Predictive Simulation of the Creation of Wrinkles during Preform Manufacturing

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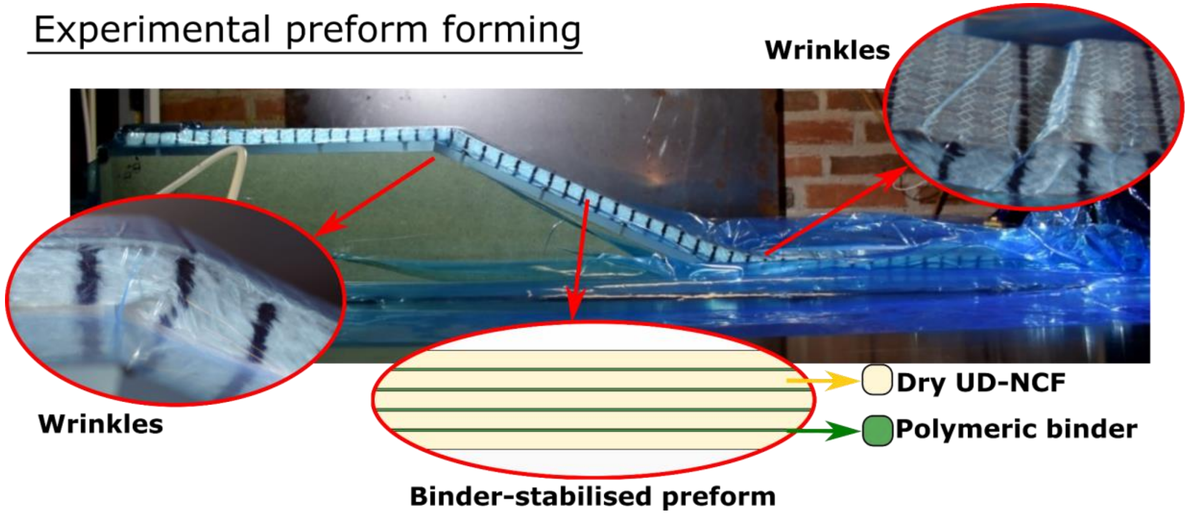
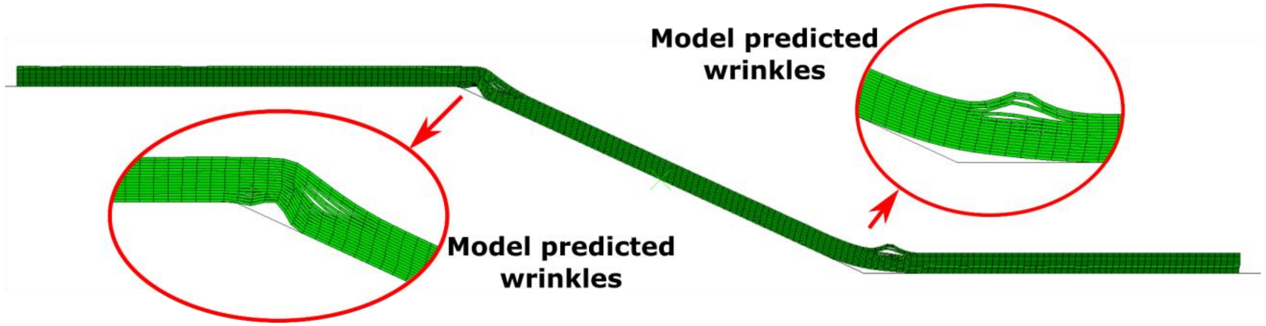
NEXT-GEN COMPOSITES RECYCLING: ANNUAL COMPOSITE MEETING 2024
MAY 23, 2024, COPENHAGEN, DENMARK

Experimental preform forming



Simulation using new preform model



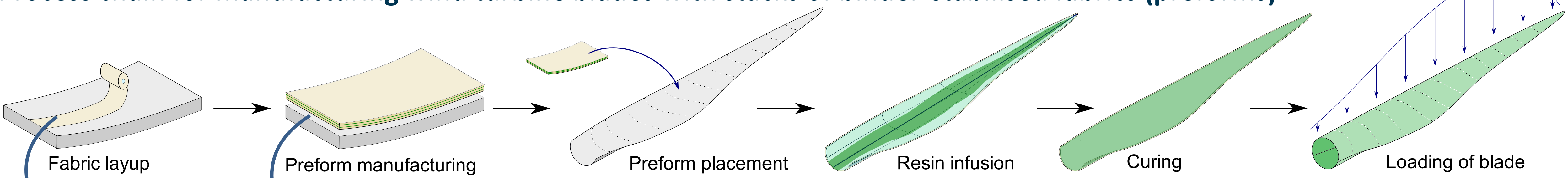
Part of the **MADEBLADES** project, made in collaboration with:

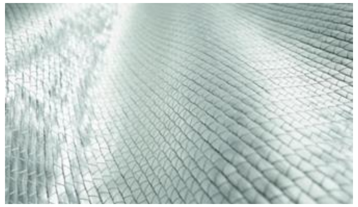
LM WIND POWER a GE Renewable Energy business; AALBORG UNIVERSITY; DTU Wind Energy Department of Wind Energy; AB INVENTECH; EUDP

