Accurate characterisation and modelling of the nonlinear bending behaviour of non-crimp fabrics for composite process simulations

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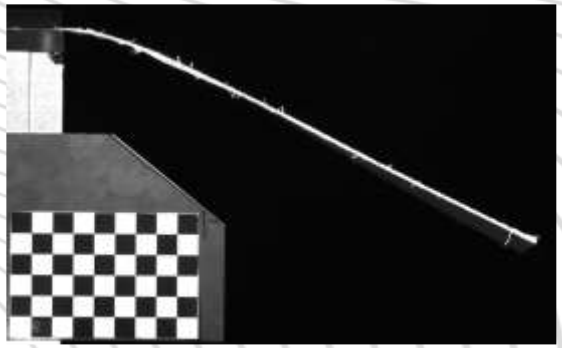
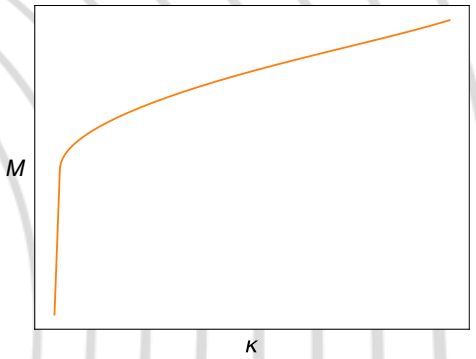
THE 11TH INTERNATIONAL CONFERENCE ON COMPOSITE TESTING AND MODEL IDENTIFICATION
GIRONA, SPAIN, 2023-06-01



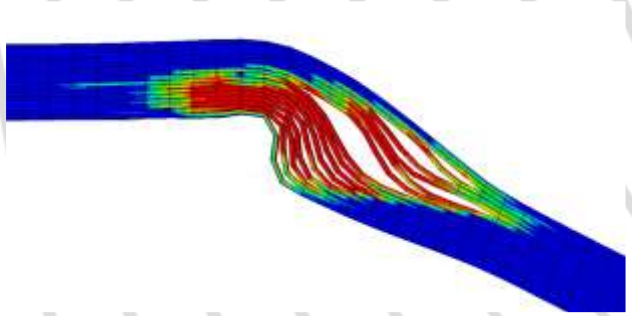
Cantilever bending test

One-click bending stiffness



Fabric bending behaviour

Process simulation

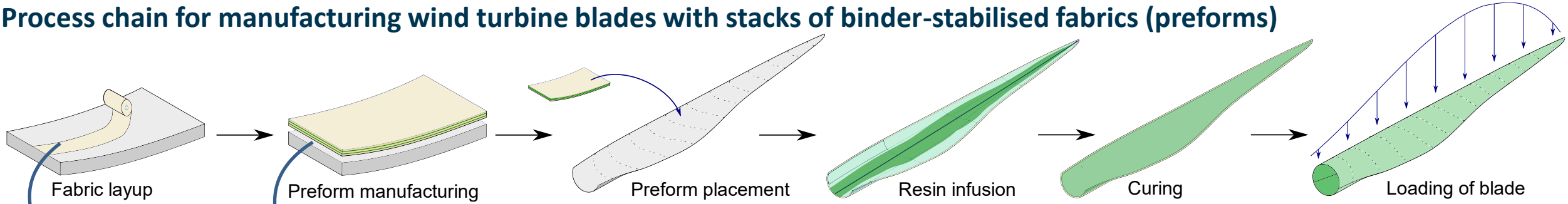


Predicted wrinkles

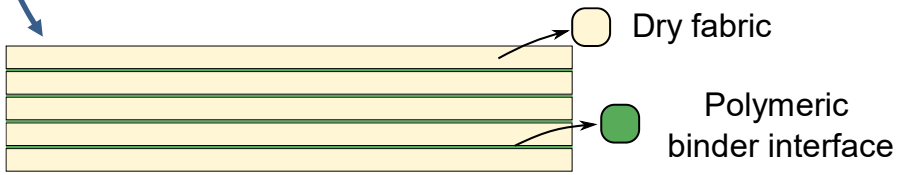
Part of the **MADEBLADES** project, made in collaboration with:

Challenge

Process chain for manufacturing wind turbine blades with stacks of binder-stabilised fabrics (preforms)



Fabric



Preform

Aim: to accurately simulate defects (wrinkles) during the manufacturing of composite structures

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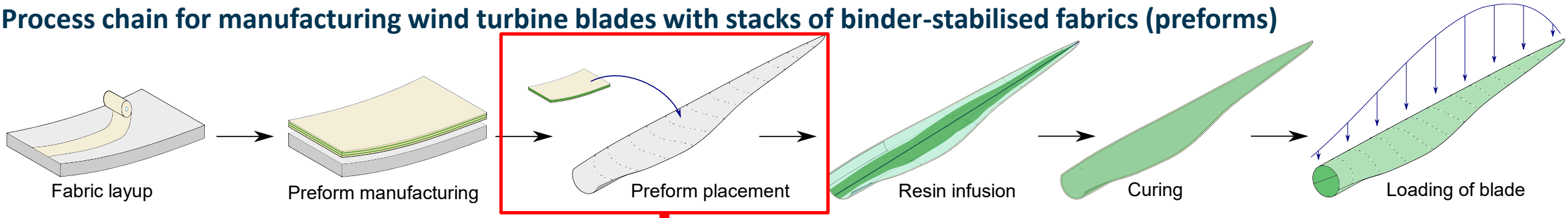
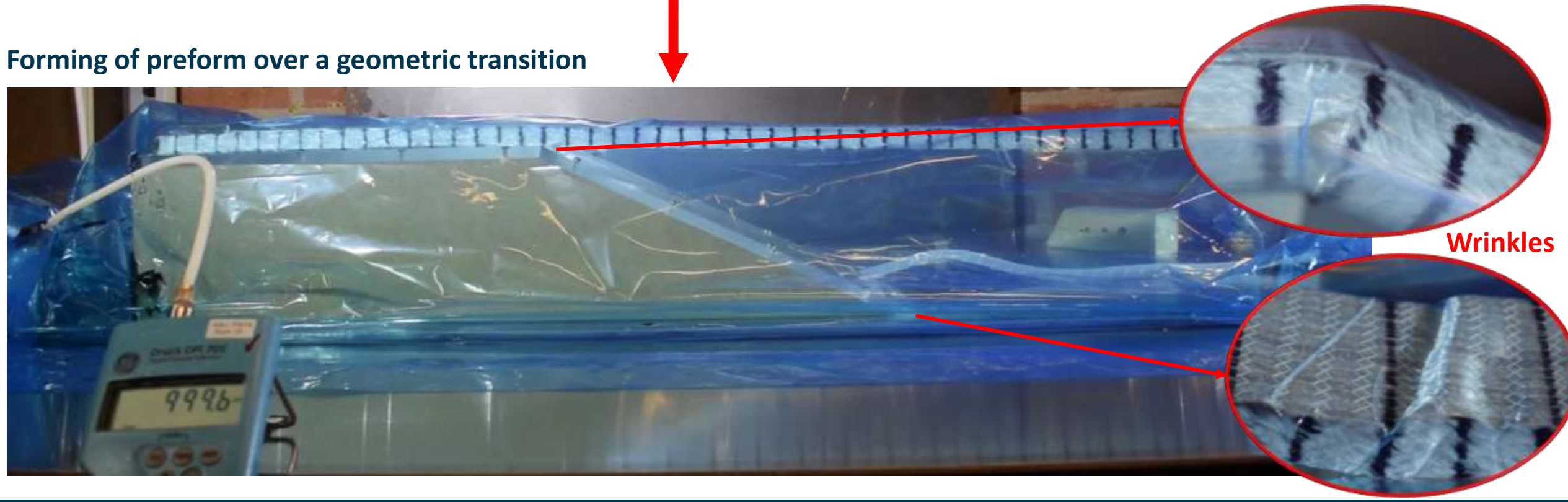
Challenge

Process chain for manufacturing wind turbine blades with stacks of binder-stabilised fabrics (preforms)



Forming of preform over a geometric transition



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Challenge and aim of this work

Accurate modelling of the bending behaviour of each fabric is important for accurate prediction of the defects arising during manufacturing

- Correct wrinkle location
- Too large wrinkles

With constant bending stiffness
(Conventional)

- Correct wrinkle location
- Representative wrinkle size

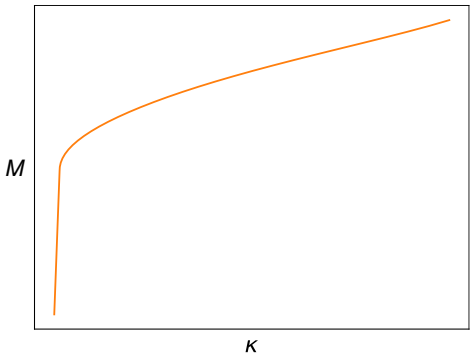
With non-constant bending stiffness
(New)

