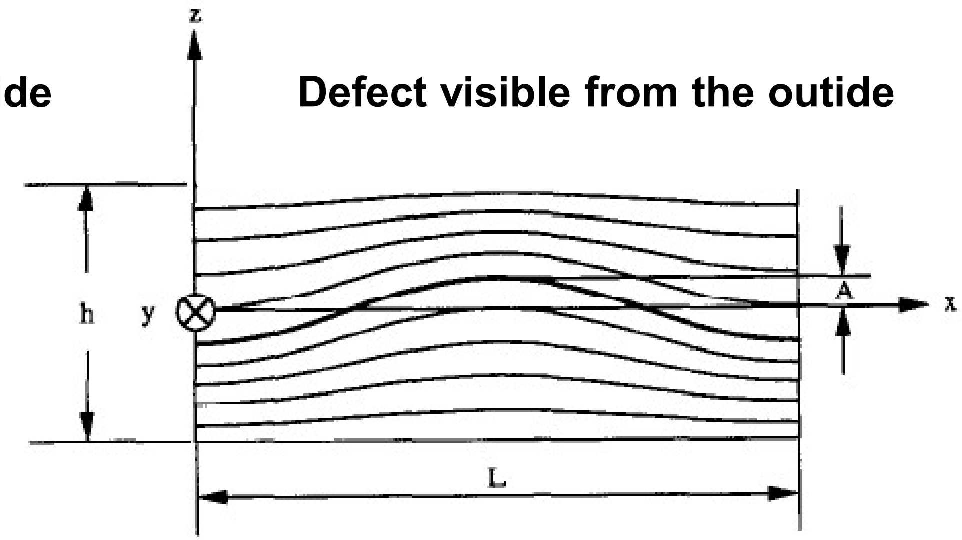
Outline of the presentation

- Context
- Why simulation?
- Definition of relevant specimens and tests
- Models and parameters identification
- Modelling of the defect
- Comparison between tests and simulation
- Conclusions

- We consider laminates made of UD plies
- Defects are present in such composite materials and structures
- They may result from deficiency/difficulty in the manufacturing process
- Here, the defect of waviness is studied
  - Internal waviness
  - External waviness => considered here



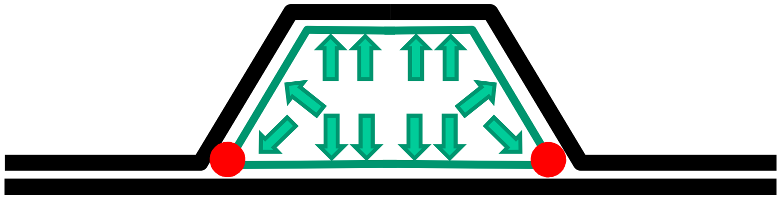


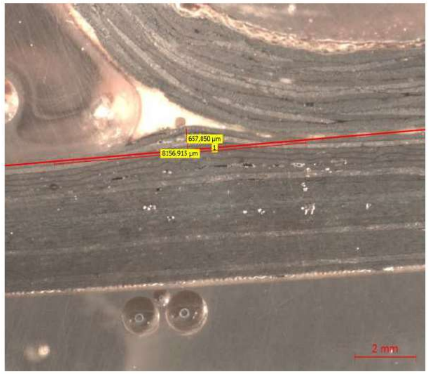


Here, the defect of waviness is studied

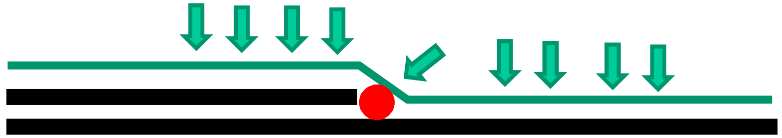
- Possible origins:
  - Defects appearing during preforming
  - Difficulty to apply a pressure and compact the laminates in regions of geometric complexity during manufacturing
- Necessity to determine the effect of defect on the mechanical performances
  - KDF = Knock Down Factor $\dfrac{Allowable_{without\ defect} - Allowable_{with\ defect}}{Allowable_{without\ defect}}$

Stiffener/skin intersection



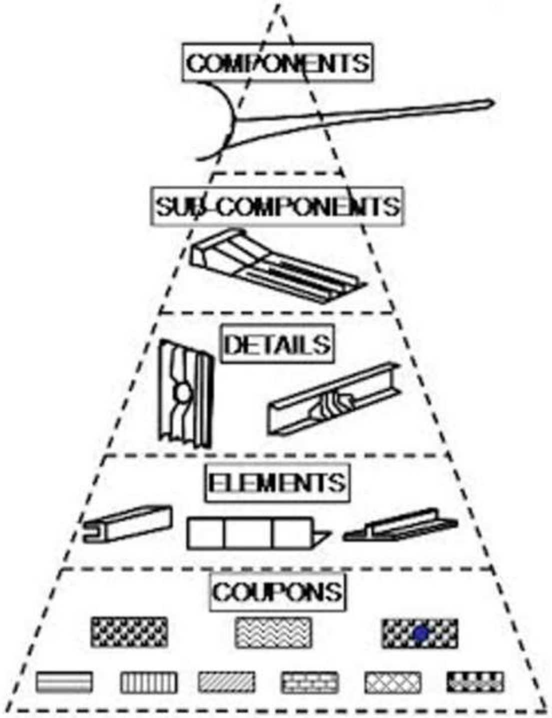


Ply-drop



Why simulation?

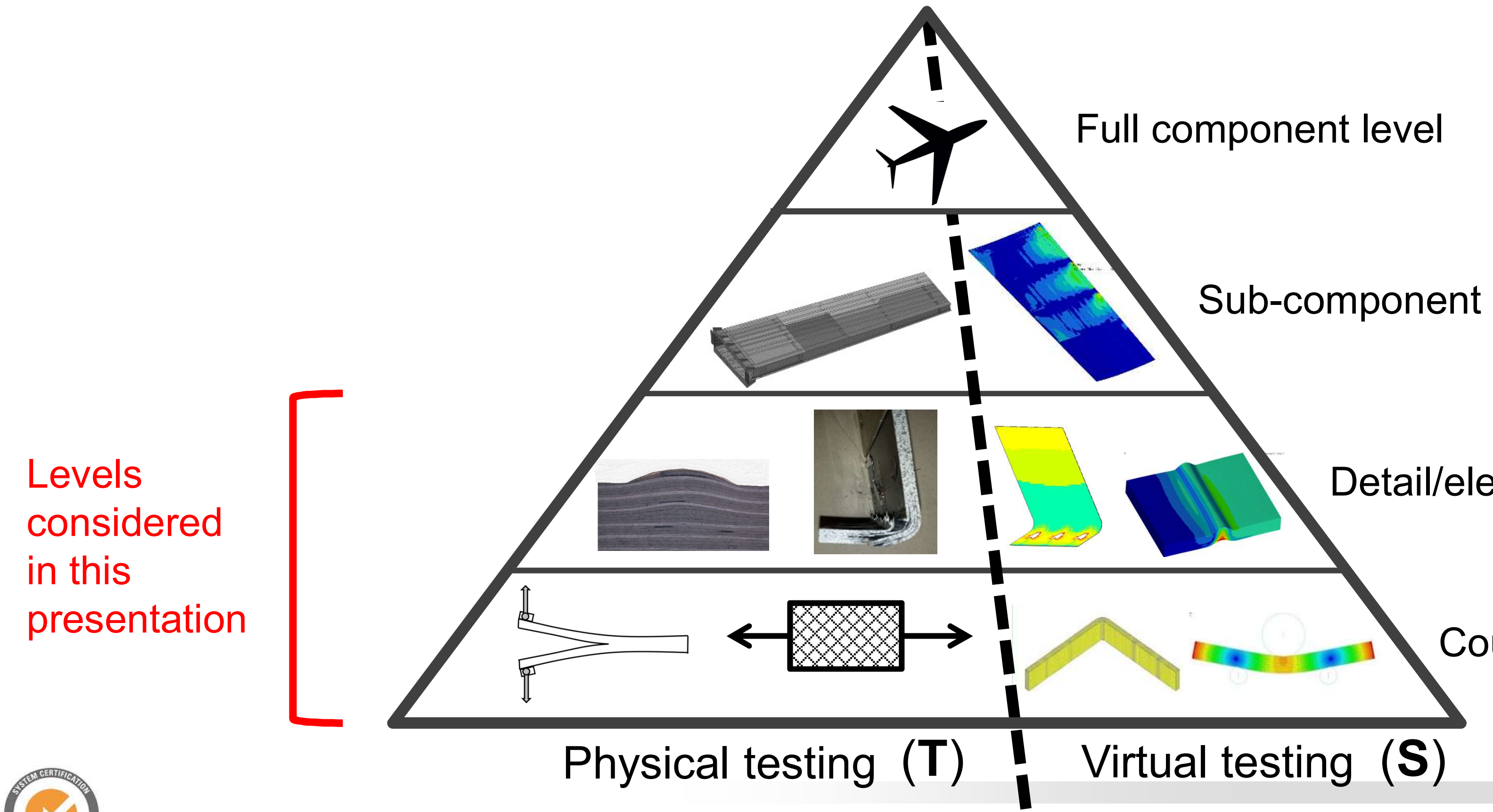
- Pyramid of test = building block approach
- Physical testing may be difficult to conduct and time consuming
- Expensive to test lots of different configurations
  - Simulation can be used as a companion of physical prototypes
  - Concept of digital twin



