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Out-of plane deformation of fabrics (and prepregs) in resin infusion (and autoclave) processes

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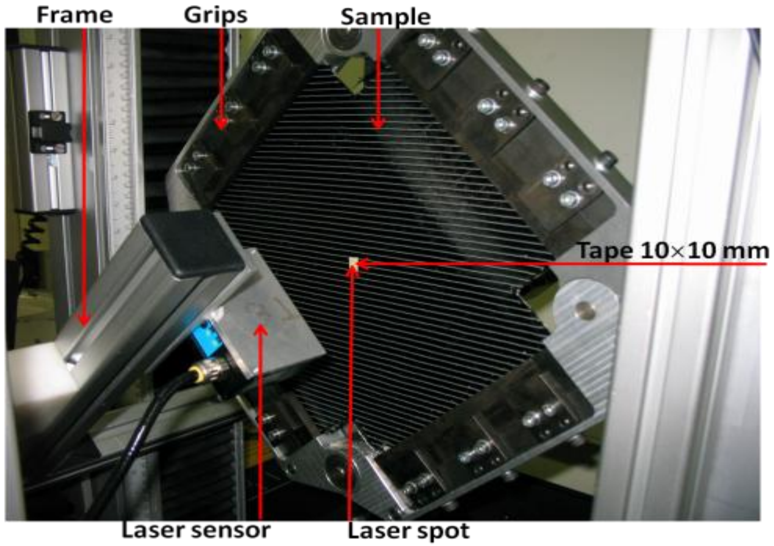
Outline

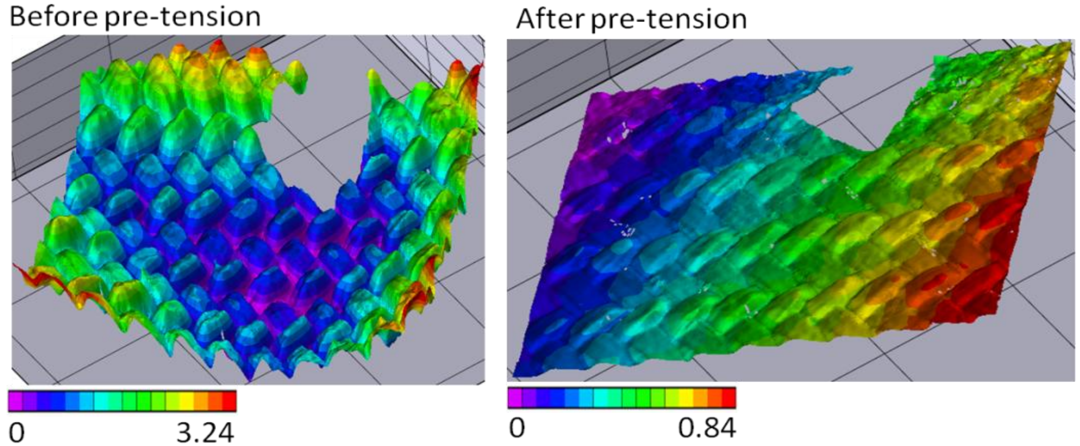
- Resin infusion: thickness of draped material? Autoclave: thickness control?
  - *Problem statement and project framework;*
- Measurements of fabric thickness evolution during draping (shear deformation)
  - *Picture frame tests and laser in-situ thickness measurements;*
- Compression of sheared fabrics (experimental simulation of resin infusion pressure)
  - *1-ply and multi-ply stacks, nesting, limit fabric thickness;*
- Modelling of the fabric compaction
  - *Yarn compression testing with in-situ width evolution measurements*
  - *Geometrical and FE models and constitutive relations;*
- Compaction of prepregs: experiments and modelling
  - *The need for a non-conventional modelling and visco-elastic extrusion model*
- Conclusions, future activity

Thickness evolution while draping

Picture frame with laser distance sensors:

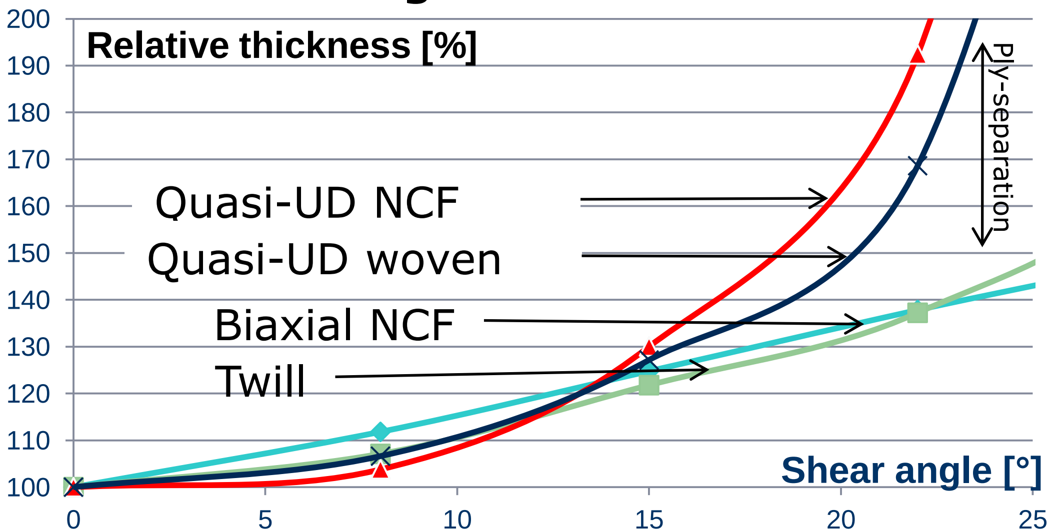


Fabric clamping (0.1-0.2% deformation):