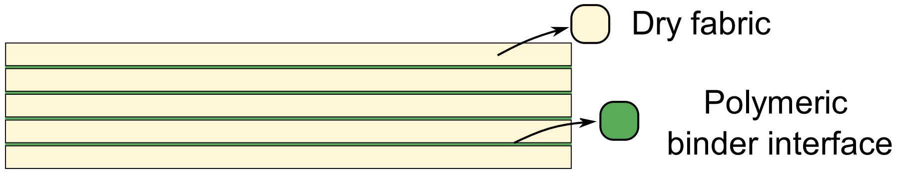
Grant number: 64019-0514

Challenge

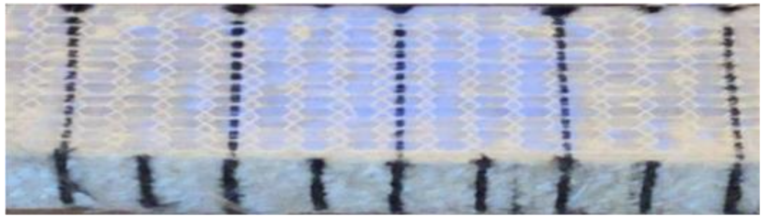
Process chain for manufacturing wind turbine blades with stacks of binder-stabilised fabrics (preforms)




Fabric



Preform


Real Preform

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

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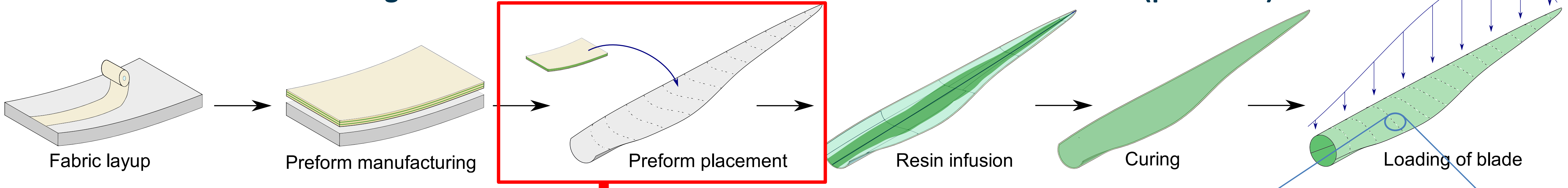
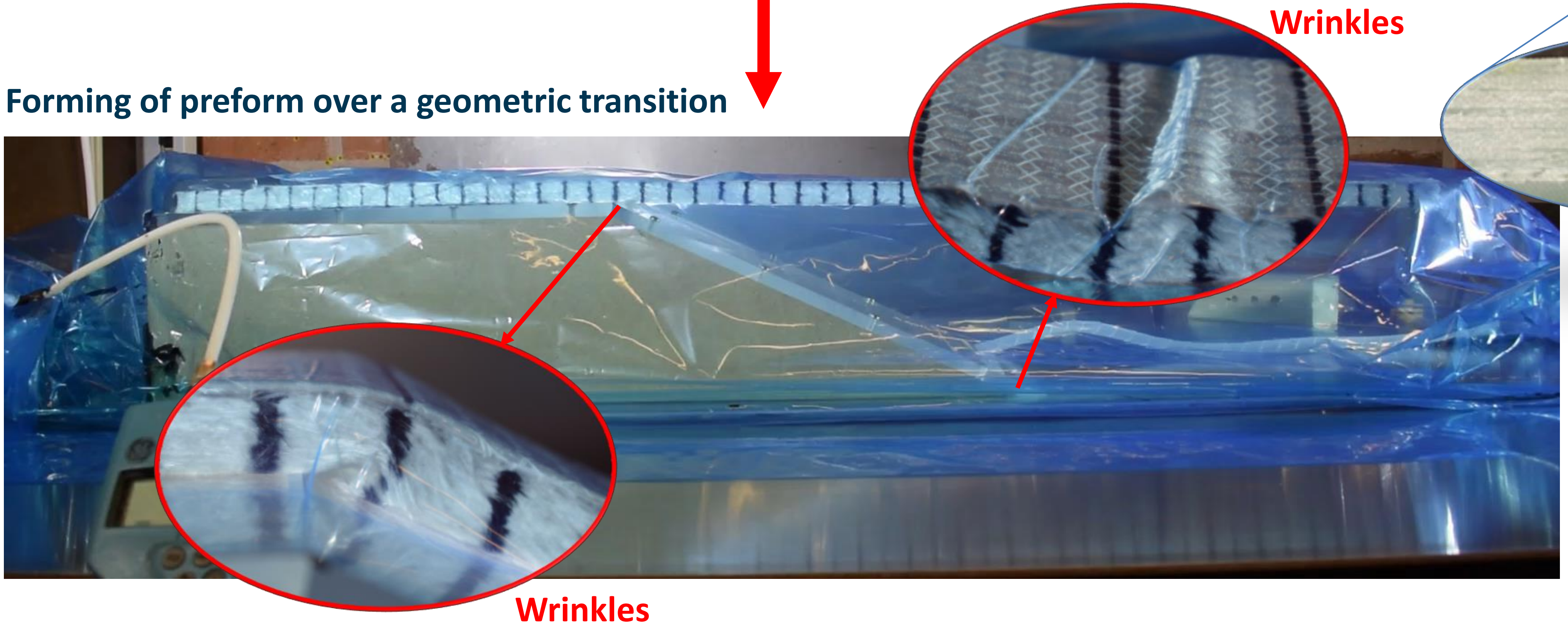
Challenge

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



Forming of preform over a geometric transition



Solidified wrinkle [1]

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Wrinkle Defects

Wrinkles can cause a reduction of strength of up to 60% for some wrinkle configurations [4]

Wrinkles are not desired in composite structures!