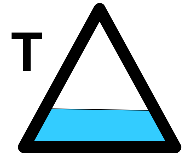
https://www.siemens.com

Why simulation?

- More and more simulation is used as a companion to physical testing
- Here, Samtech/Siemens numerical tools
  - **Simcenter Samcef** for the FEM computation (non linear FEM analysis)
  - **BACON** and **Simcenter** for pre and post-processing

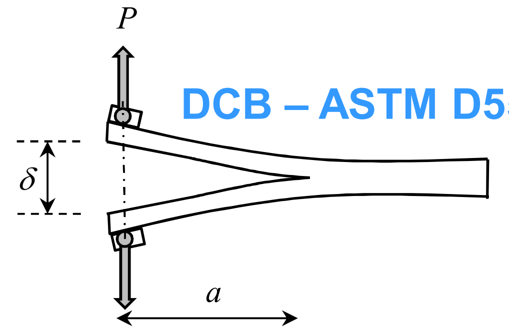


Specimens and tests

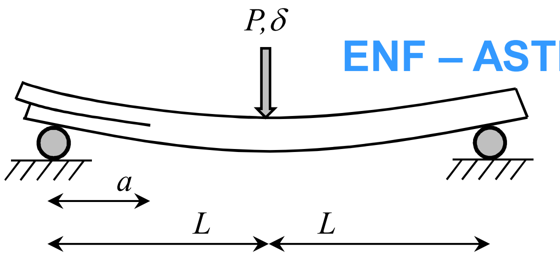


- **Coupon level**
- Test campaign conducted to determine
  - the **intra-laminar** properties => inside the plies
  - the **inter-laminar** properties => at the interface between plies (delamination)
  - Standard testing: set of limited tests to conduct
  - Specific stacking sequences and loading/unloading scenario

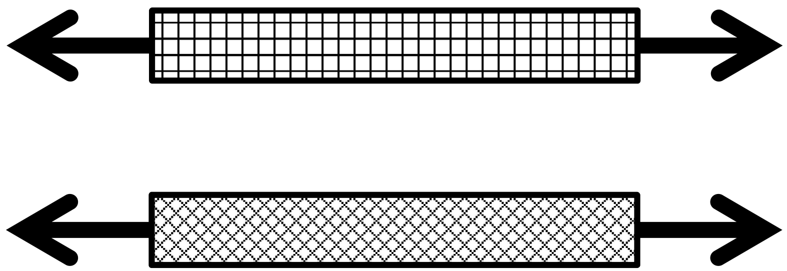
DCB – ASTM D5528



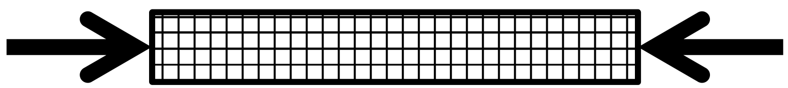
ENF – ASTM 7905



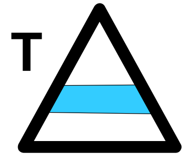
ASTM D3039



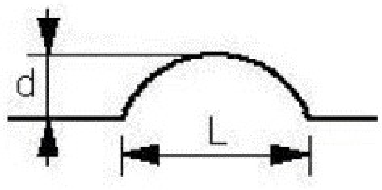
ASTM D6641



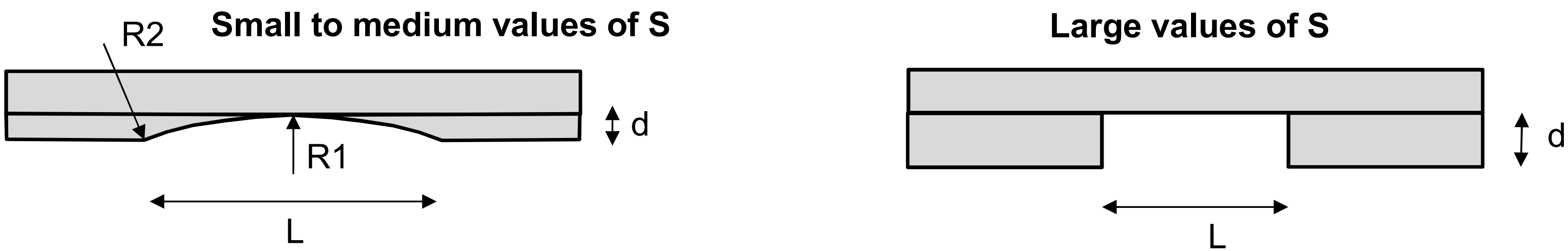
- **Element/detail level**
- Different values of severity S are considered



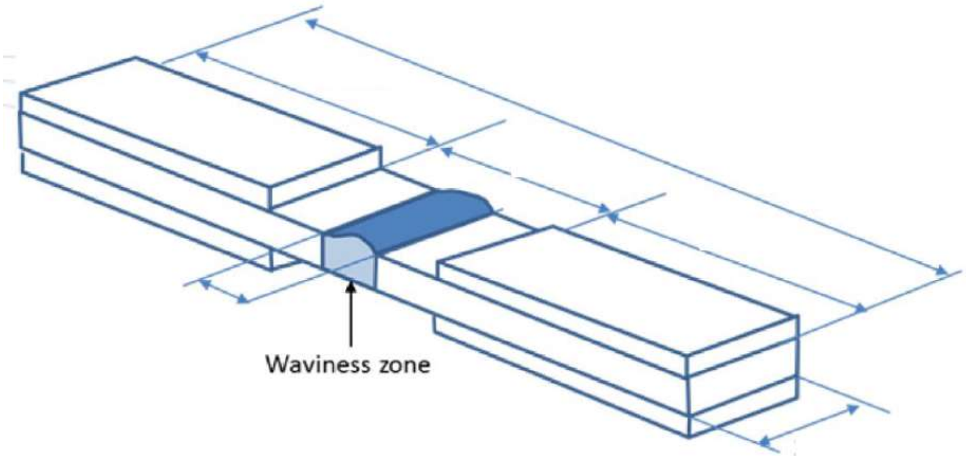
Severity = d/L



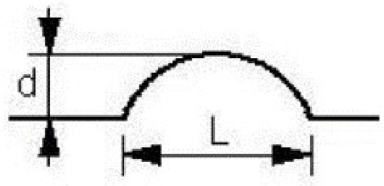
- Relevant specimens were designed and manufactured to reproduce the defect of waviness
  - Specific caul plates were used in autoclave process