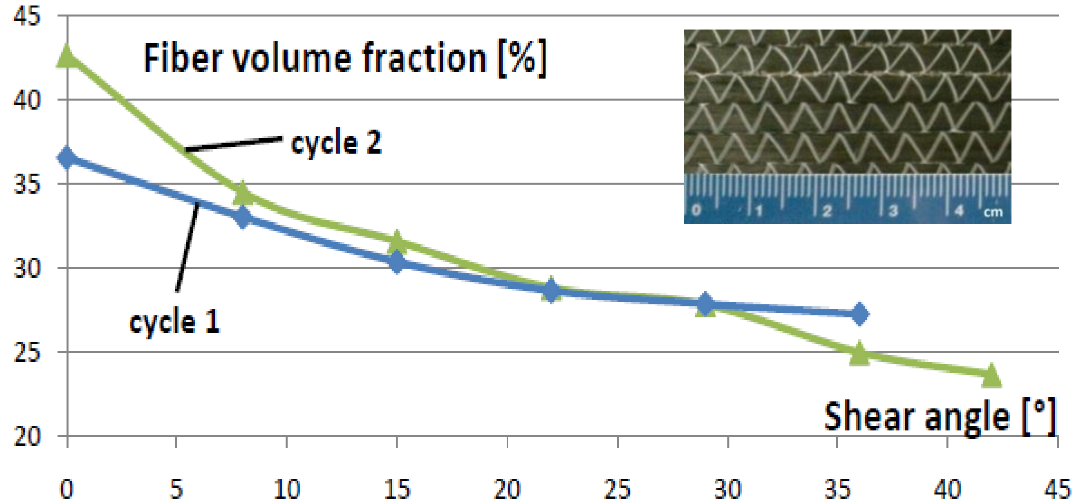


Displacement profiles of twill fabric by DIC

Fabric thickening:



Fibre volume fraction drop (NCF fabric):



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Draping leads to substantial thickening and drop of the fibre volume fraction (2 times at 40°)

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Textile deformation mechanisms

✓ *Substantial hysteresis and cycle dependence*

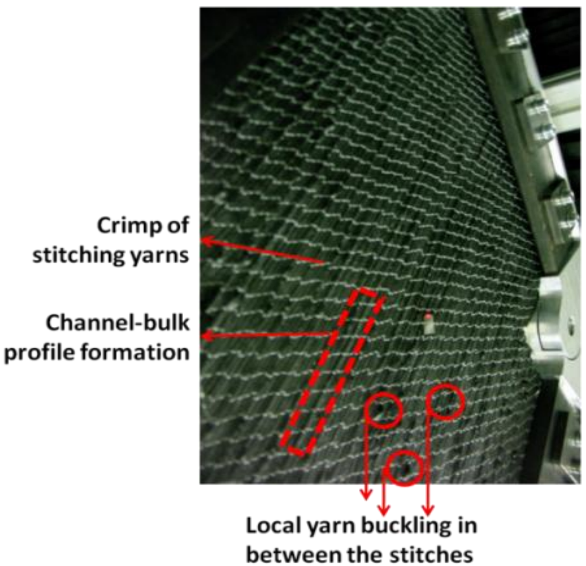
✓ *Compression/buckling of the stitching yarns*. The shearing causes buckling of the stitching yarns and the regrouping the carbon fibre bundles

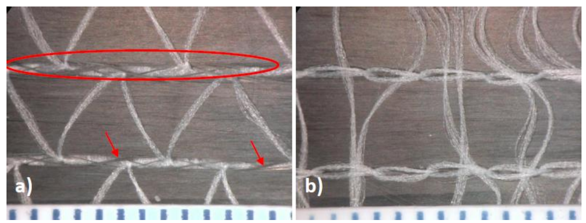
✓ *Formation of channels* and bulk profiles

✓ *Significant role of the binder*

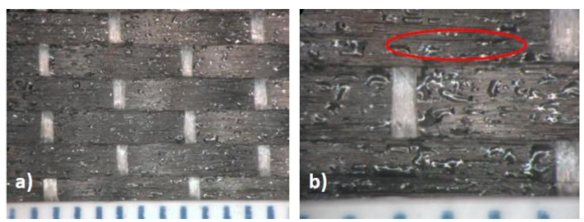
✓ *Possible damage of the sizing* due to the yarn contact and the evolution of inter-yarn, inter-fibre friction