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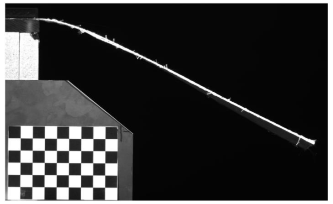
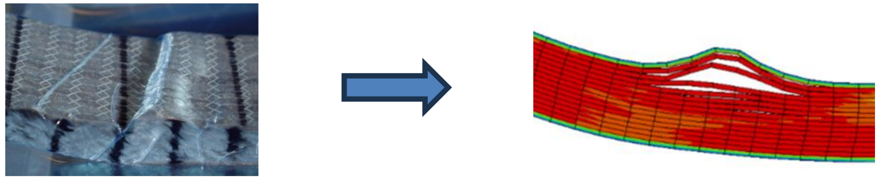
Outline of the Presentation

	Introduction and Objectives
	Experimental Characterisation
	Preform Modelling
	Parameter Studies
	Conclusions

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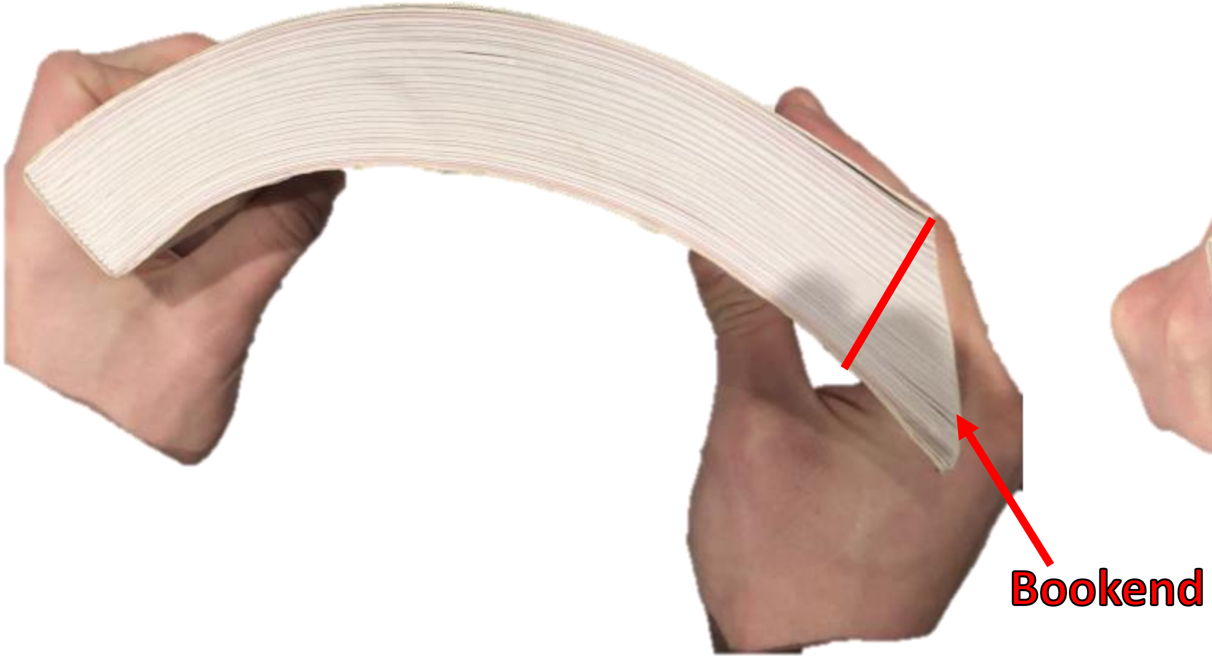
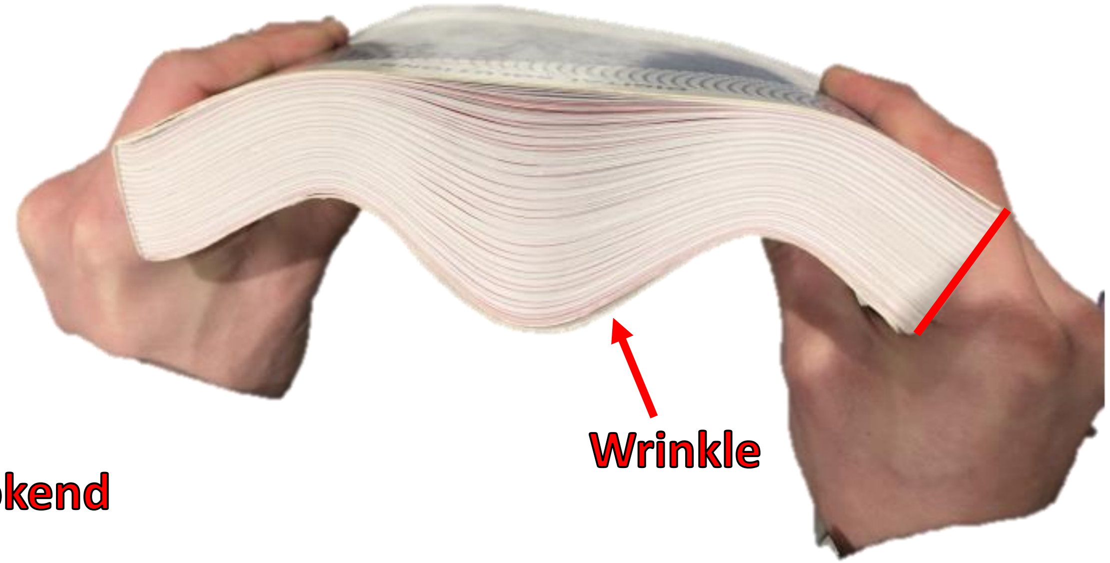
Wrinkle Mechanisms