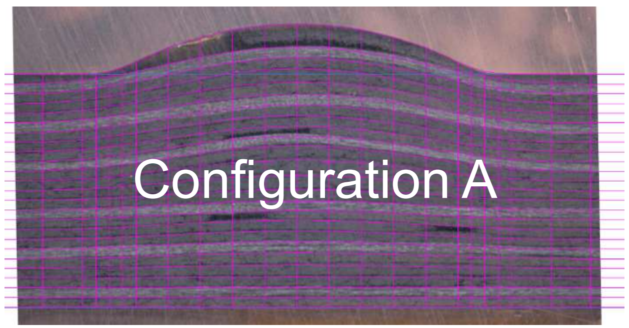


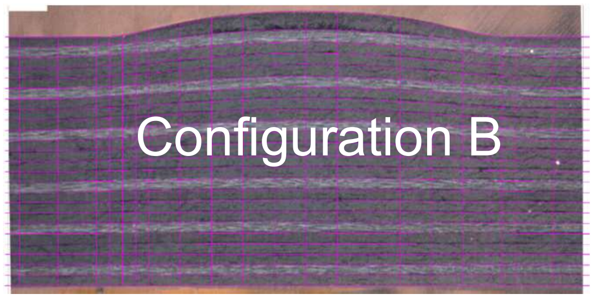
- **Element/detail level**
- Different values of severity S are considered
- 3 configurations are considered + one without defect as reference

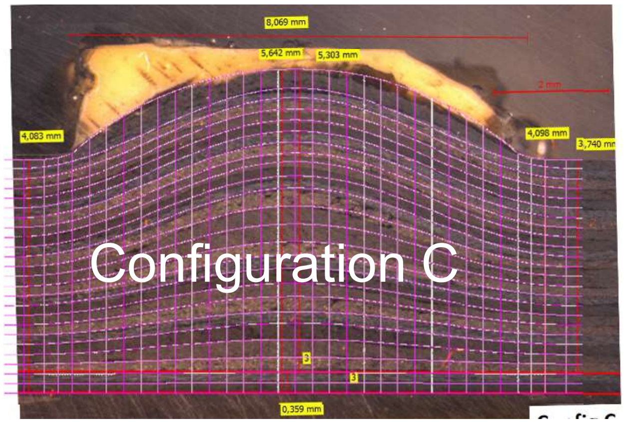


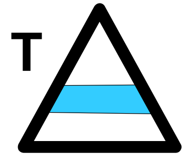
Severity = d/L



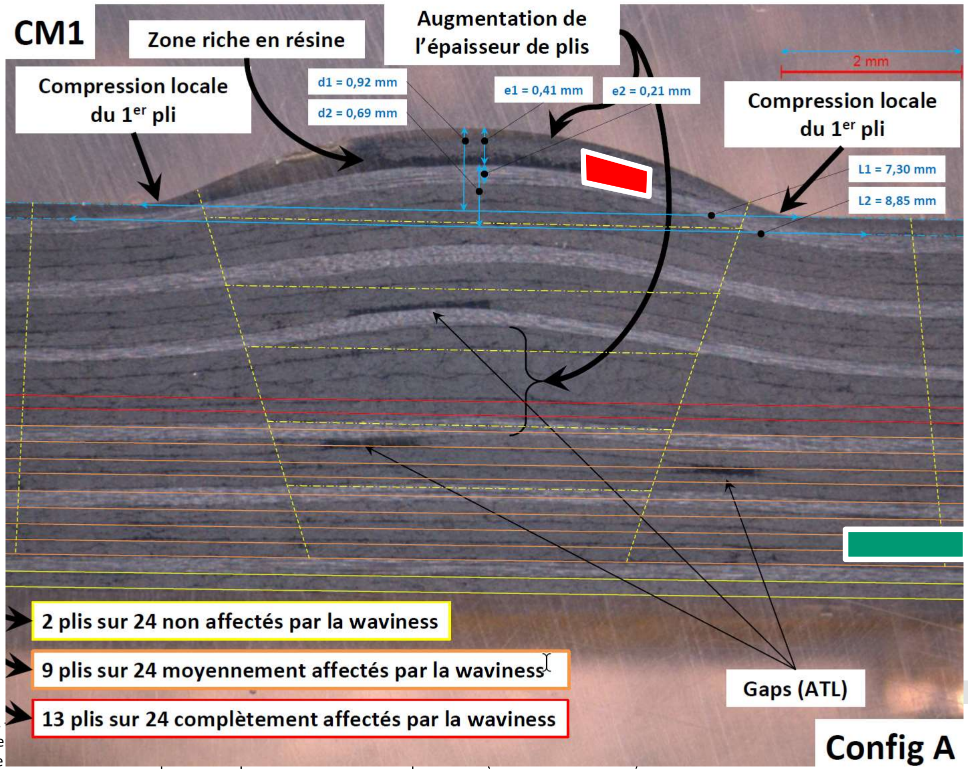




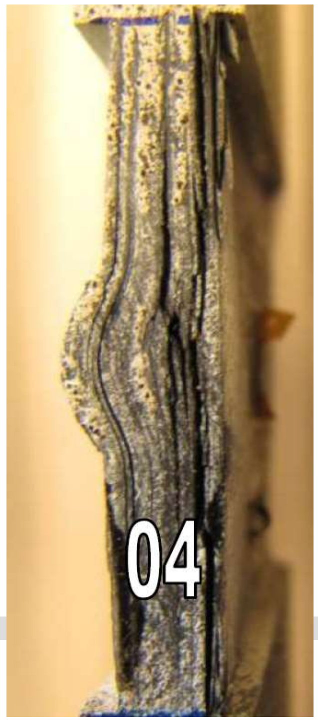




- **Element/detail level**
- Inspections to characterize the defects (real geometry, number of impacted plies, internal defects,…).
- Variations in thickness & Vf (and)
- **Compressive tests** to assess the mechanical performances



AITM 1-0008 B

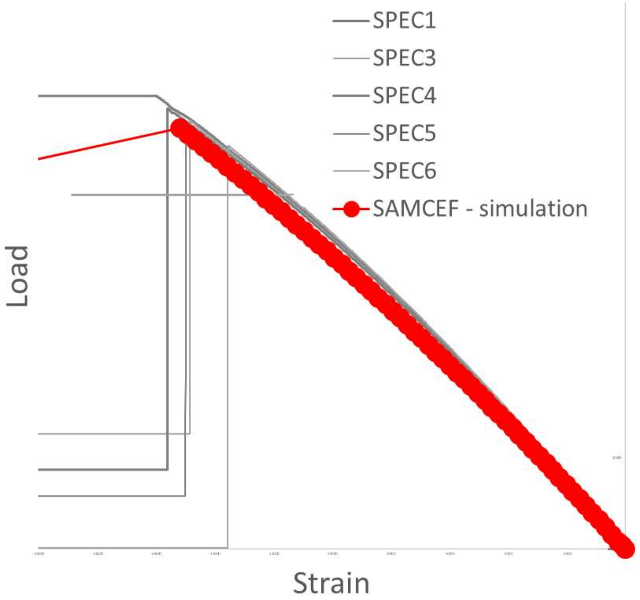


Models and parameters identification

Coupon level

- Intra-laminar properties: Ladevèze model of SAMCEF
- Identification of the model parameters (23 parameters)
- Comparison between tests and simulations for validation
- Here:
  - Tensile test on a $[45/-45]_{ns}$ laminate => shear response
  - Compressive test
  - Simulation can reproduce the physical results => material model validated