✓ *Reorientation of the fibres in the grips of PF and pretension decay*



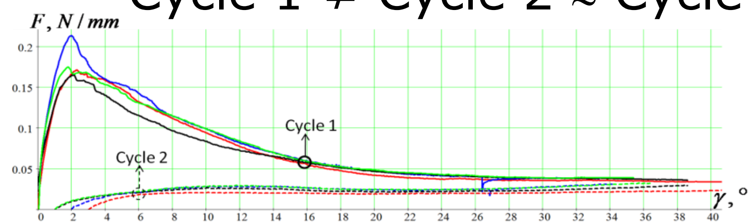


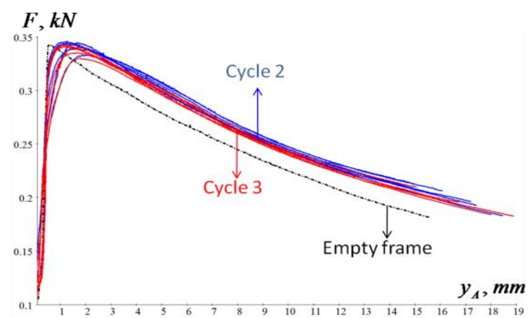
Before and after deformations



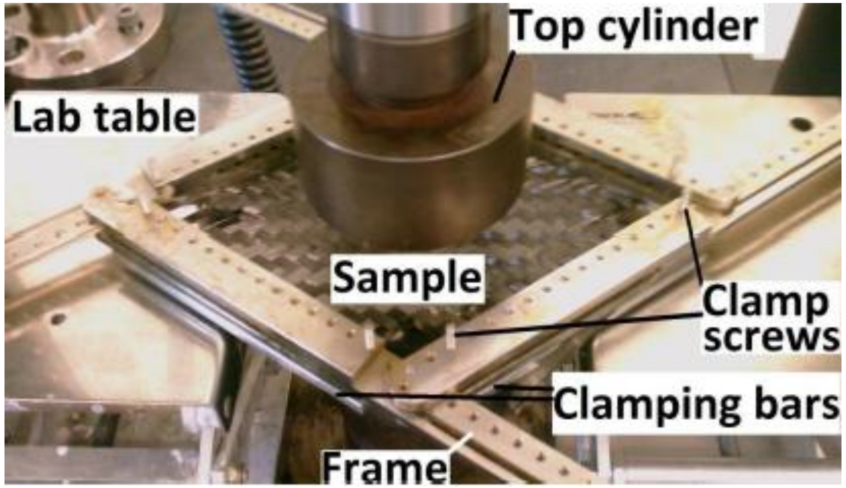
Binder is seemingly intact

Cycle 1 ≠ Cycle 2 ≈ Cycle 3





Thickness evolution while compression



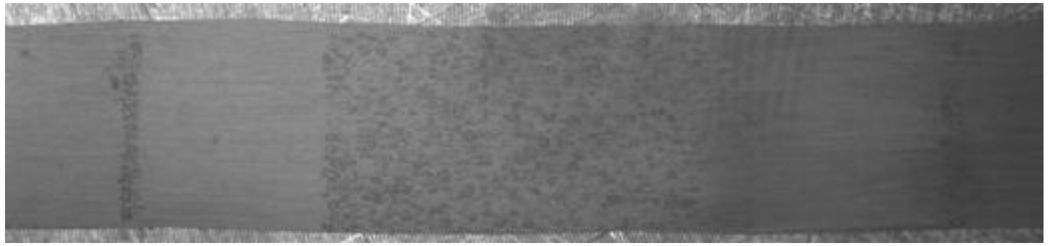
Compression of sheared fabrics

The fabrics are sheared to a predefined angle in the rigid frame

After shearing the frame is fixed by screws

The fabrics are placed on the rotating platform and compressed in the through-thickness direction

One ply and two ply stacks are tested



Compression of yarns with measuring widening

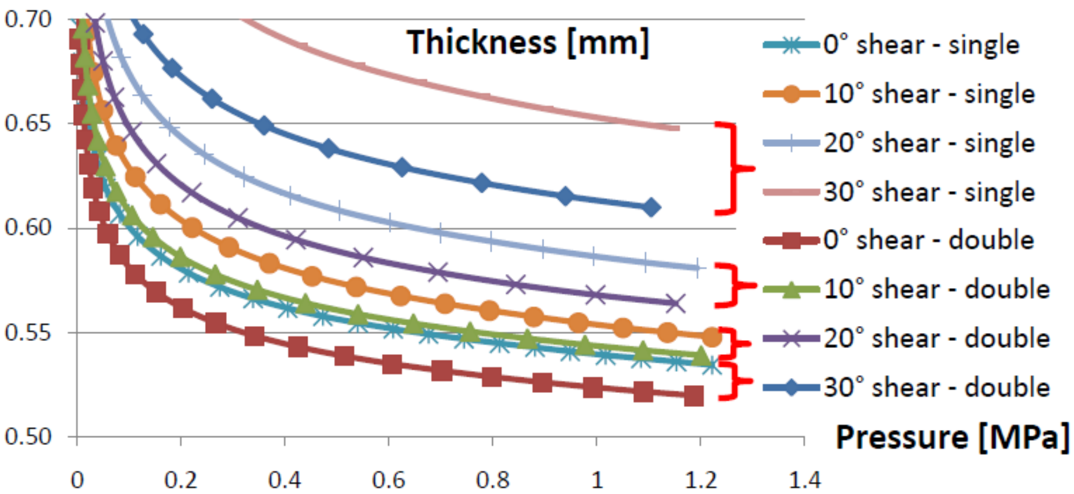
The test is performed on a glass platform – yarn widening is watched through the bottom glass