In this work, we will present:

- An accurate and reliable method for characterising fabric bending stiffness
- Application of FE models with non-constant bending stiffness

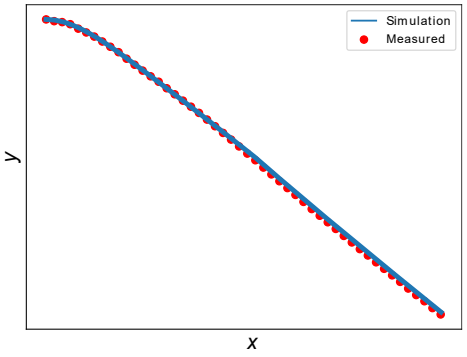
Input image

One-click bending stiffness



Computed bending stiffness

FE-simulation



Simulated deflection curve

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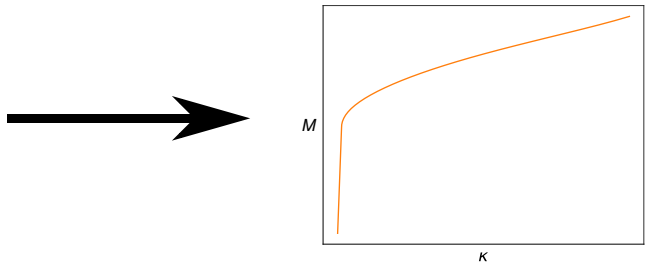
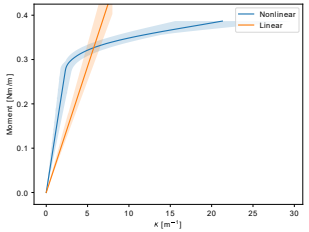
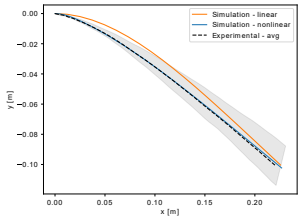
Outline

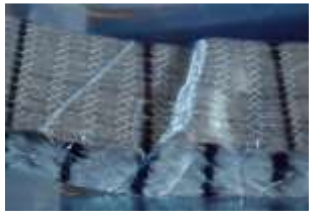


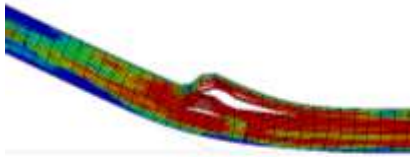
Methodology for characterising the bending stiffness





Results





Applications to process simulations

Conclusions

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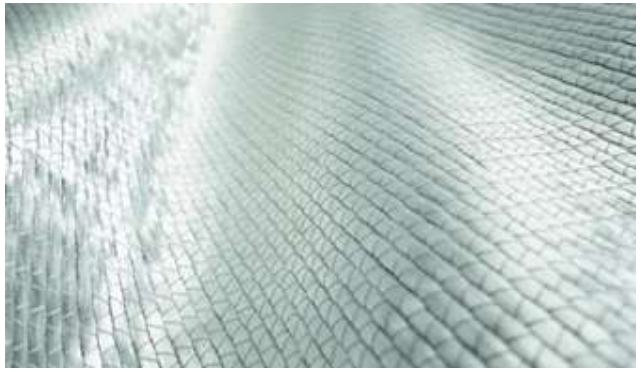
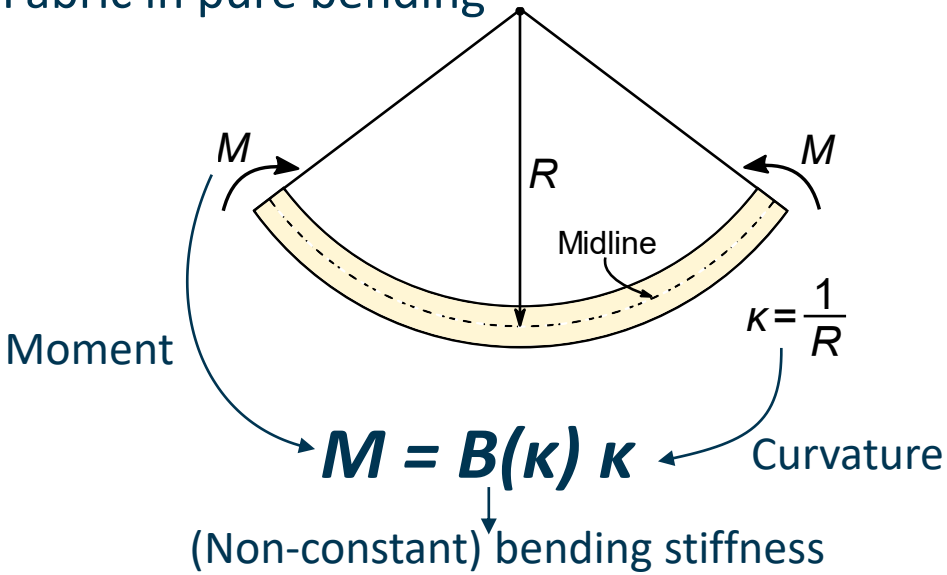
Background

Material and bending stiffness

Unidirectional non-crimp fabric



Fabric in pure bending



State-of-the-art

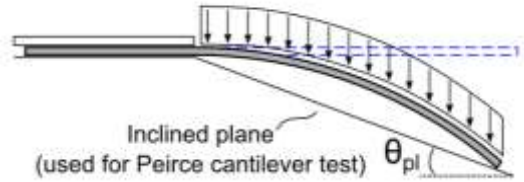
Direct methods

[1]

- Expensive equipment
- Strong assumptions

Indirect methods

[1]



- Many user choices that lead to uncertainties

We have developed an automated method for characterising the bending stiffness without needing user choices

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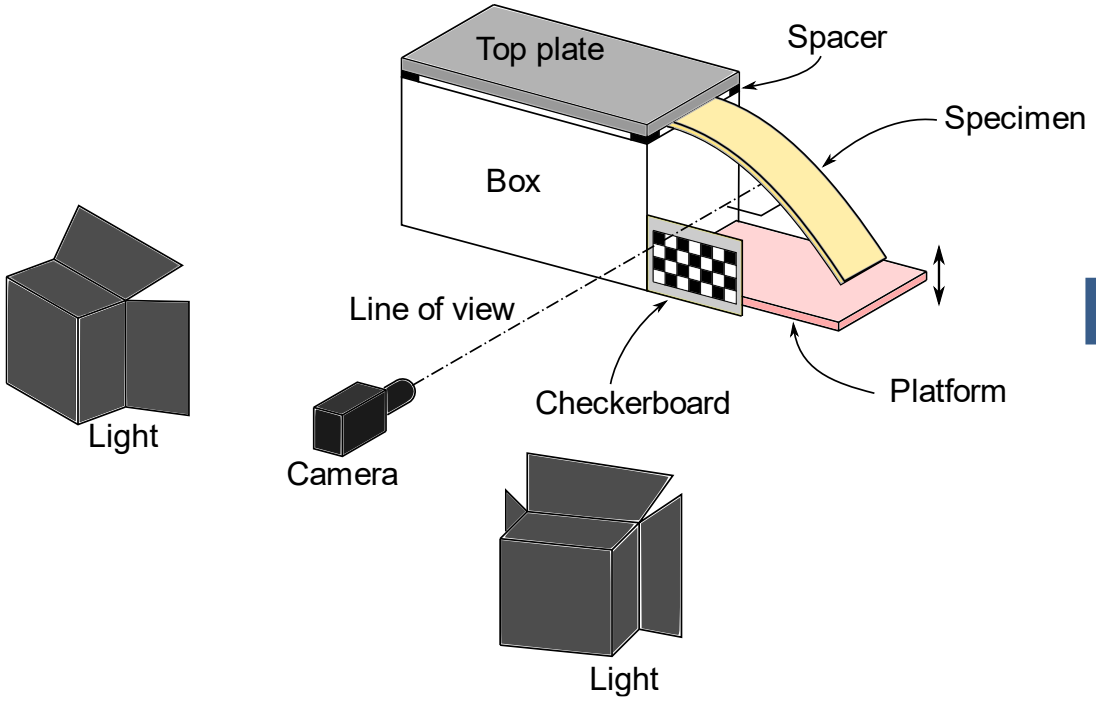
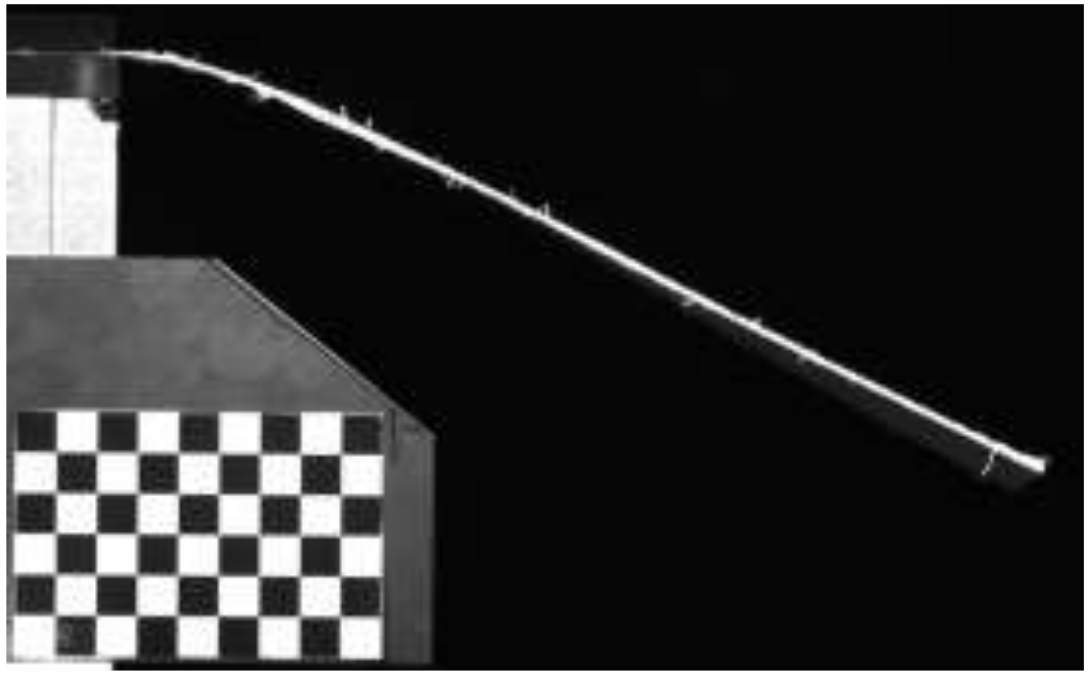
Methodology - Experimental setup