Compressive test



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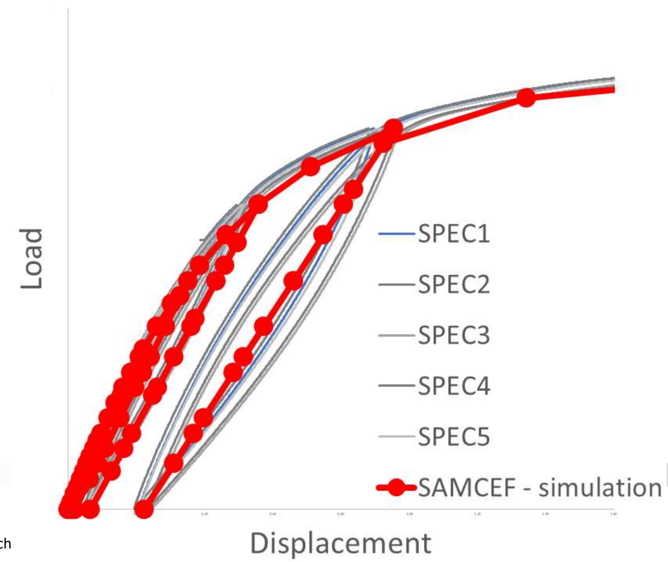
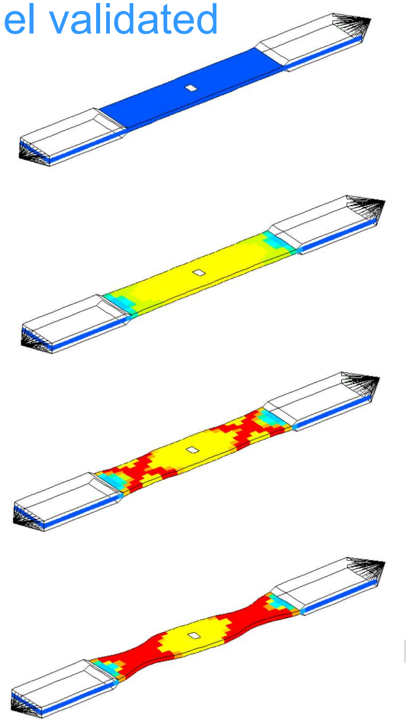
Shear test

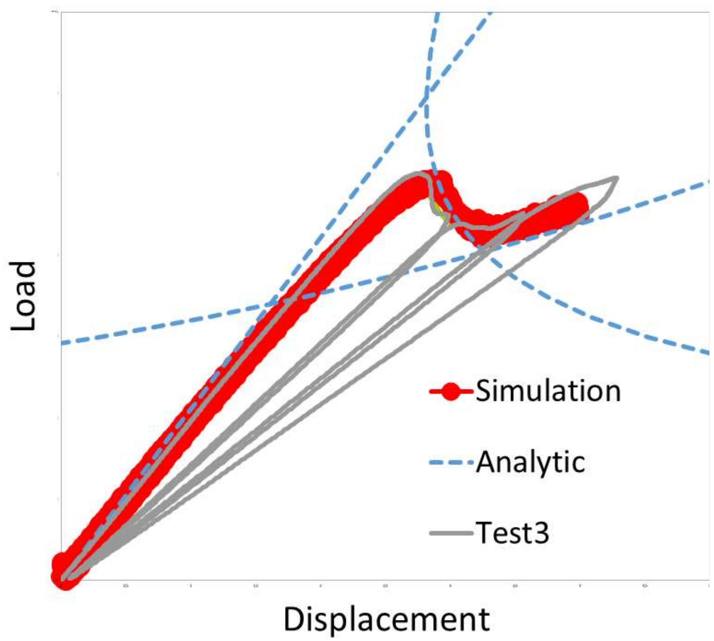




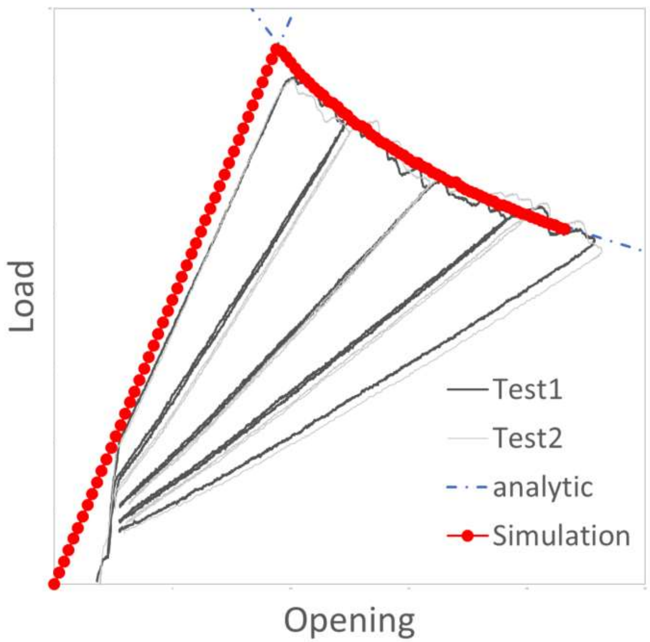
Coupon level

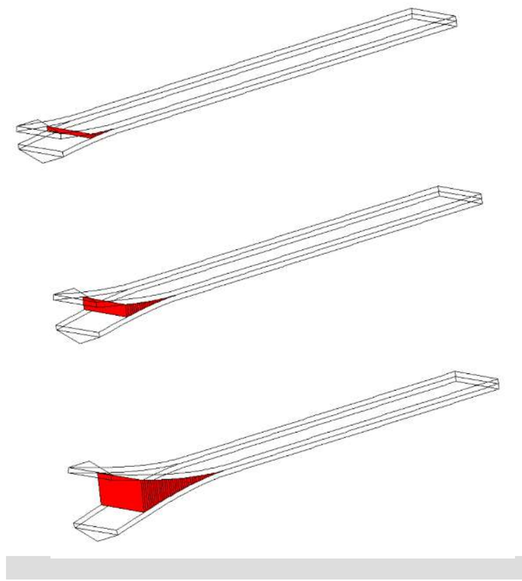
- Inter-laminar properties: Allix and Ladevèze model of SAMCEF
- Cohesive element approach
- Illustration for
  - DCB and ENF: delamination
  - Simulation can reproduce the physical results => material model validated

ENF

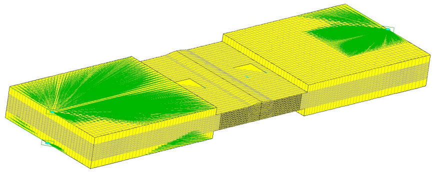


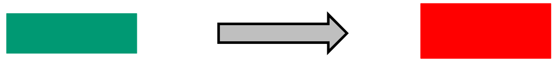
DCB





- Different strategies for modelling the defect
  1. Accurate modelling of the defect
     - To try to have a perfect representation of the defect => 3D solid finite elements
     - Representation of each layer with its own thickness variations
     - Adaptation of the mechanical properties (linked to Vf) for each ply
       - One possible different material and thickness per finite element