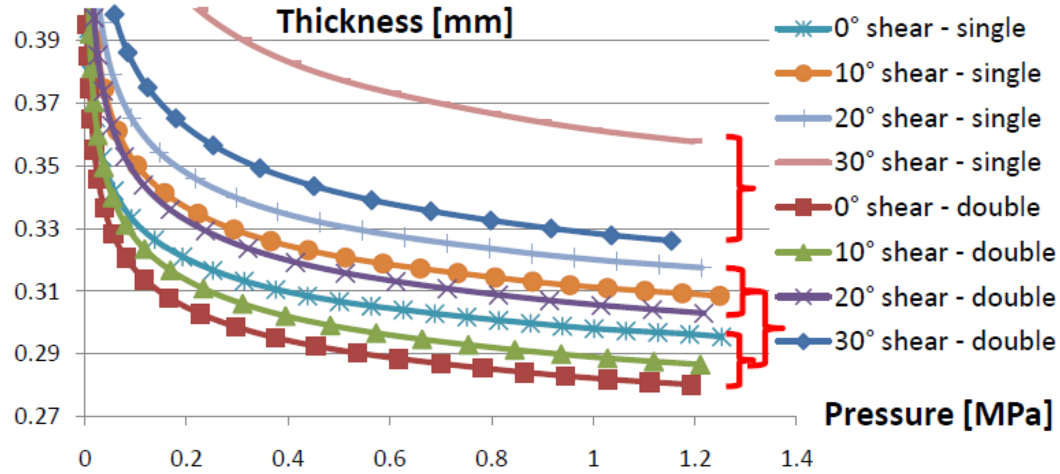
The transverse strain is processed via digital image correlation. The binder creates a sufficient speckle pattern.

The yarns are directly extracted from the fabrics.

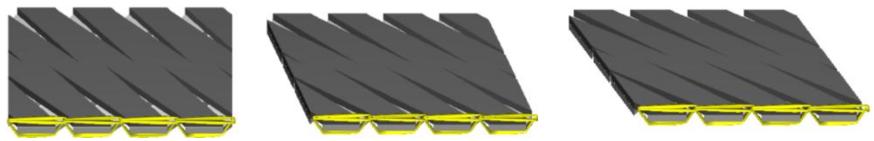
The yarns are tested with and without slight pretension.