Bending of book with unconstrained edges



Bending of book with constrained edges



Fibre sliding govern wrinkle creation

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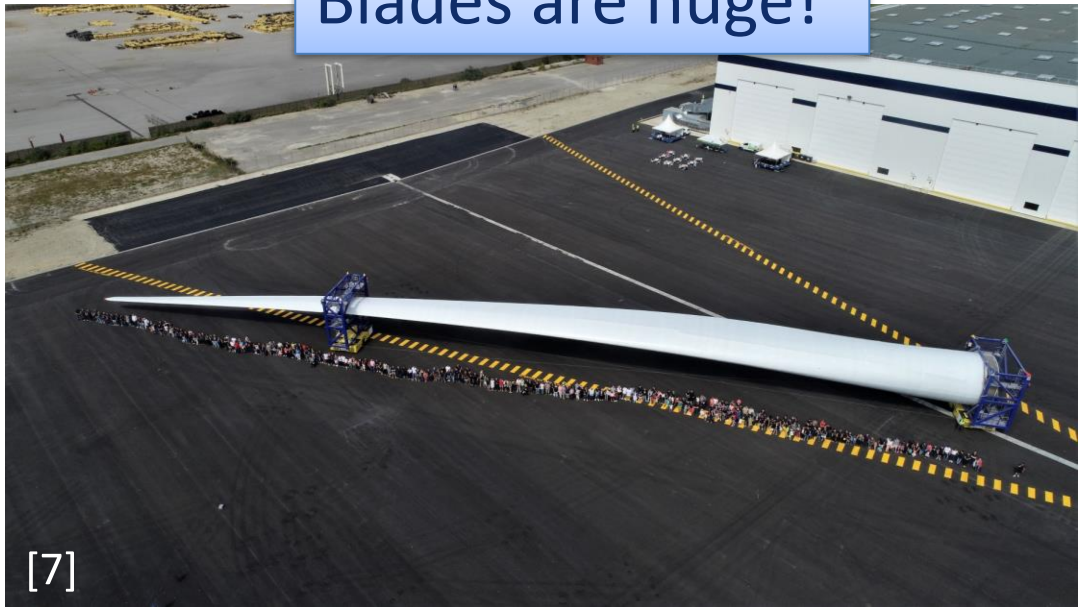
Multi-scale Challenges

[5]

Compromise between formability and handleability of the preform

[6]

Blades are huge!



[7]

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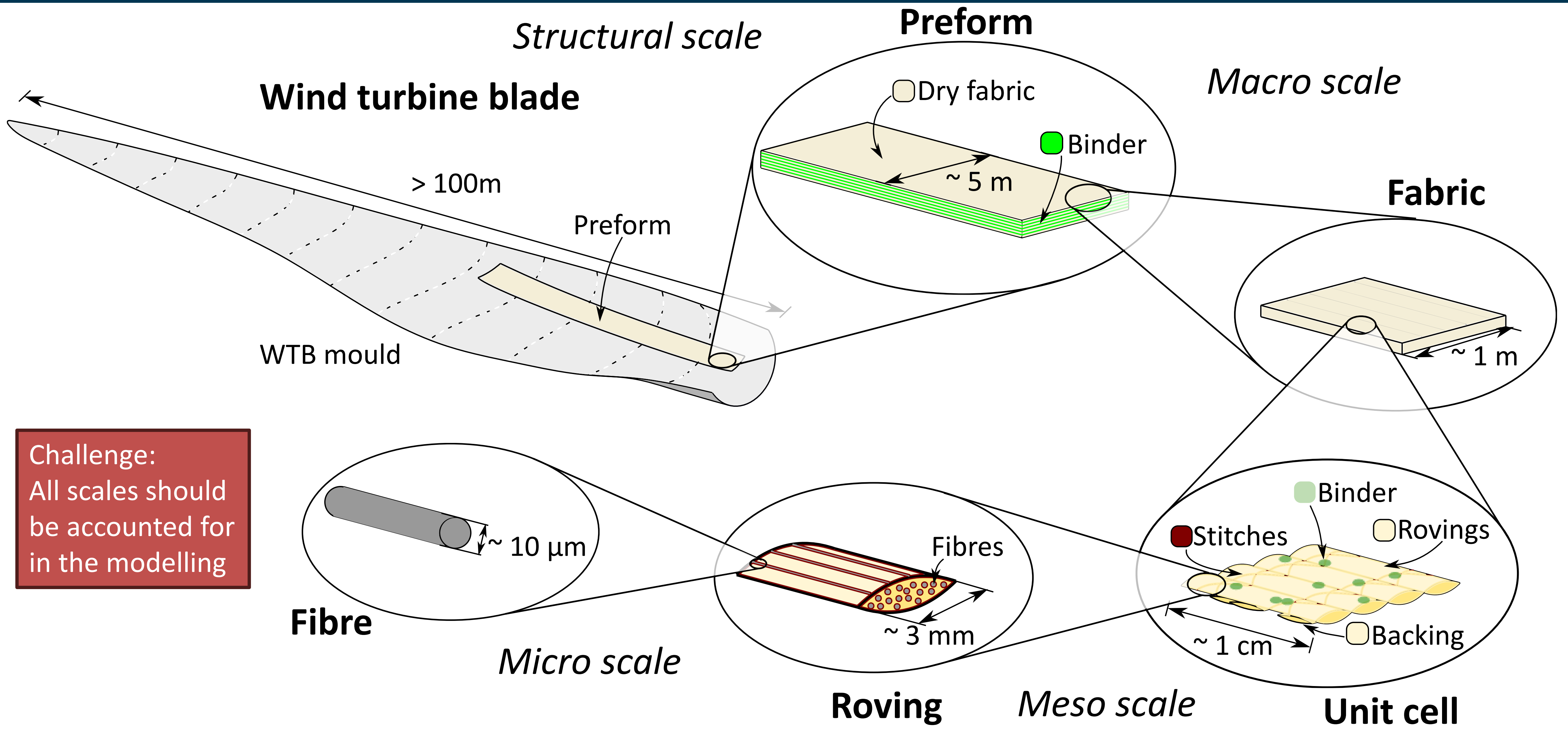
Multi-scale Challenges