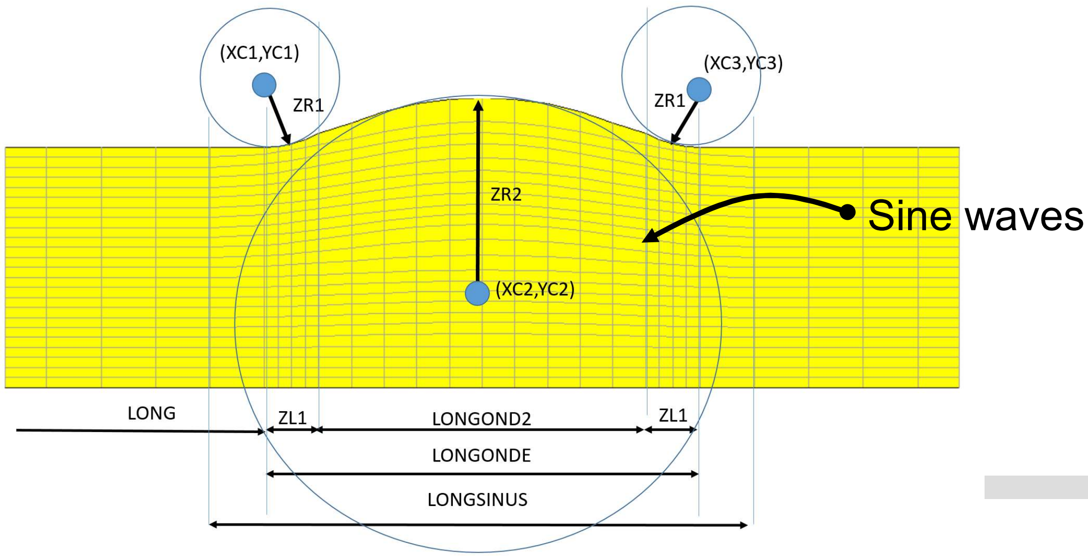




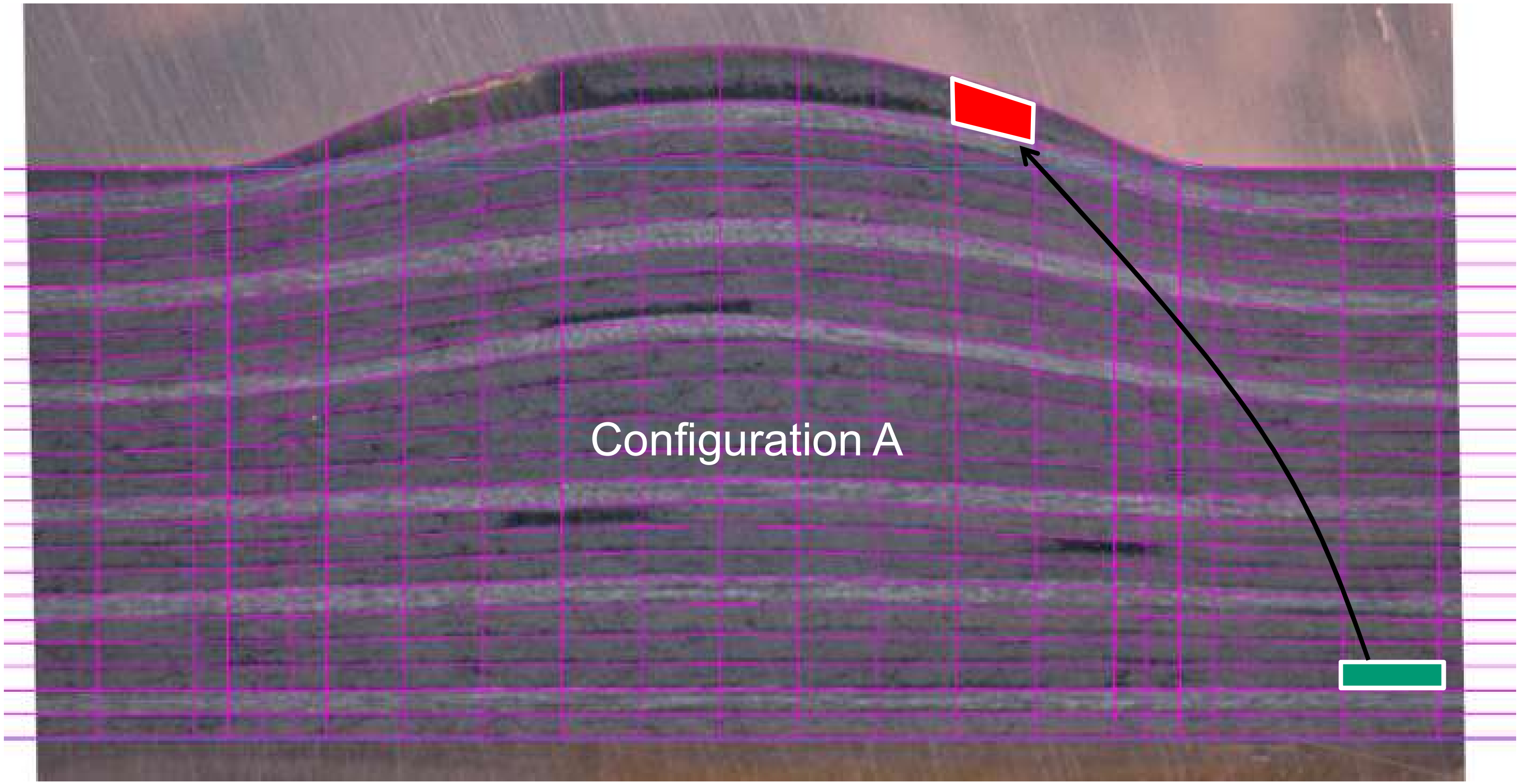
Properties identified for a given thickness and Vf

Values adapted to thickness and Vf

- This approach requires the development of specific meshing capabilities

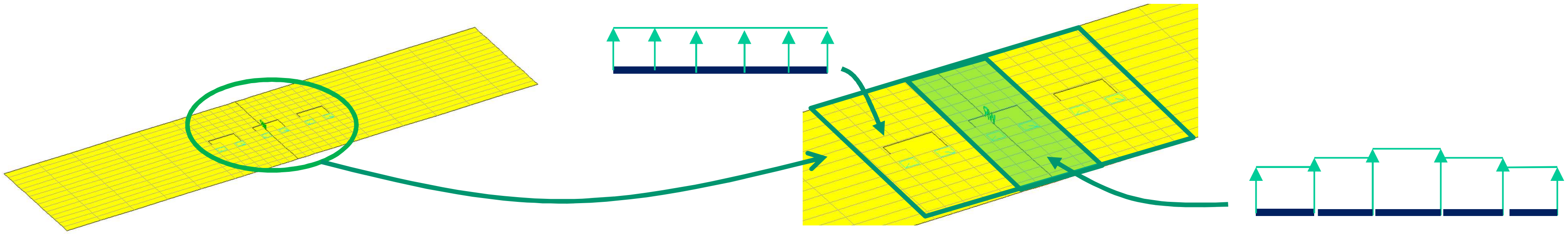


- Different strategies for modelling the defect
  1. Accurate modelling of the defect
     - OK for configurations A and B with arcs and sinus representation
     - Should be improved to have a perfect match for Configuration C (too large defect)

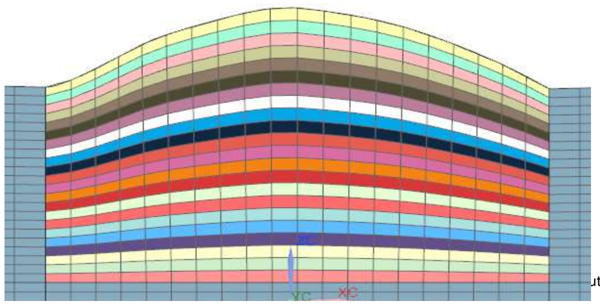


- Different strategies for modelling the defect

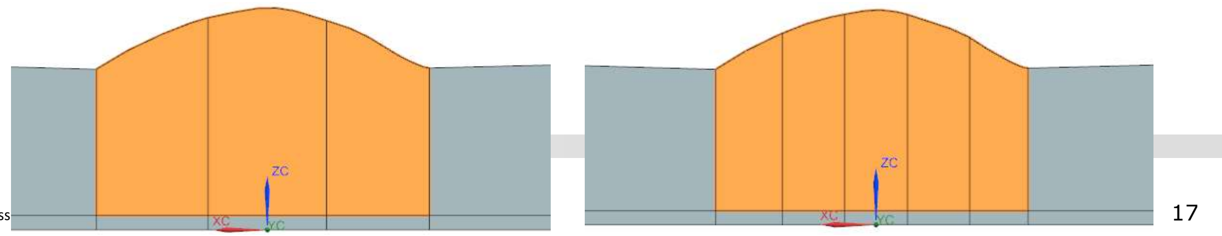
2. Simplification of the previous accurate model: shell modeling
   - For fast computation
   - Use of shell finite elements (2D representation of the specimen, with variable thicknesses)
   - No modelling of the interfaces between the plies => possible delaminations not considered