Compaction and nesting effects

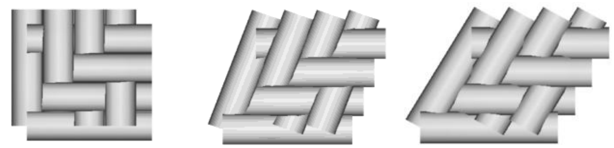




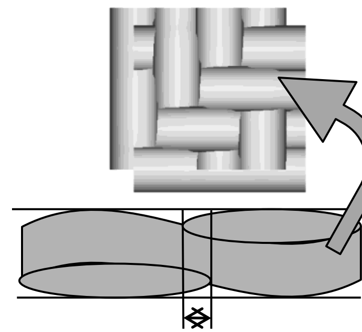
Biaxial NCF



Twill

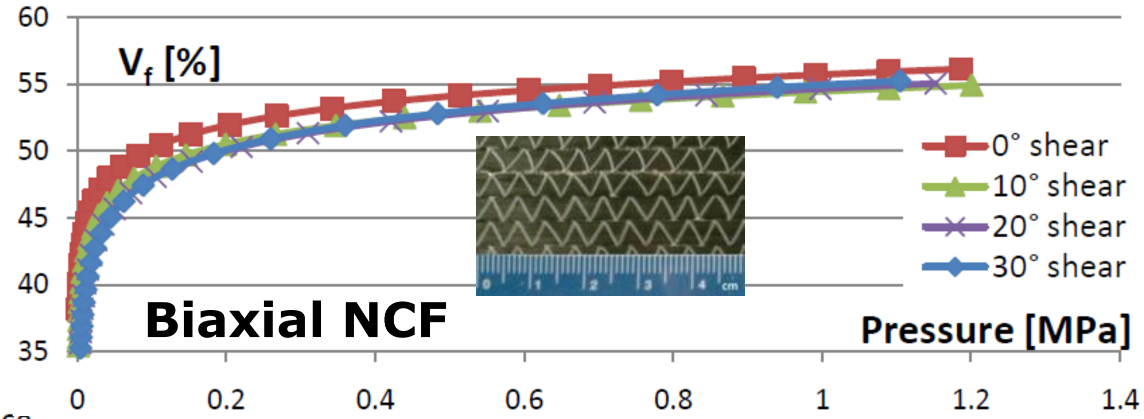


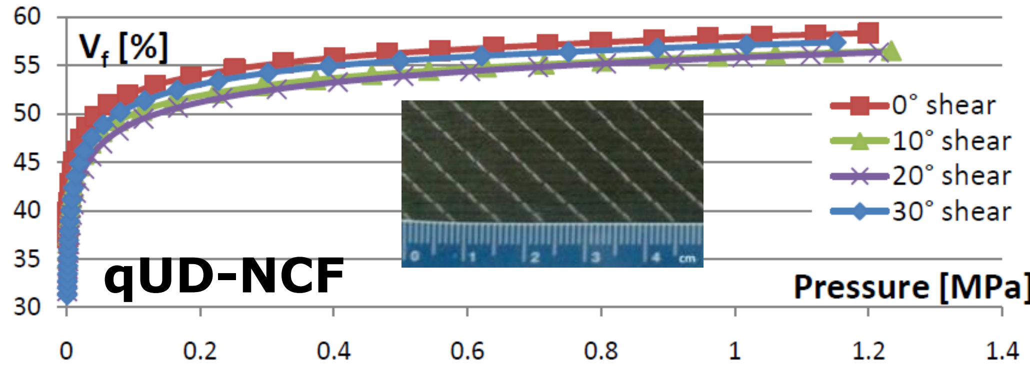
- NCF (one ply): 20% increase of the limit thickness. Twill (one ply): >50%
- Substantial nesting: 10% fibre volume fraction is added
- Higher nesting at large shear angles. Higher nesting for the twill than for the NCF
- A complex yarn interaction needs to be described. The limit thickness is not just the yarn limit thickness*2

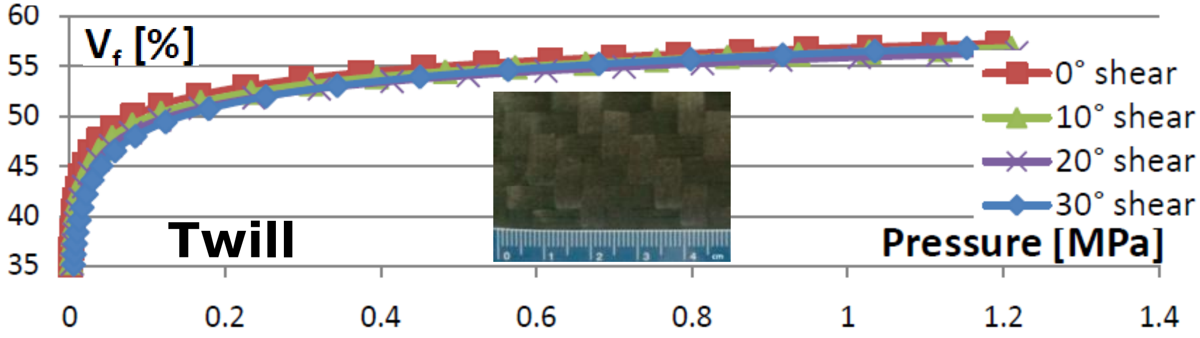


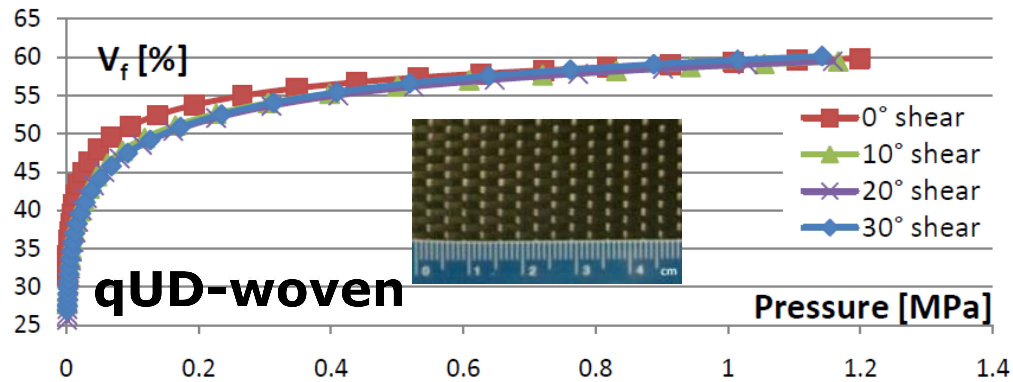
3 yarns over each other

Volume fraction evolution (single ply)