Challenge:
All scales should be accounted for in the modelling

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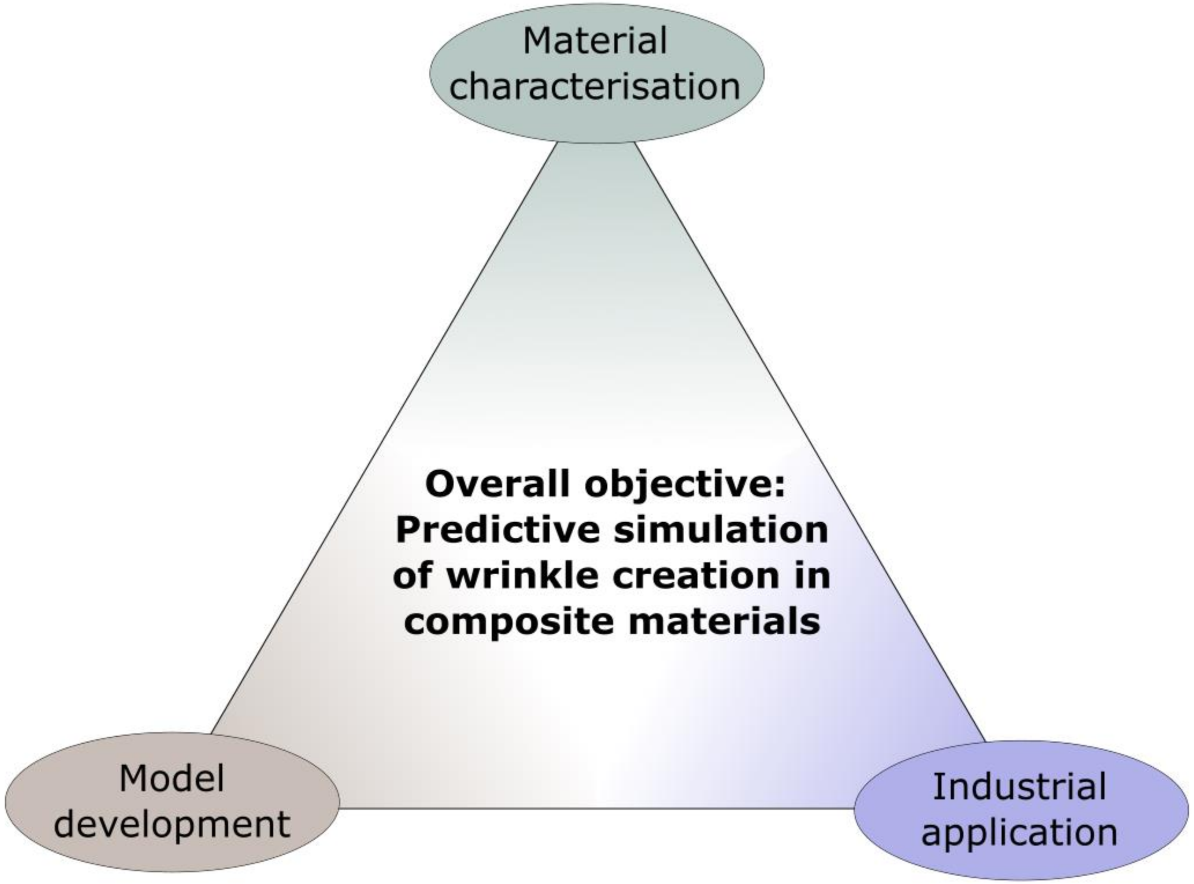
Overall Objective of the PhD Studies

Tasks involved in the project:

- Development of a novel and advanced mechanical preform model that can describe the response before, during, and after wrinkling develops.
- Development of a complete framework for experimental characterisation of the preform material.
- Applying the framework on an industrial application to obtain design allowable for wrinkle-free manufacturing of wind turbine blades.