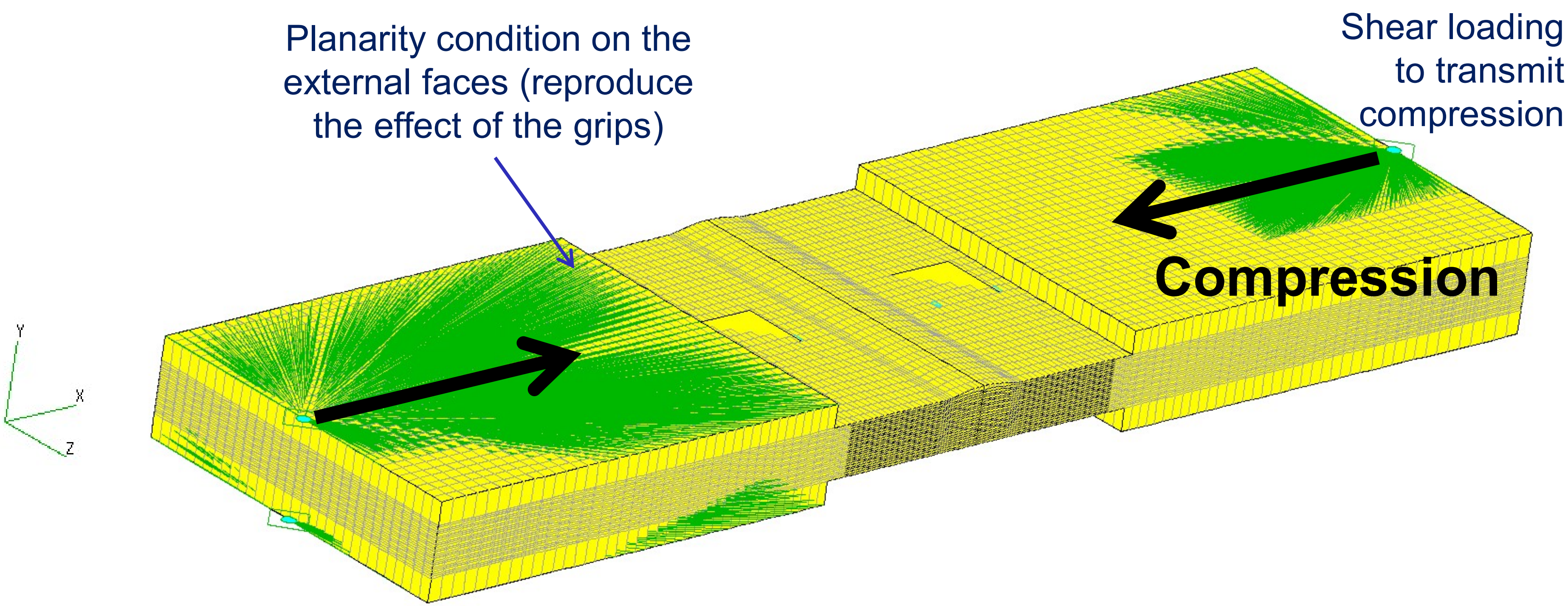
3. Fast 3D representation in a user friendly interface
   1. Fast modelling: Simcenter environment
   2. Assumption in terms of the repartition of the internal geometries of the plies
   3. Assumption in terms of equivalent fiber volume fraction for each ply



One different material per vertical position

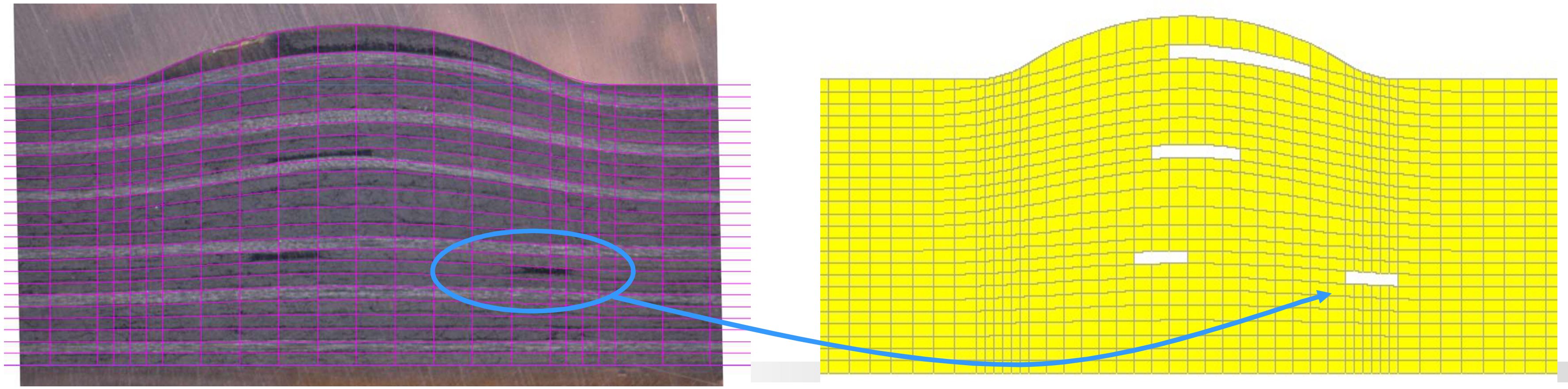


- Results for Strategy 1 (accurate geometrical representation of the defect – 3D solid finite element model)
  - Problem characteristics and FEM model size
    - Quasi-isotropic specimen with 24 plies made up of 0°, 45°, -45° and 90° plies
    - Around $2x10^6$ degrees of freedom; computation on 4 processors; elapsed time around 7h