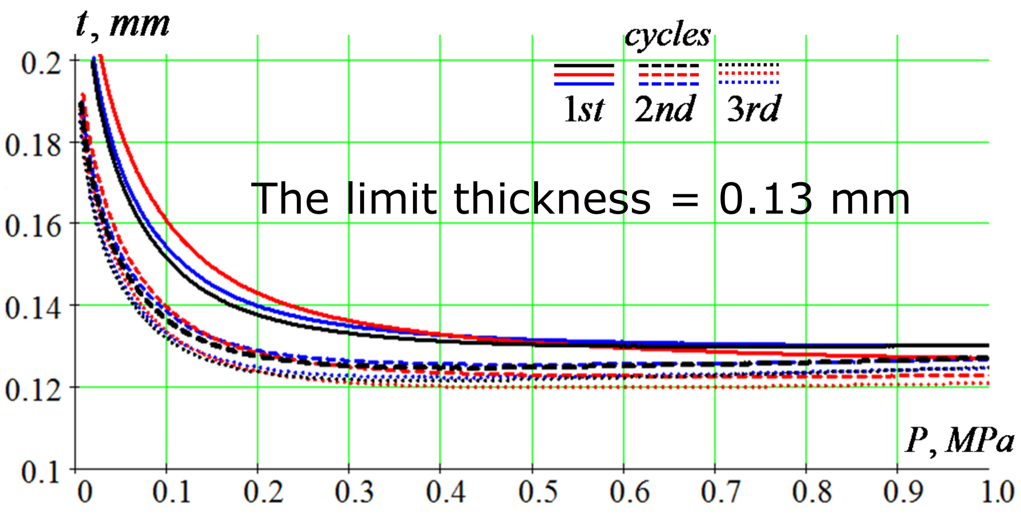




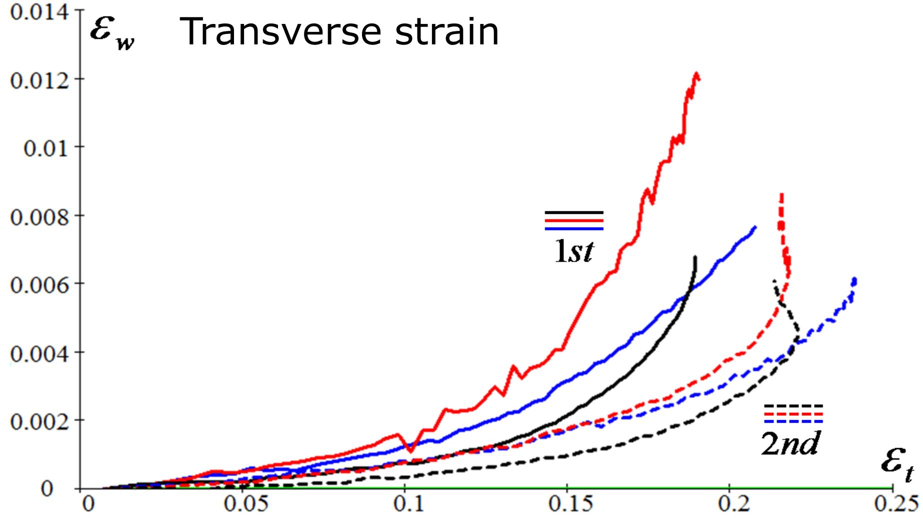
- The limit thickness of the compressed fabrics is dependent on the fabric architecture
- The limit fibre volume fraction is in more narrow range: 55-60%. Almost independent on the shear angle (within the experimental scatter).

Yarn compaction and widening

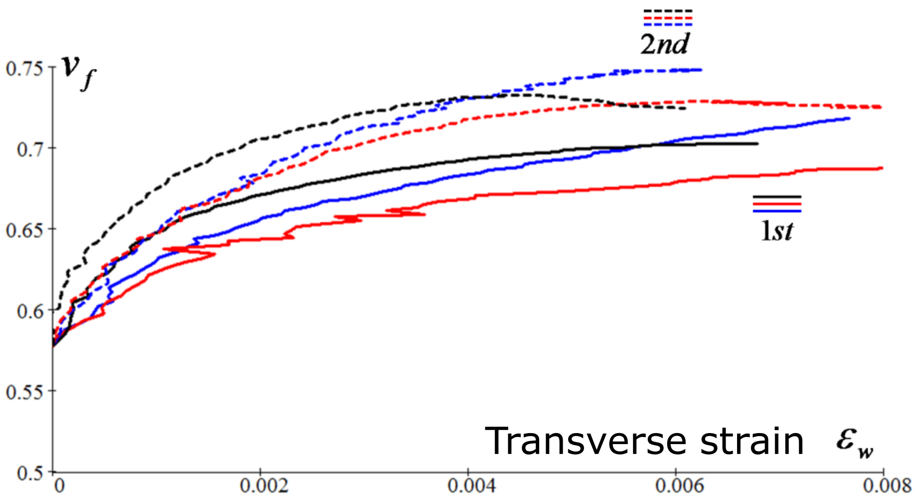
The thickness-pressure dependence:



Yarn widening:



Fibre volume fraction evolution:

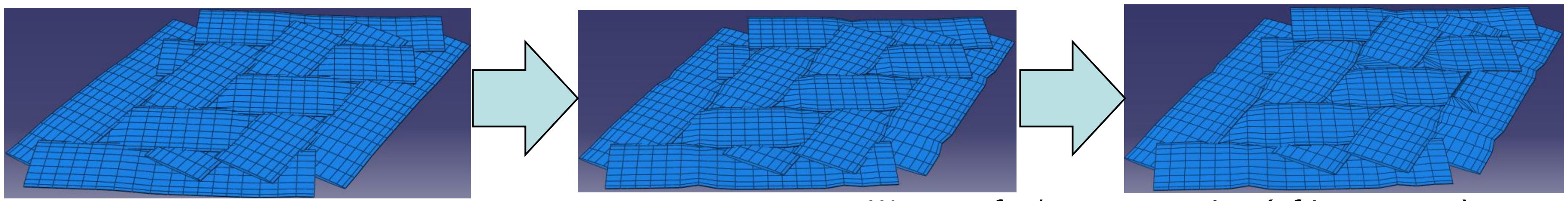


- Yarn widening is about 1% at the limit thickness (an effect of the yarn twist)
- Slight pre-tension does not affect the measurements
- The material behaviour is cycle dependent. The second cycle = input for a hypo-elastic material model

Simulations of fabric behaviour

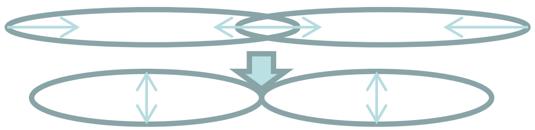
WiseTex: approximate model of fabrics based on yarn energy minimization – constant yarn cross-section shape.

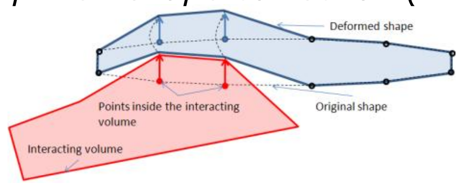
Preprocessor script (Python): *automatic* geometric adjustment of yarn shapes, input for Abaqus



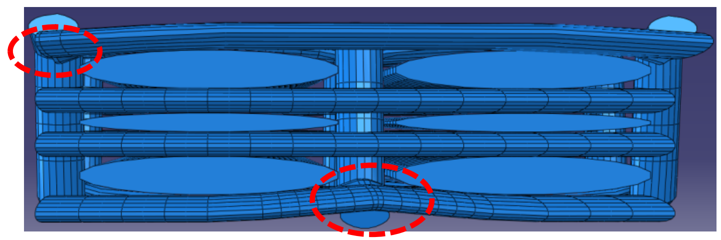
Lateral warp-warp weft-weft adjustment (vf is constant)

Warp-weft shape correction (vf is constant)





Resultant tool can operate with rather complex cases including 3D fabrics



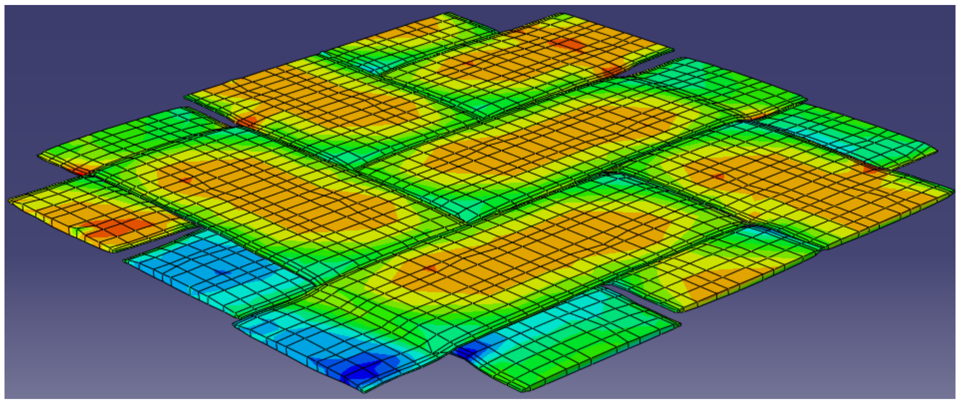
Simulations of fabric behaviour

User-defined hypo-elastic material model, which traces the local fibre directions and rotates the material frame (B.Hagege).

Numerical challenges related to almost asymptotic hardening of the transverse yarn stiffness when approaching limit fibre volume fraction

Fundamental challenges related to highly uncertain initial thickness: the strain needs to be defined with respect to the final thickness but not initial thickness

Simulations of the contact problem in explicit formulation (Abaqus).
State of the art: preliminary results