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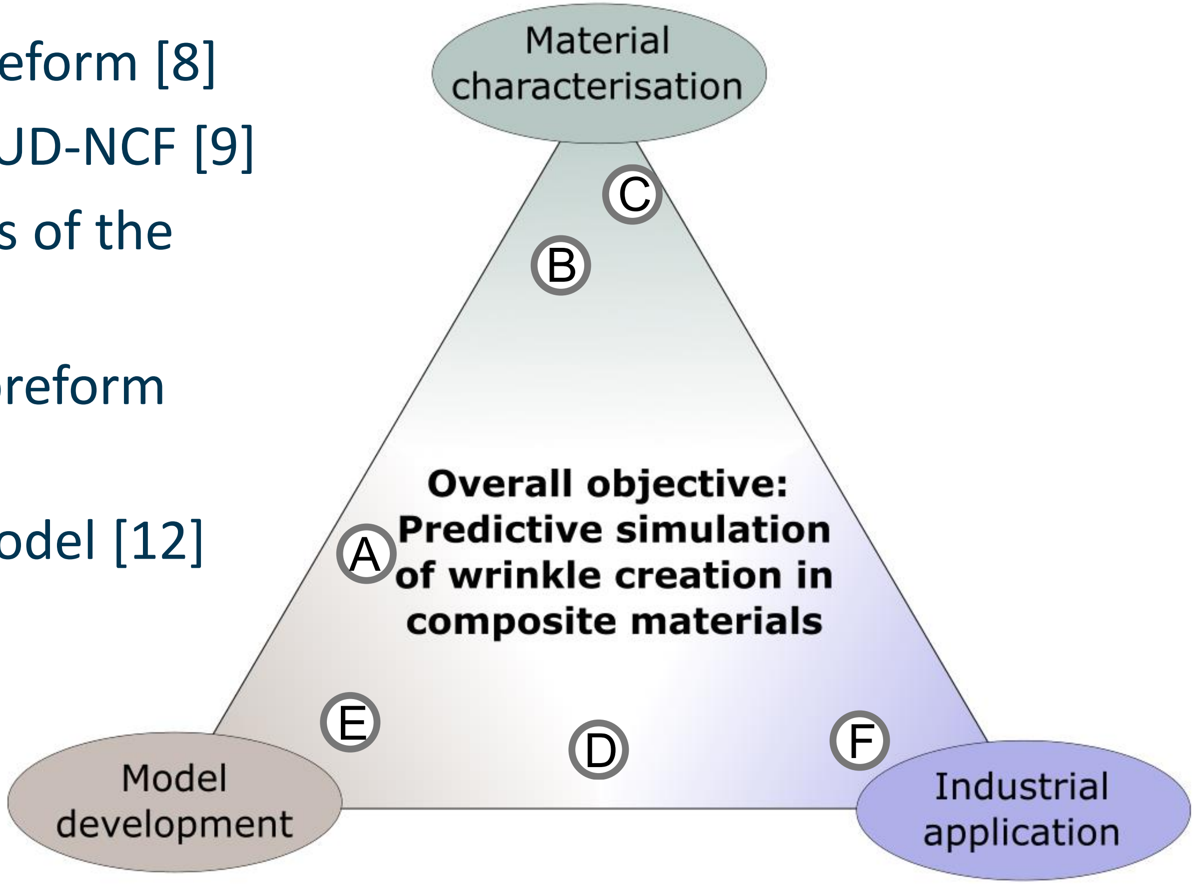
Overall Objective of the PhD Studies

Main journal Papers for the PhD thesis:

A. Establishing the modelling framework for the preform [8]
B. Characterisation of the bending stiffness of the UD-NCF [9]
C. Characterisation of the transverse shear stiffness of the preform [10]
D. Vacuum forming experiments on full thickness preform specimens [11]
E. Development of advanced nonlinear preform model [12]
F. Parameter studies on the preform model [13]



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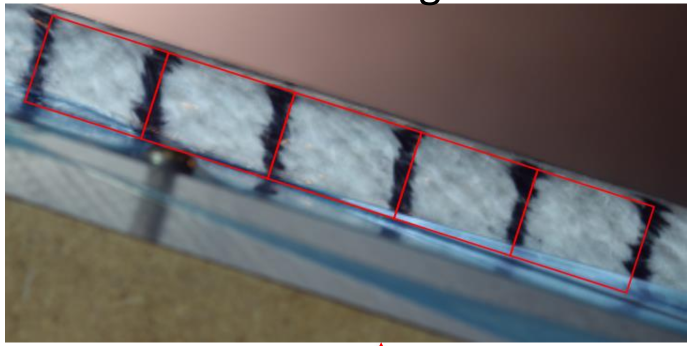
Experimental Forming of Preform [11]