Experimental setup [2]



Input image



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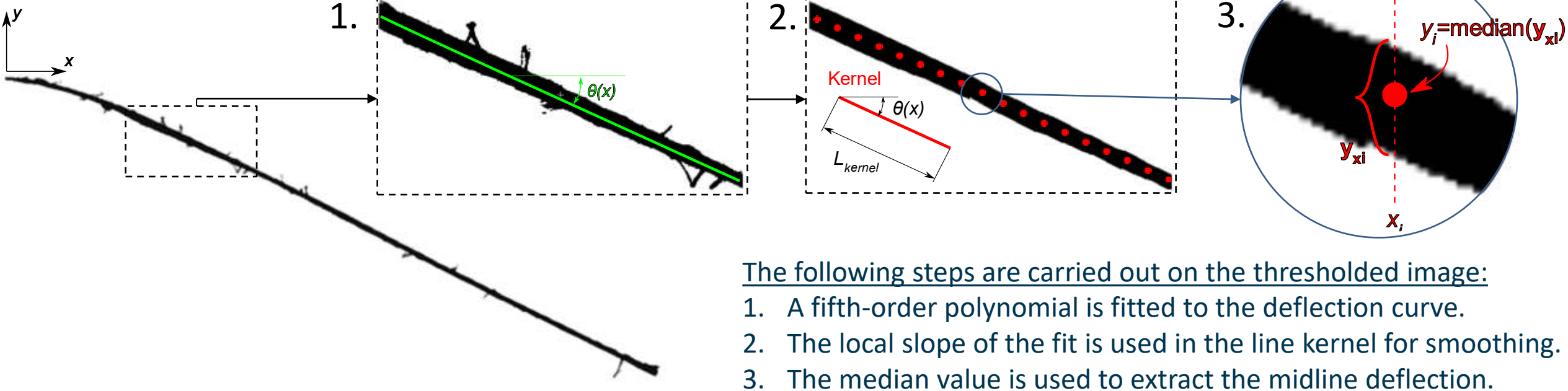
Methodology – Data processing

Original image of the textile specimen → Image processing module → Discrete set of coordinates (x_i, y_i) of the midline deflection curve → Curve fit module (Automatic parameter selection; Smoothing spline) → Smoothing spline fit (continuous) of the midline deflection curve → Moment and curvature calculation module → Moment-curvature relationship (continuous) of the textile



The following steps are carried out on the thresholded image:

1. A fifth-order polynomial is fitted to the deflection curve.
2. The local slope of the fit is used in the line kernel for smoothing.
3. The median value is used to extract the midline deflection.

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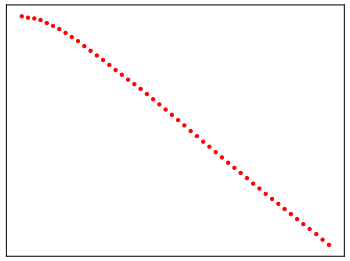
Methodology – Data processing

Original image of the textile specimen

→ Image processing module →



Discrete set of coordinates (x_i, y_i) of the midline deflection curve

→ Curve fit module (Automatic parameter selection; Smoothing spline) →

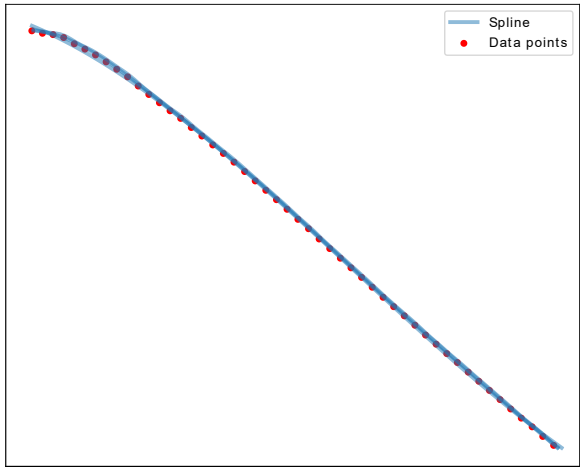
Smoothing spline fit (continuous) of the midline deflection curve

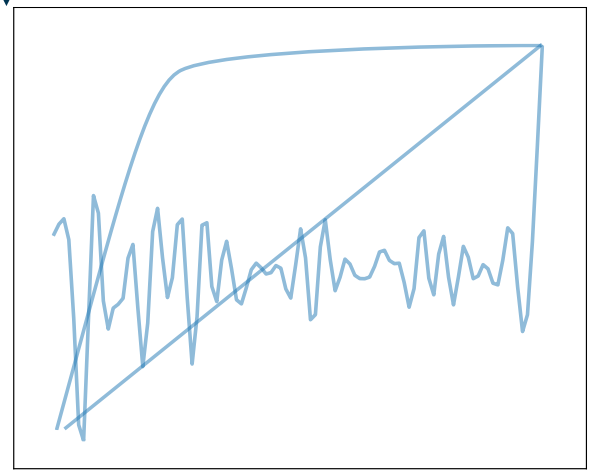
→ Moment and curvature calculation module →

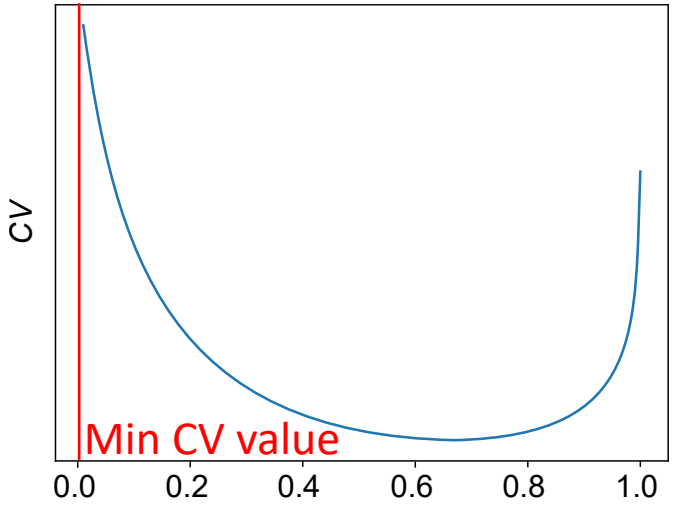
Moment-curvature relationship (continuous) of the textile

Challenges:

- The data going into the curve fit is noisy
- Second derivative information is needed







Solutions to this problem are often:

- Biased (over-simplified)
- Overfitted (Noisy)

Smoothing spline

$$\min \quad p\sum_{i=1}^{n}\{y_i - f(x_i)\}^2 + (1-p)\int\{f^{(m)}(x)\}^2 dx$$

1 hyperparameter found automatically →

Cross-validation

$$CV = \frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{f}_{\lambda}^{[-i]}(x_i))^2$$

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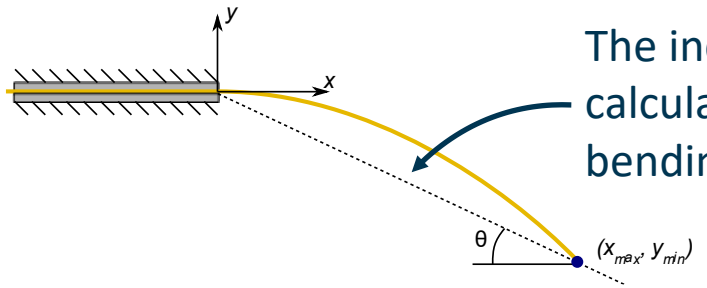
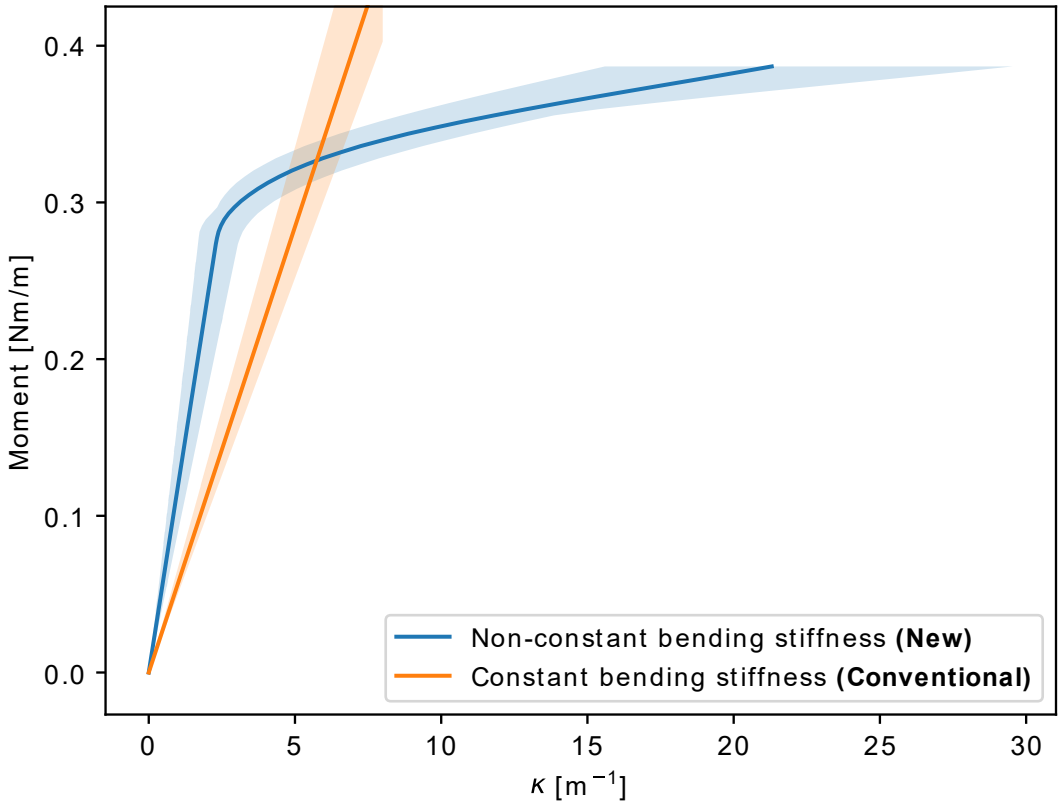
Results

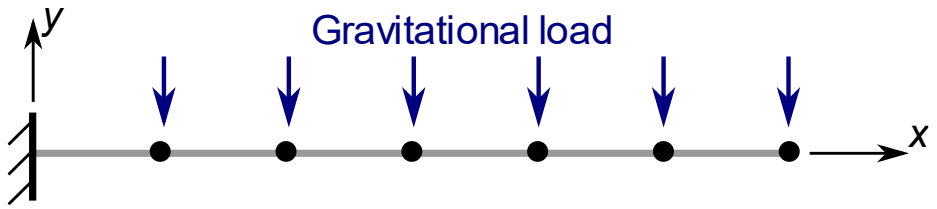
Measured bending behaviour

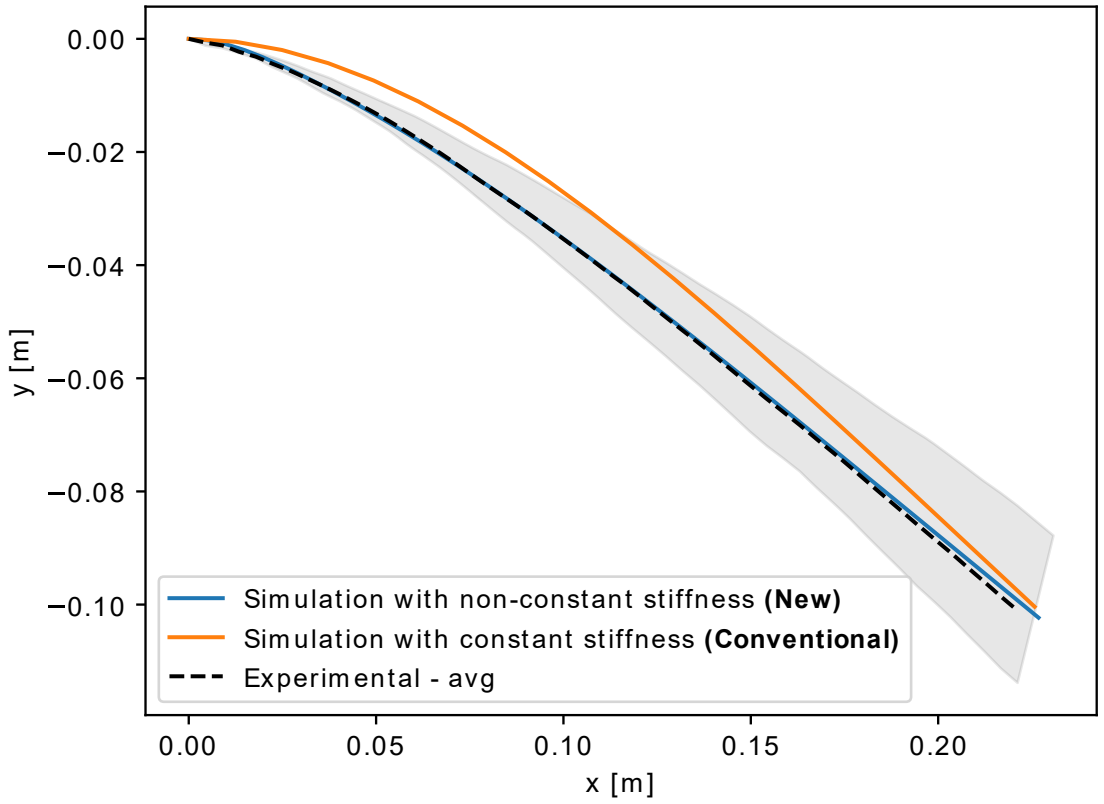


The inclined plane used to calculate the constant bending stiffness



Simulated deflection curve





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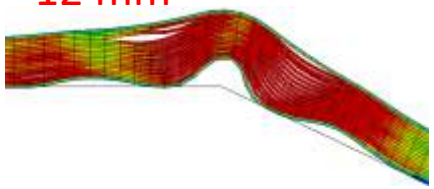
Application to process simulations