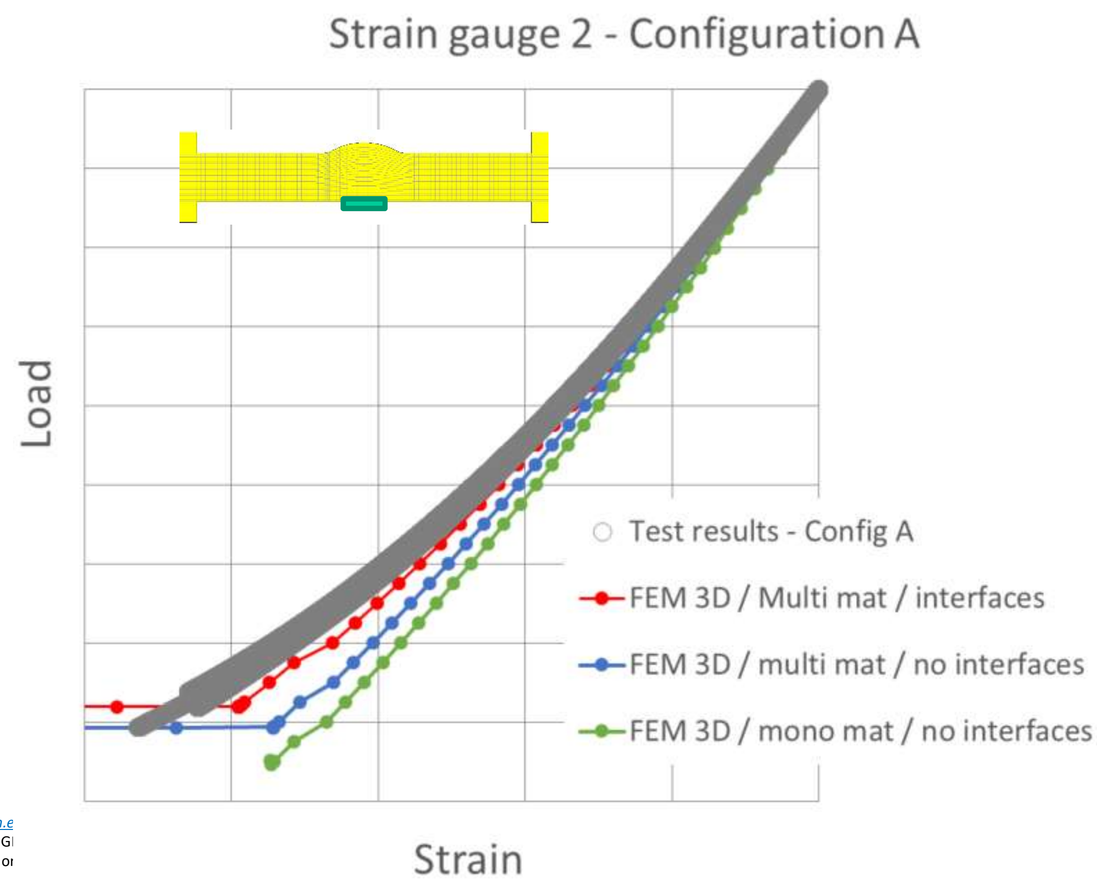
Comparison between tests and simulation

- Results for Strategy 1 (accurate geometrical representation of the defect – 3D solid finite element model)
  1. The parameters of the material models determined at the coupon level are used here
  2. Different strategies are applied on Configuration A for validation of the modeling
     - Correct local thickness but unique set of material properties
     - Correct local thickness and material properties adapted wrt thickness & Vf
     - Correct local thickness and material properties adapted and delamination
     - Effect of some internal defects: illustration with resin rich regions



Comparison between tests and simulation

- Results for Strategy 1 (accurate geometrical representation of the defect – 3D solid finite element model)
  1. Correct local thickness but unique set of material properties
  2. Correct local thickness and material properties adapted wrt thickness & Vf
  3. Correct local thickness and material properties adapted and delamination

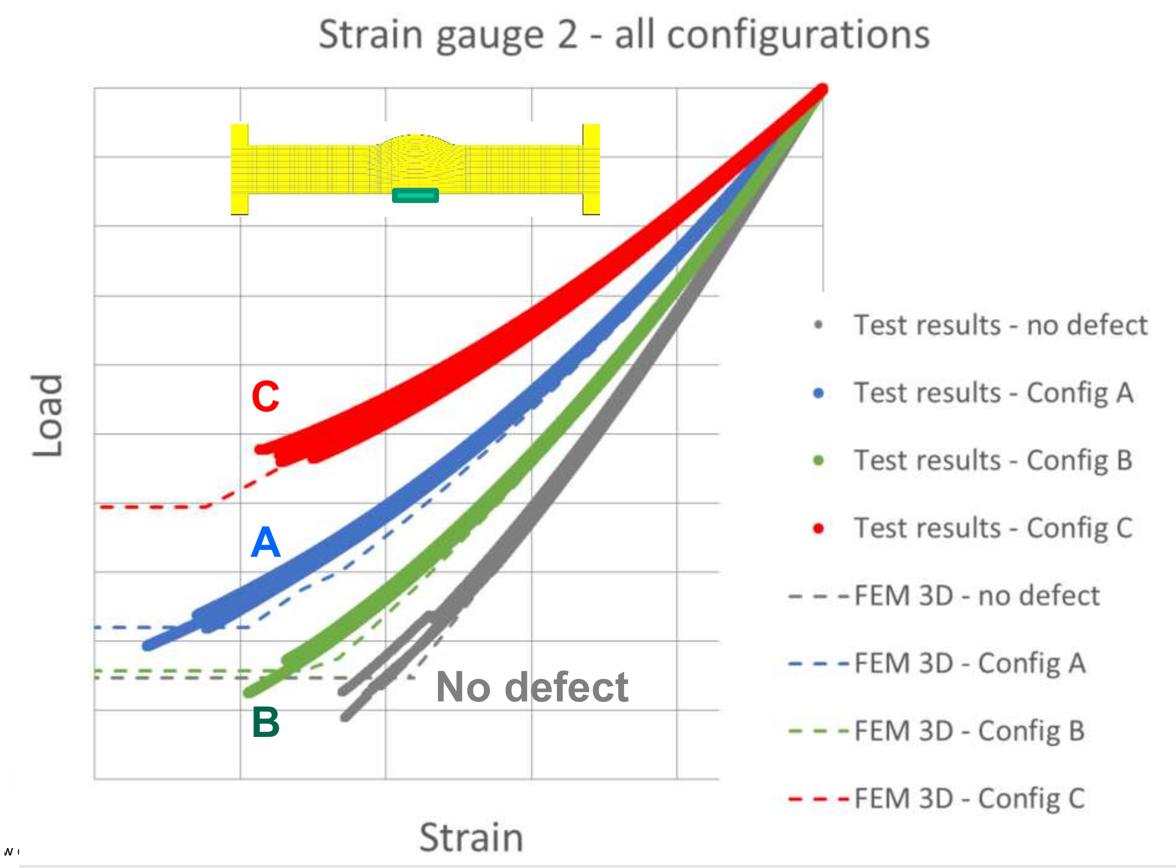


Comparison between tests and simulation

- Results for Strategy 1 (accurate geometrical representation of the defect – 3D solid finite element model)
  - Modeling strategy now used for Configurations B, C and “no defect”