Top transition

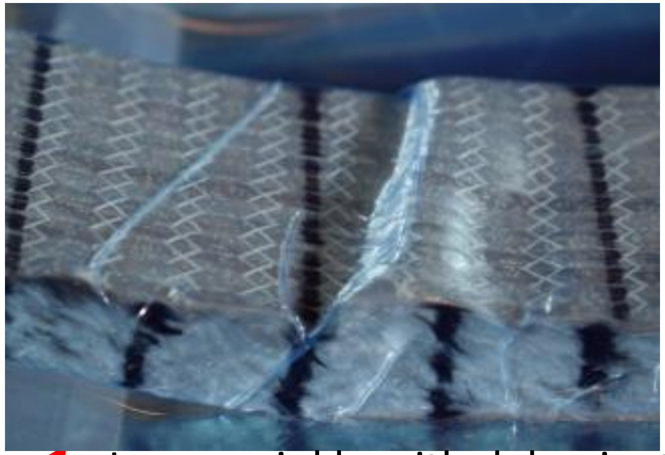
Large wrinkle with delamination

Shear region

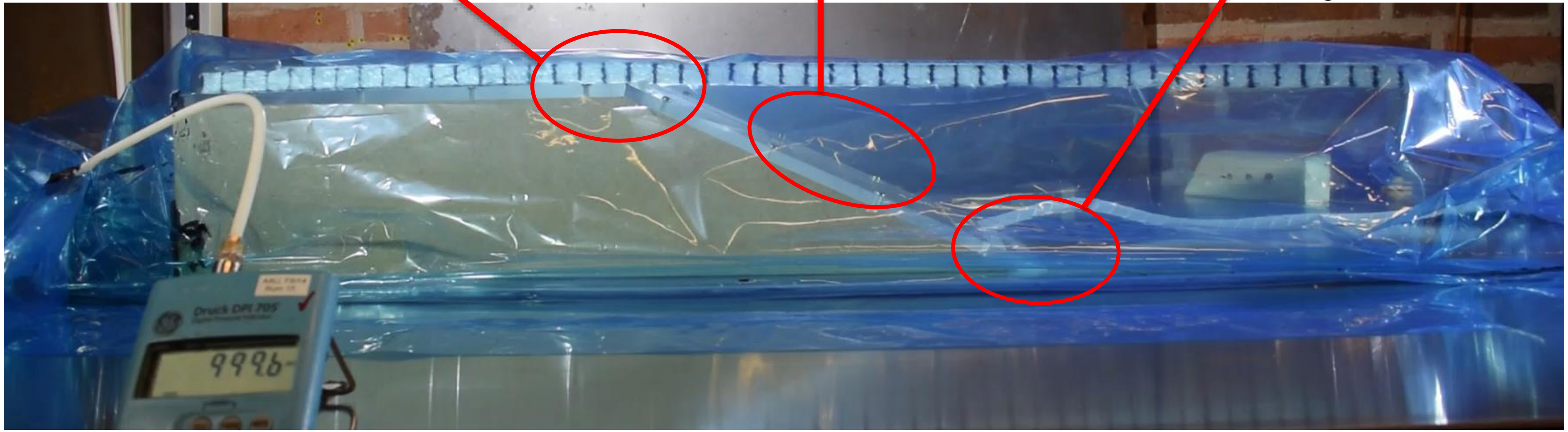
Transverse shearing



Bottom transition



Large wrinkle with delamination



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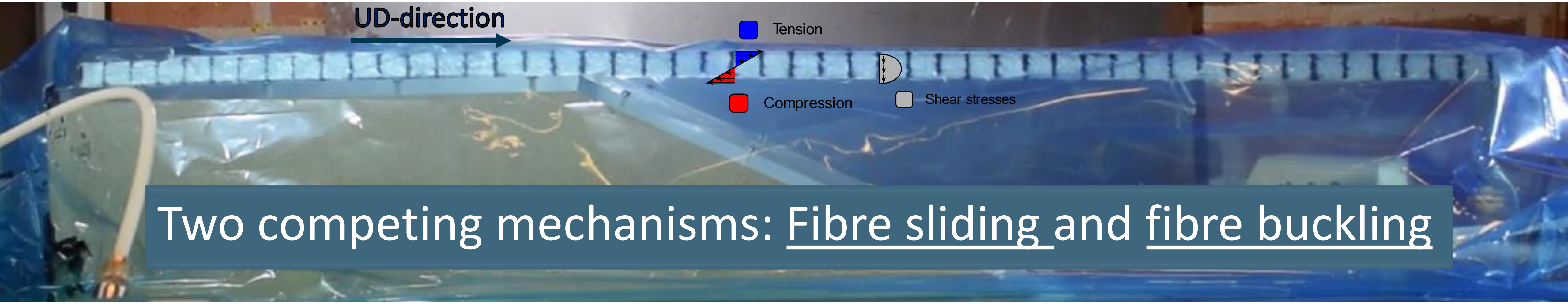
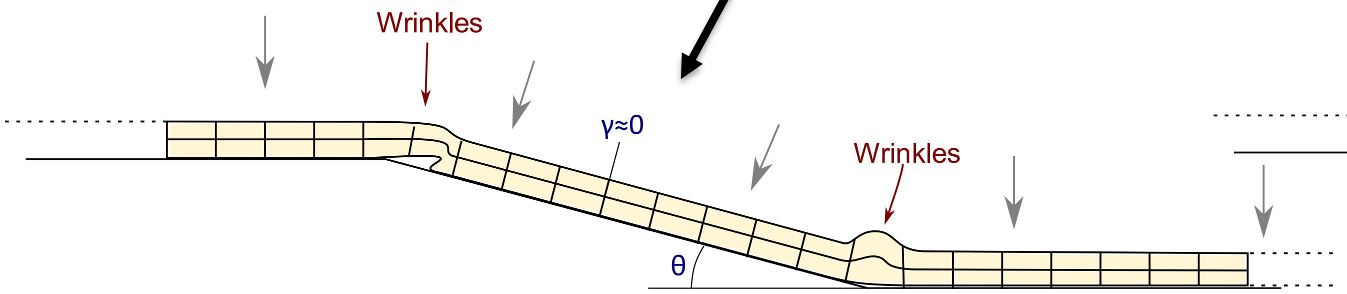
Governing Deformation Modes