Model with constant bending stiffness

W = 30 mm
A = 12 mm

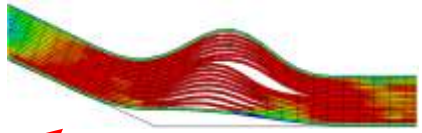


Simulation

Experiment

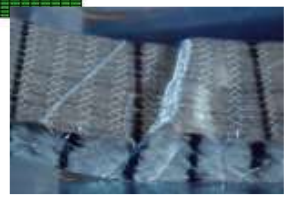
W = 13 mm
A = 4 mm

W = 54 mm
A = 11 mm



Simulation

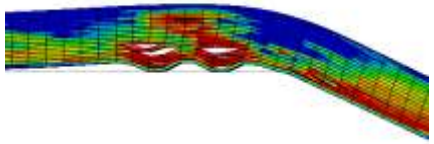
W =37mm
A = 5 mm



Experiment

Model with non-constant bending stiffness

W = 14 mm
A = 2.5 mm

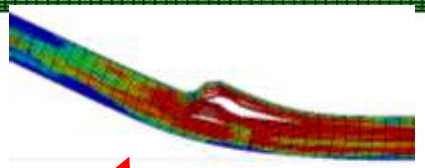


Simulation

Experiment

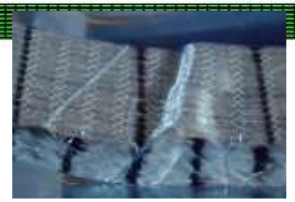
W = 13 mm
A = 4 mm

W = 37 mm
A = 7 mm



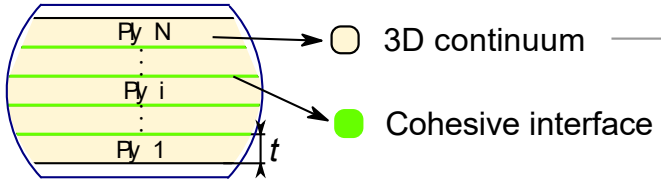
Simulation

W =37mm
A = 5 mm

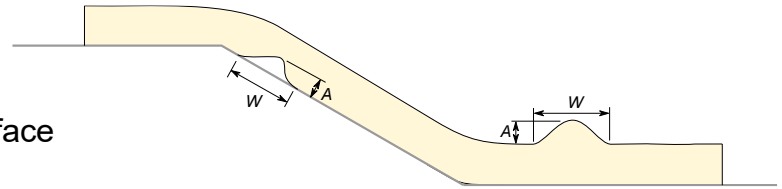


Experiment

Preform model [3]



Wrinkle metrics



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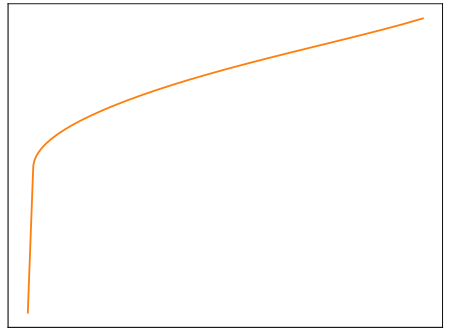
Conclusions

- Accurate characterisation and modelling of fabric bending stiffness are needed to predict process-induced wrinkles.
- An automatic and reliable method for processing the images from a cantilever bending test has been presented.

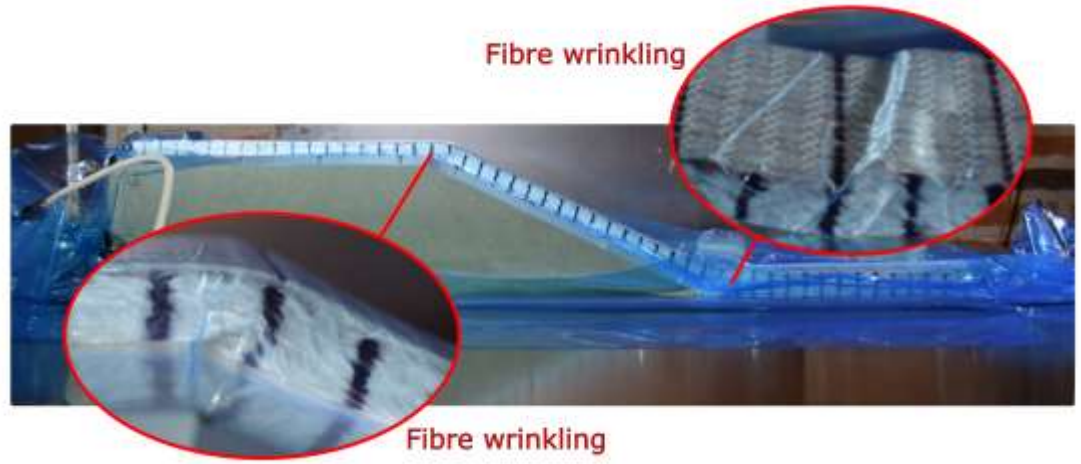
Input image

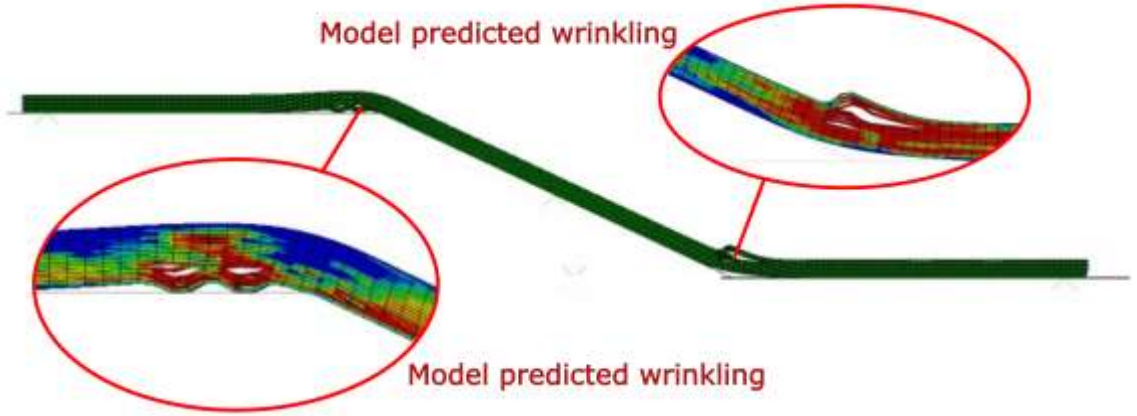
One-click bending stiffness



Computed bending stiffness

- Using the measured bending stiffness, accurate predictions of wrinkle size and location is obtained.





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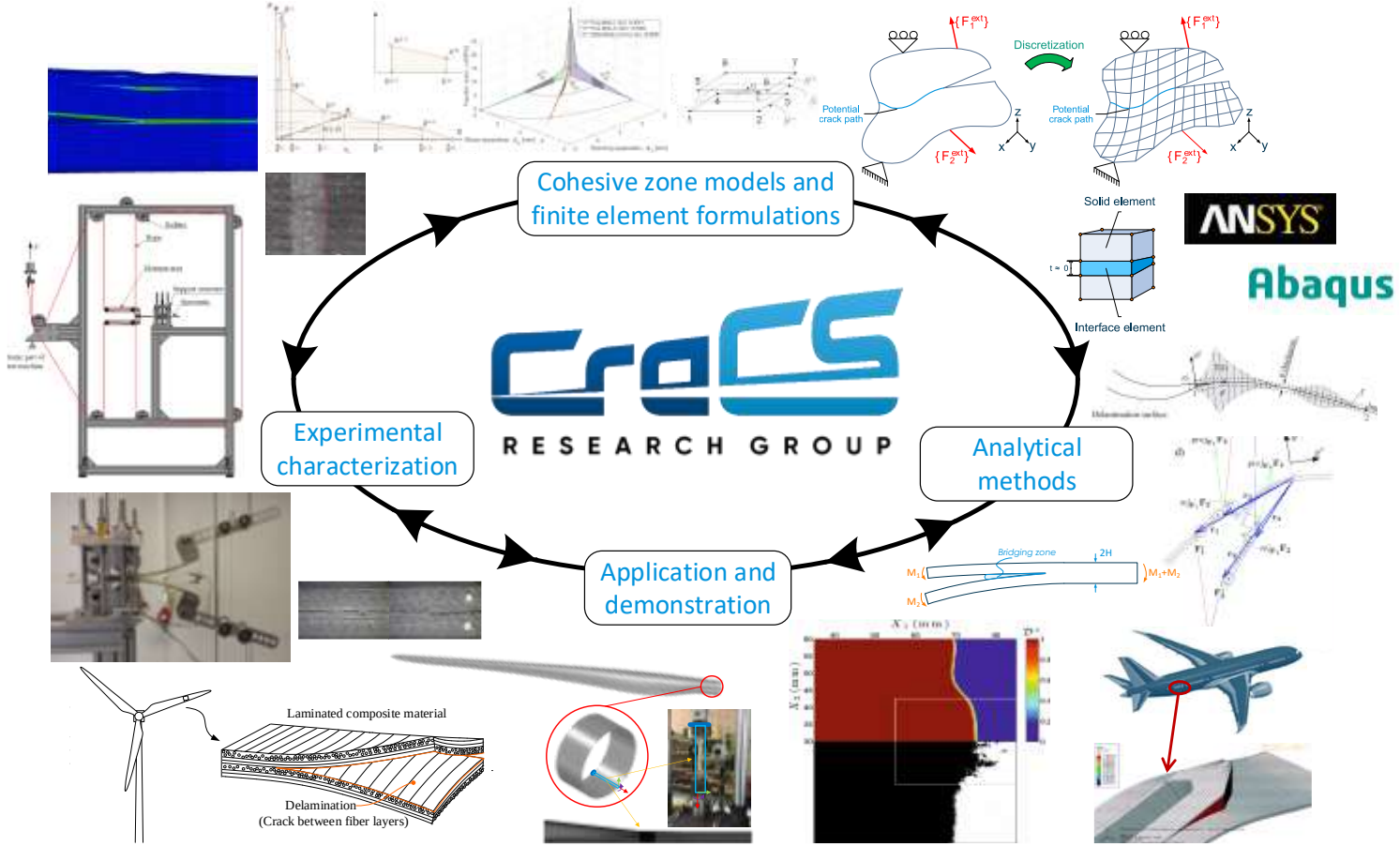
THANK YOU FOR YOUR ATTENTION