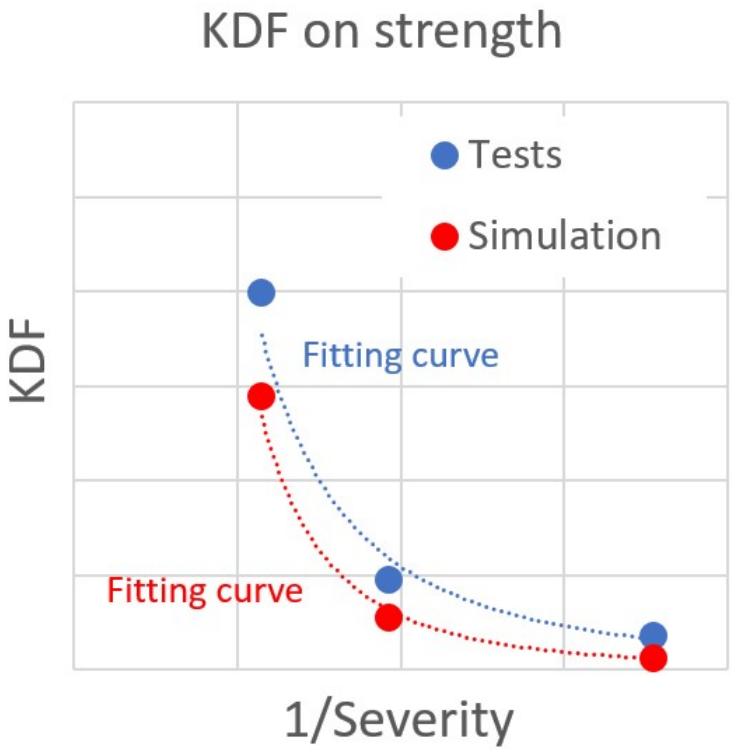
<u>Analysis of the results:</u>

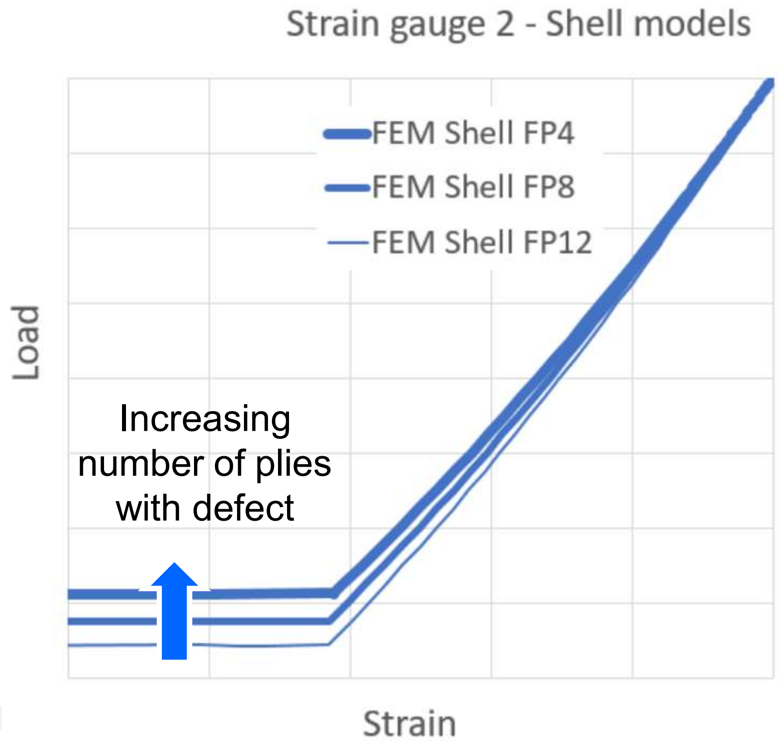
- Stiffness
  - Non linear stiffness well represented for all the configurations
- Strength (final failure)
  - Loss of accuracy on the prediction with an increase in the defect thickness
  - Max error is 15% for Configuration C (not conservative)
- Possible causes of inaccuracy
  - Too many internal defects in thick defect, not modeled
  - Adaptation of identified material properties no longer accurate enough
  - Need to improve meshing for good geometric representation



Comparison between tests and simulation

- Results for Strategy 1 (accurate geometrical representation of the defect – 3D solid finite element model)
  - Prediction of material allowables
  - Sensitivity analyses wrt defect thickness, stacking sequence, severity,…conducted with simulation
    - in practice done with shell models to save CPU time – 30’ instead of 7h





Conclusions

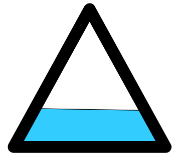
- The defect of waviness was studied
- Specimens were designed to reproduced the defects, with different severities
- Compression tests were conducted
- Finite element models were developed, with different levels of fidelity for the representation of
  - the defect geometry
  - the material inside the defect
- For the results presented here (3D accurate model only):
  - the non linear stiffness behavior is well represented by simulation
  - the strength is well estimated except for very thick defects (max error of 15%)
- The possible reasons for inaccuracy should be investigated
  - e.g. test coupons with different Vf and thickness for model parameter ID

Acknowledgement

- The results presented here were obtained in the frame of the **SW_TECCOMA** project.

- The authors acknowledge the support of Wallonia (DGO6) and Skywin

Back up slides



Coupon level

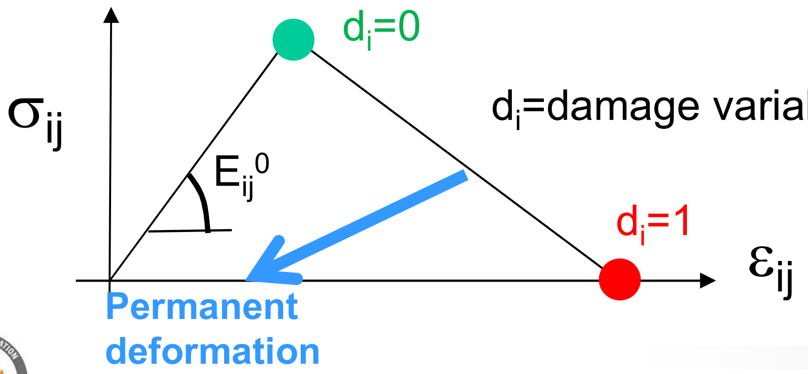
- Coupons with nominal ply thickness and Vf
- Intra-laminar properties: Ladevèze model of SAMCEF

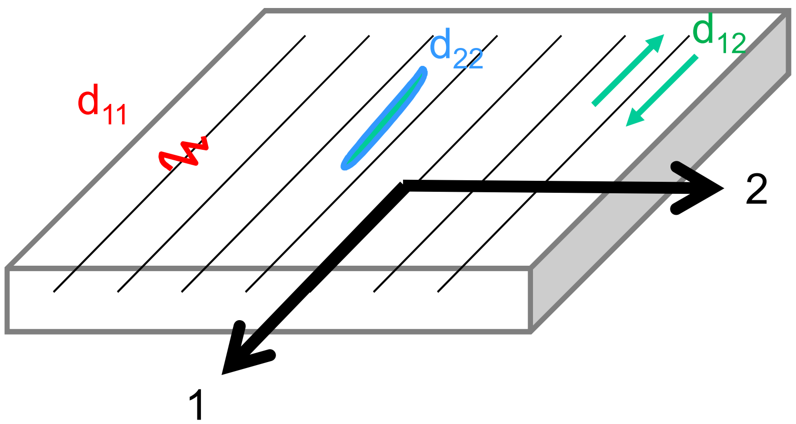
$$e_d = \frac{\sigma_{11}^2}{2E_1^0} - \frac{\nu_{12}}{E_{11}^0}\sigma_{11}\sigma_{22} + \frac{\sigma_{22}^2}{2E_2^0} + \frac{\sigma_{12}^2}{2G_{12}^0}$$

↓ Damage variables d_{11}, d_{12}, d_{22}

$$e_d = \frac{\sigma_{11}^2}{2(1-d_{11})E_1^0} - \frac{\nu_{12}}{E_{11}^0}\sigma_{11}\sigma_{22} + \frac{\sigma_{22}^2}{2(1-d_{22})E_2^0} + \frac{\sigma_{12}^2}{2(1-d_{12})G_{12}^0}$$

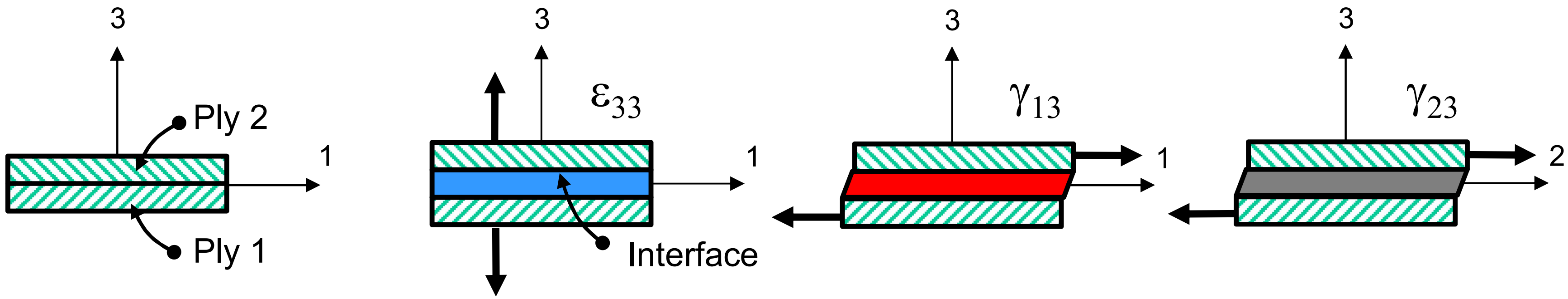
Material behavior inside the ply





Coupon level

- Inter-laminar properties: Allix and Ladevèze model of SAMCEF
- Cohesive element approach
  - Modeling of the interfaces between the plies
  - Damage may appear in the interfaces => modelling of delamination



$$2e_d^i = k_I^0\langle\epsilon_{33}\rangle^2 + k_I^0(1-d_I)\langle\epsilon_{33}\rangle_+^2$$
$$+ k_{II}^0(1-d_{II})\gamma_{13}^2$$
$$+ k_{III}^0(1-d_{III})\gamma_{23}^2$$

Material behavior inside the interface