Displacement in the through-thickness direction

Compaction of prepregs

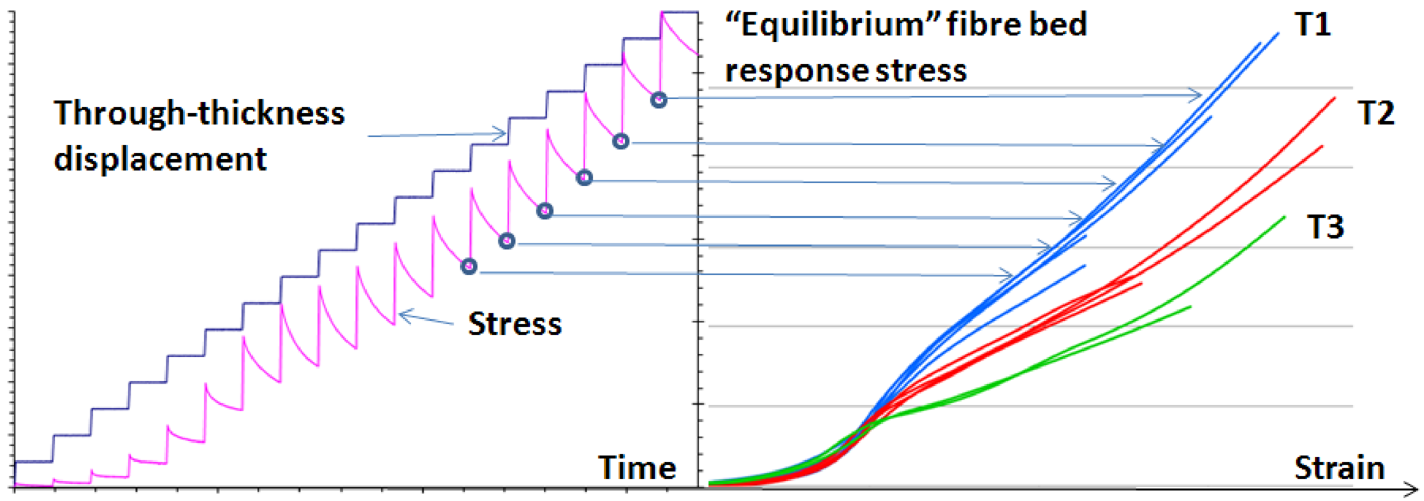
The purpose of the compaction is a control of the material thickness and the fibre volume fraction *prior* to autoclaving

Needed: to choose an optimum regime (temperature-pressure-speed), at which the maximum fibre volume fraction can be achieved

The conventional approach to analysis: to distinguish the elastic fibre bed and the visco-elastic matrix responses by means of step-wise ramp-dwell loading

It does not work for highly viscous (toughened) resins: no equilibrium state.

A non-conventional meso-model is needed to describe the higher rates and longer times for relaxation at higher loads



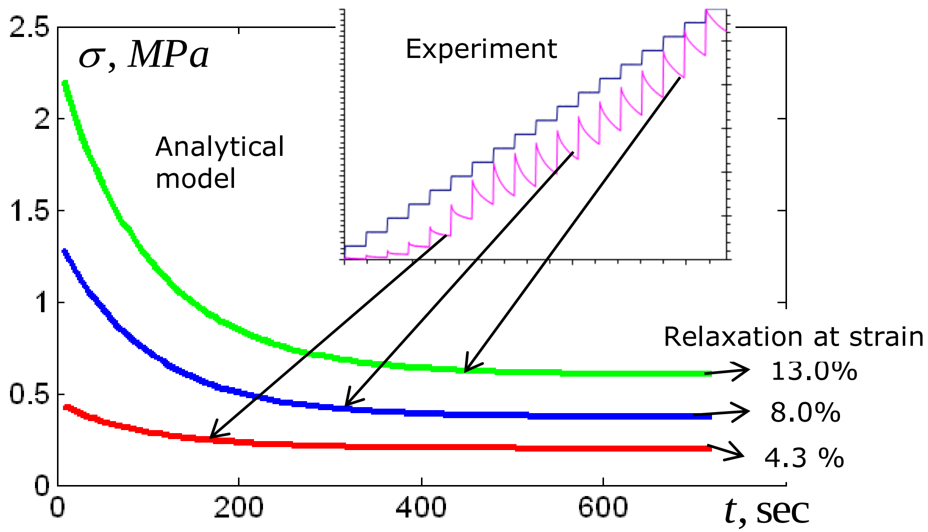
Viscoelastic model with extrusion

The physical reason for this effect = the resin extrusion. Needs to be accounted for! Considering squeezing flow in fibre reinforced uncompressible liquid gives the following:

$$\eta k \frac{\dot{\varepsilon}}{(\varepsilon+1)^n} = \sigma$$

where *k*- non-dimensional geometrical parameter, *n* – depends on type of a contact:

n=0: classical viscous element;
n=1: zero friction constant, contact zone is constant;
n=2: zero friction, zone evolves;
n=3: no-slip contact, zone is constant;
n=4: no-slip contact, zone evolves.



New model adapts the extrusion element instead of the viscous element

An analytical solution is found for the UD with the zero-friction constant-size contact.

The relaxation is described qualitatively correct: the model predicts an increase of the relaxation rates at high deformation levels.

Conclusions

Resin infusion:

- The initial thickening of the fabric while draping is substantial: up to 100% at 30°. A similar trends for all the fabrics. Accompanied by the fibre distortions. Fibre volume fraction drops.
- Out-of plane compression: a strong dependence of the limit thickness on the fabric pattern, the shear angle, and the nesting.
- Sheared fabrics have worse compressibility but there is a higher degree nesting for them. Woven fabrics = higher nesting.
- No direct relation between the through-thickness behaviour at the two stages: draping (shear) – compaction.
- A tool for the meso-scale modelling has been built and a good set of data for model validation is ready.

Autoclave:

- The compaction potential is governed by competing processes of resin extrusion and stress relaxation of the viscous resin
- A new model of visco-elastic extrusion is introduced. It describes correctly evolution of the relaxation rates in the course of loading