You can read more about the method in our newly published journal paper:

Broberg PH, Lindgaard E, Krogh C, Jensen SM, Trabal GG, Thai AF-M & Bak BLV (2023), One-click bending stiffness: Robust and reliable automatic calculation of moment-curvature relation in a cantilever bending test, Composites Part B: Engineering, 110763, https://doi.org/10.1016/j.compositesb.2023.110763



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Ph.D. Student Peter H. Broberg


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Project partners:

LM WIND POWER a GE Renewable Energy business
The von Kármán Institute for Fluid Dynamics
Fraunhofer
WAVESTONE
Universitat de Girona
AMADE
WAGENINGEN UNIVERSITY & RESEARCH
UNL Universidad Nacional del Litoral
AWS TRUEPOWER
SIEMENS
Envision
SIEMENS Gamesa RENEWABLE ENERGY
DTU Wind Energy Department of Wind Energy
AB INVENTECH
SINTEF
PONTIS ENGINEERING
Clobotics
SAMTECH
FORCE TECHNOLOGY

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References:

[1]: Krogh C, Broberg PH, Kepler J & Jakobsen J (2022). Comprehending the Bending: A Comparison of Different Test Setups for Measuring the Out-of-Plane Flexural Rigidity of a UD Fabric, Key Engineering Materials 926 1257-1267

[2]: Broberg PH, Lindgaard E, Krogh C, Jensen SM, Trabal GG, Thai AF-M & Bak BLV (2023), One-click bending stiffness: Robust and reliable automatic calculation of moment-curvature relation in a cantilever bending test, Composites Part B: Engineering, 110763

[3]: Broberg PH, Krogh C, Lindgaard E & Bak BLV (2022). Simulation of wrinkling during forming of binder stabilized UD-NCF preforms in wind turbine blade manufacturing, Key Engineering Materials 926 1248-1256

[4]: Colin D (2022). Virtual development of non-crimp fabrics: numerical textile description at the scale of the filaments and forming simulation, Technische Universität München.

[5]: Thompson AJ, Belnoue JP-H, Hallett SR (2020). Modelling defect formation in textiles during the double diaphragm forming process, Composites Part B: Engineering, 108357

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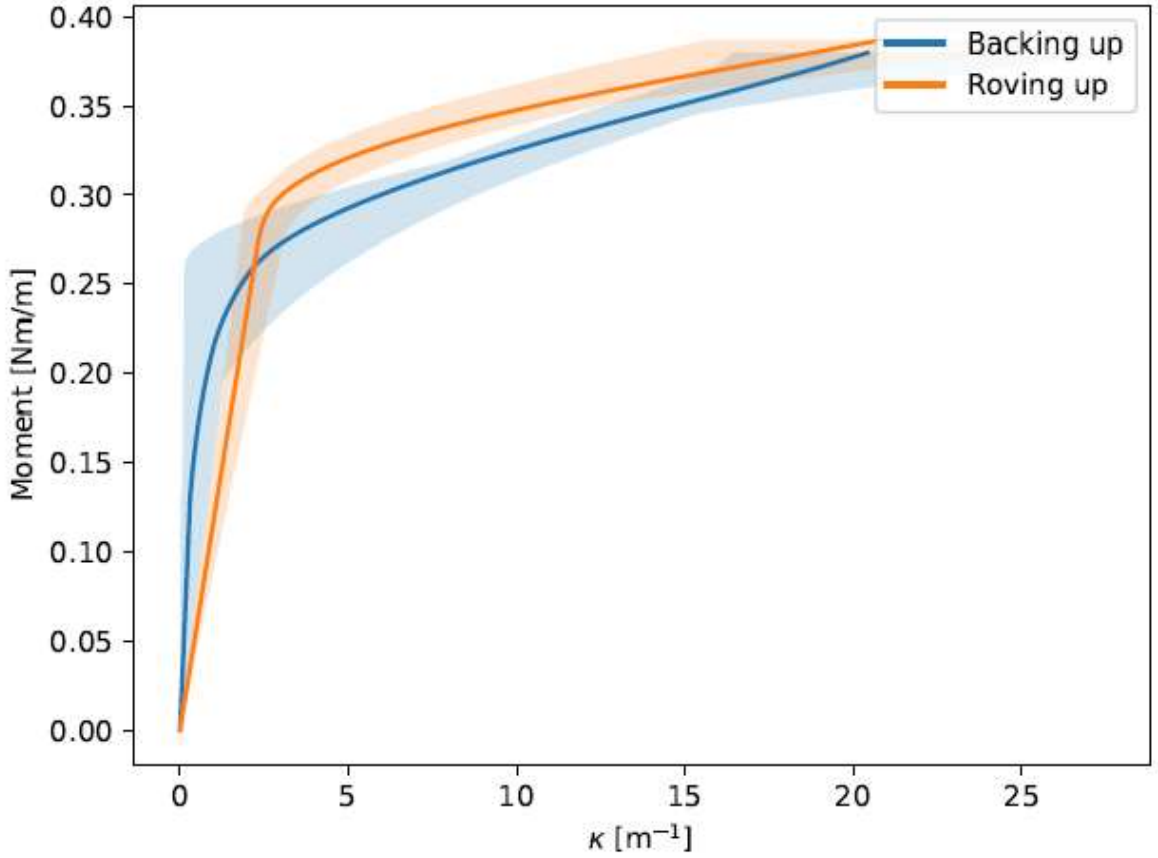
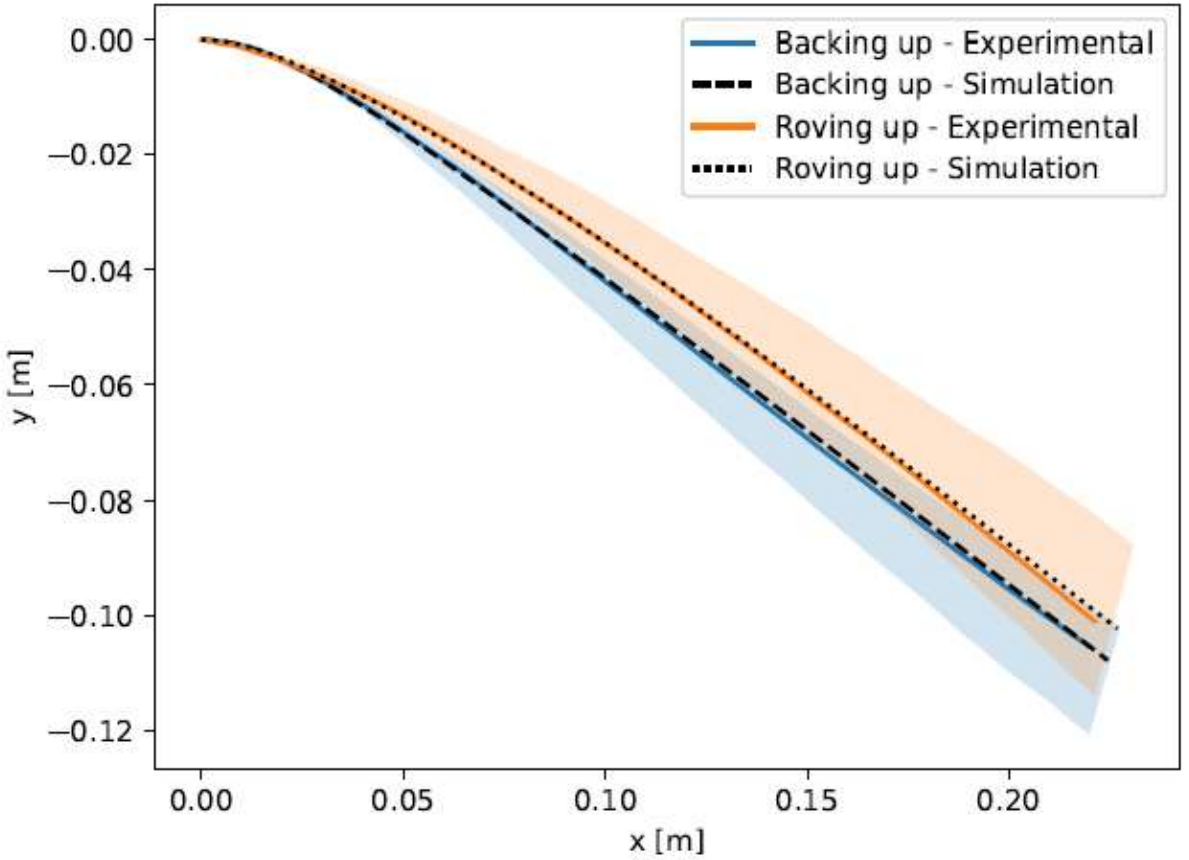
Bonus slides

Results backing up and roving up [2]





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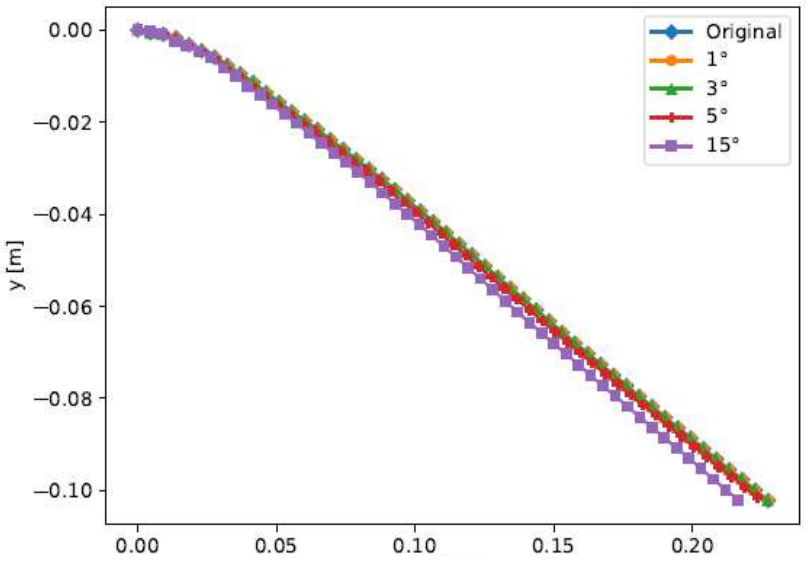
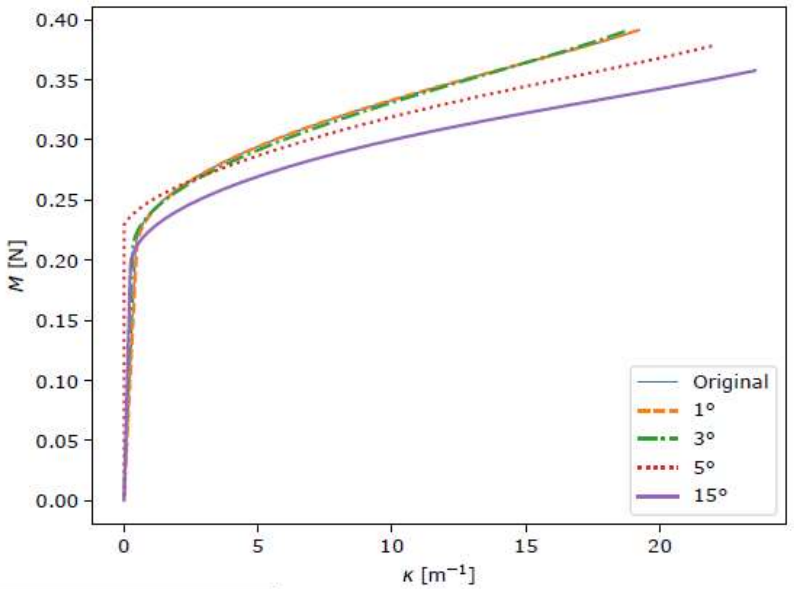
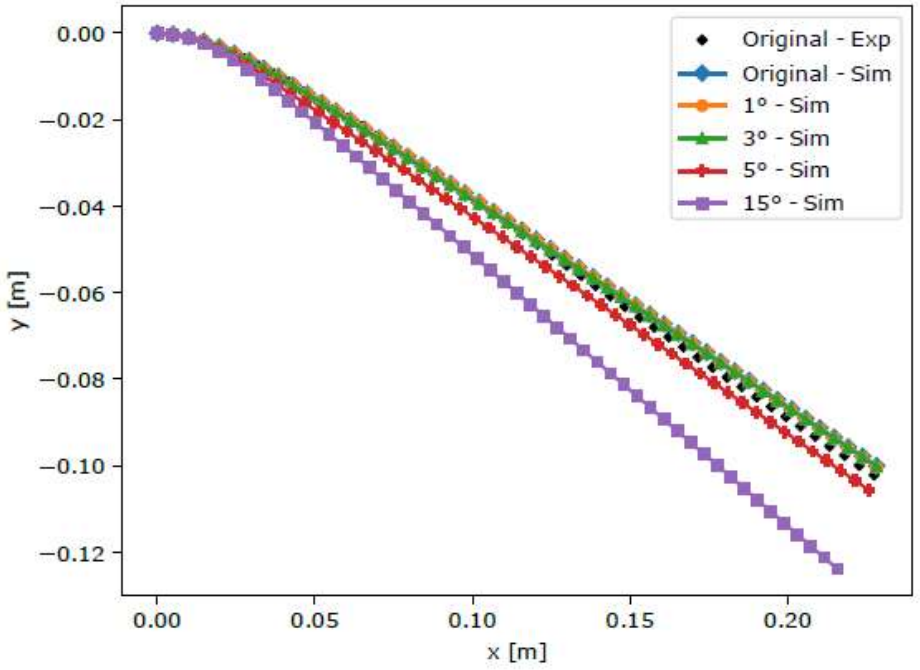
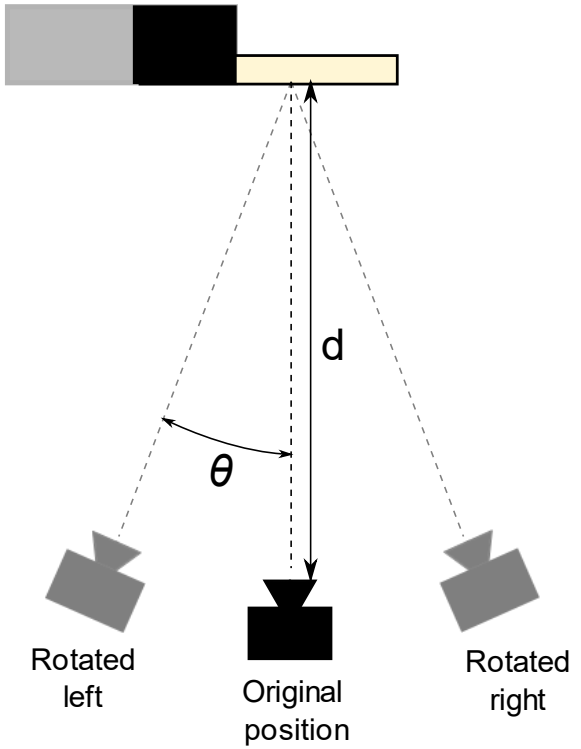
Systematic errors









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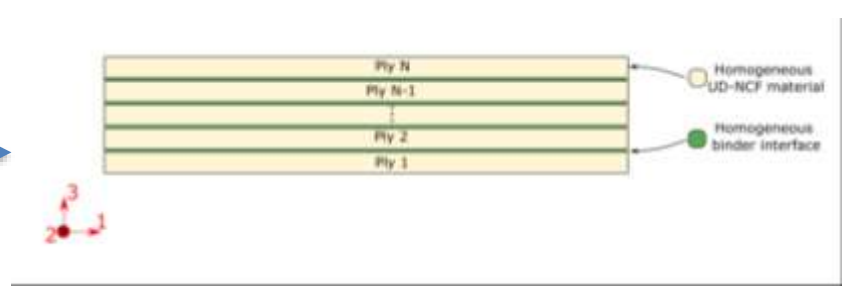
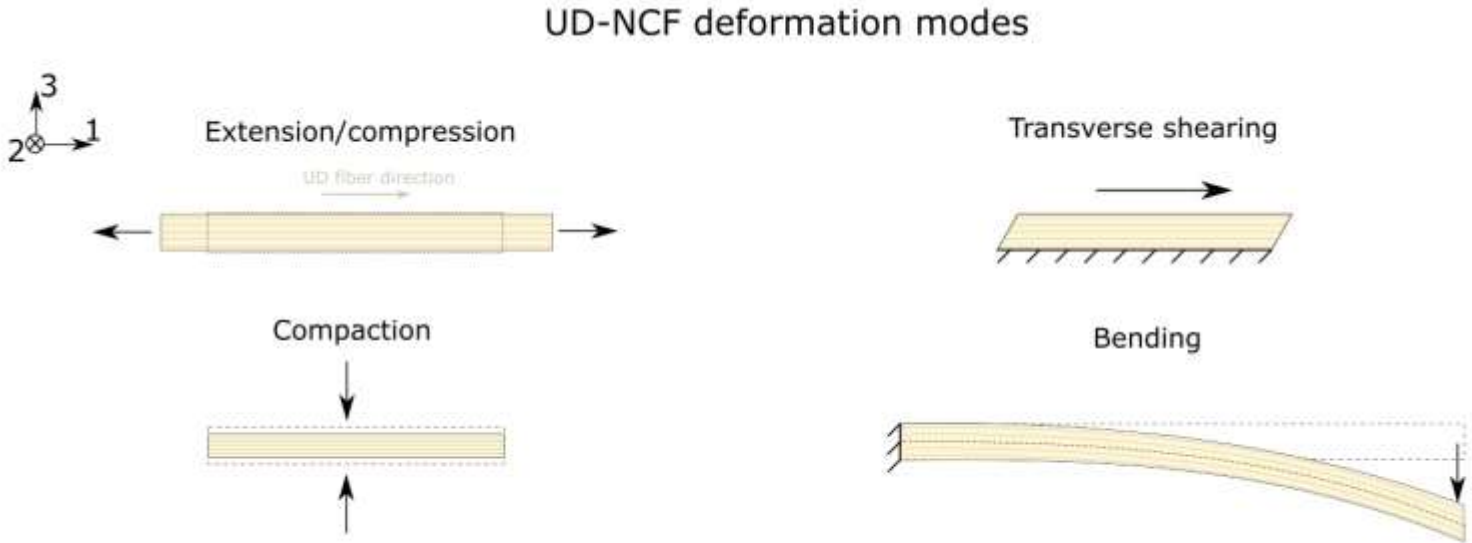
Modelling

Ply-by-ply macro-scale modelling [3].

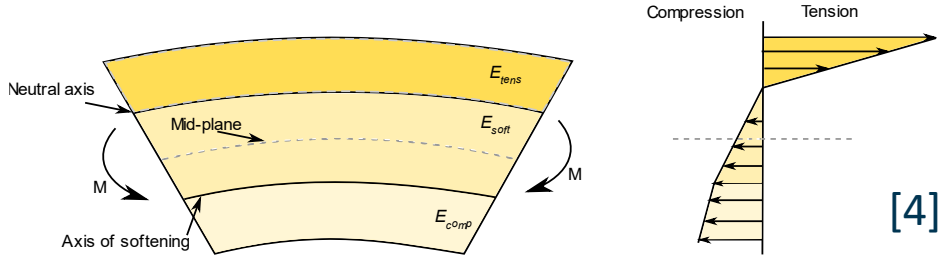


How to model a strongly heterogenous structure consisting of loose fibres as a homogenous continuum?

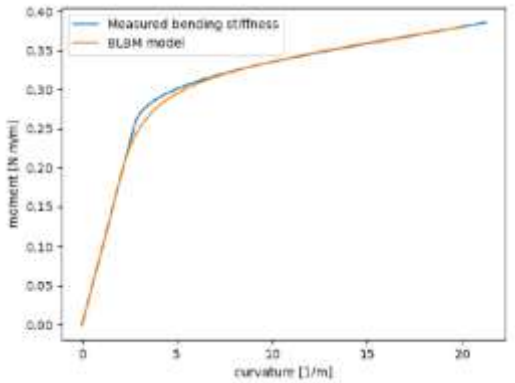
Deformation modes of the preform model



Bending model using asymmetric modulus



[4]



Ply deformation modes should be decoupled due to relative fibre motion
Need a high tensile stiffness and a low bending stiffness.

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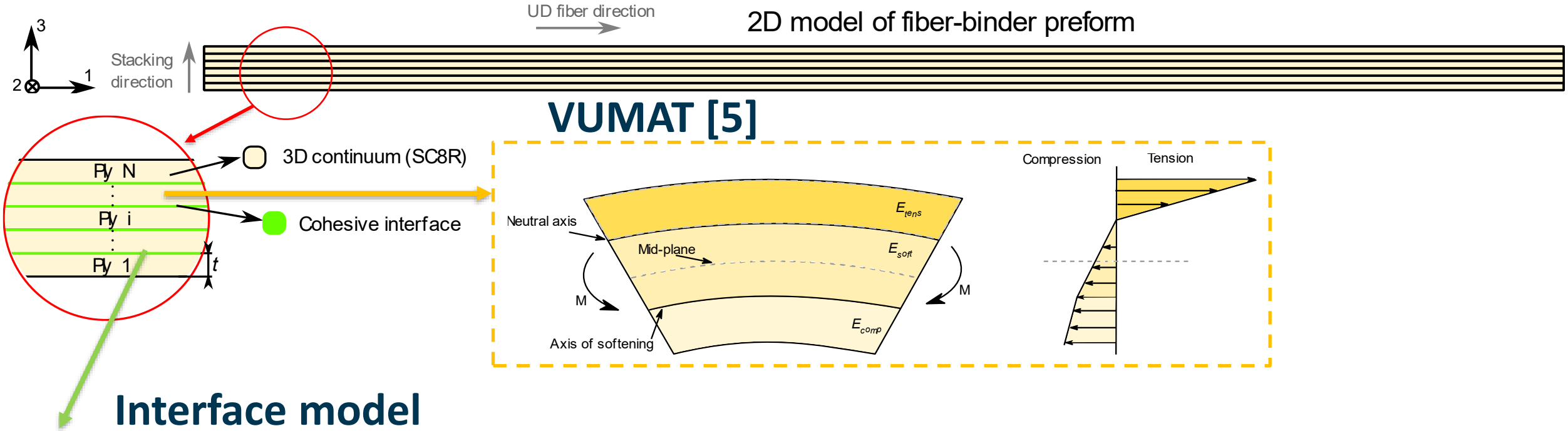
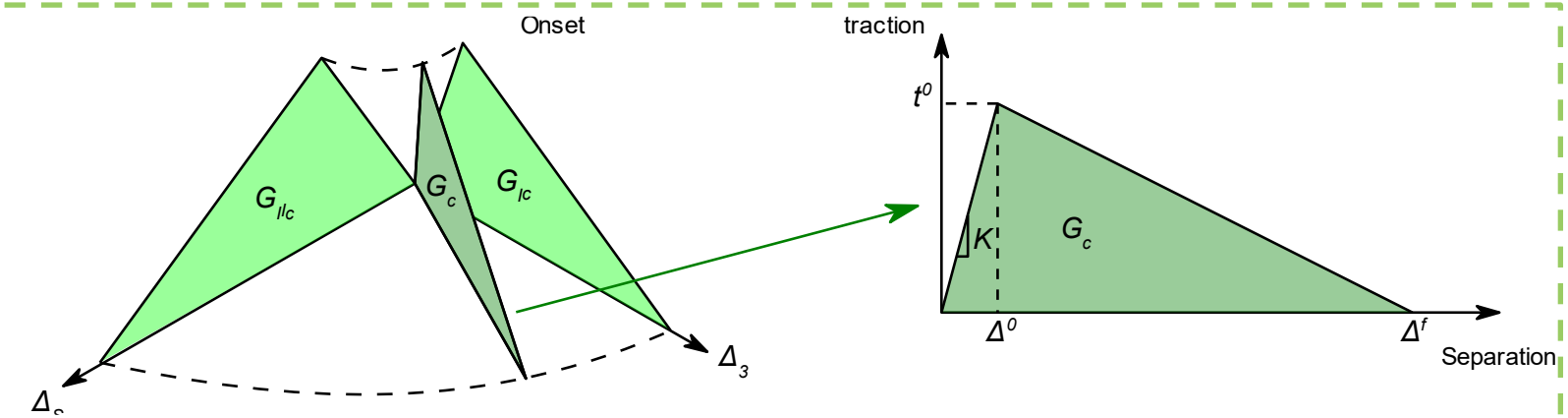
Simulation model



Interface model



- The model is made using commercially available software (ABAQUS/Explicit) with user subroutines for describing the material behaviour.

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