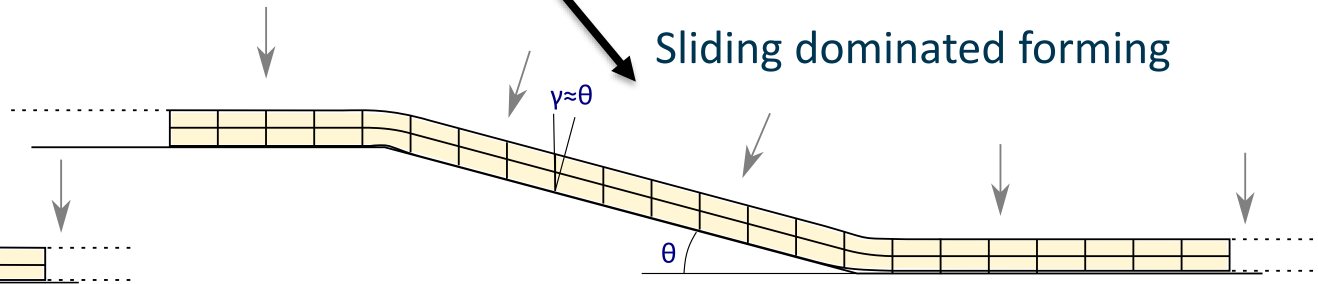
Two competing mechanisms: Fibre sliding and fibre buckling

Buckling dominated forming



Non-optimal forming

Sliding dominated forming



Optimal forming

Important deformation mechanisms:

- Bending of NCF → Wrinkling/Fibre instabilities
- Transverse shearing of preform → Fibre sliding
- Decohesion of binder → Onset of wrinkles

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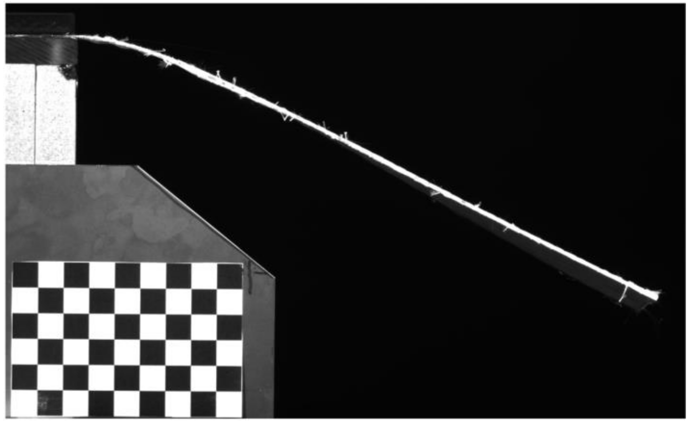
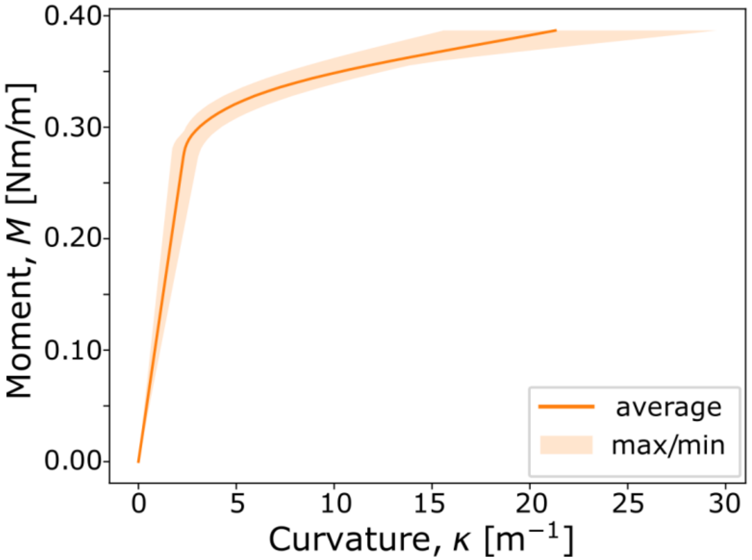
Material characterisation

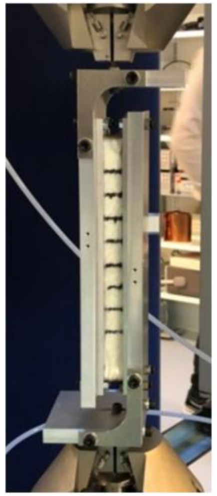
Cantilever bending test



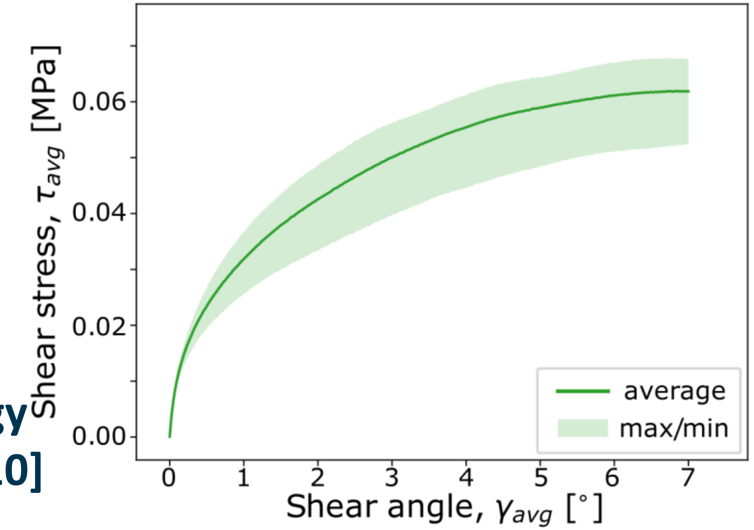
New methodology developed [9]



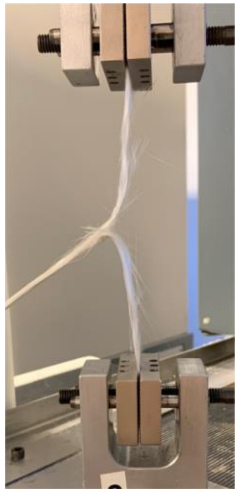
Transverse shear test

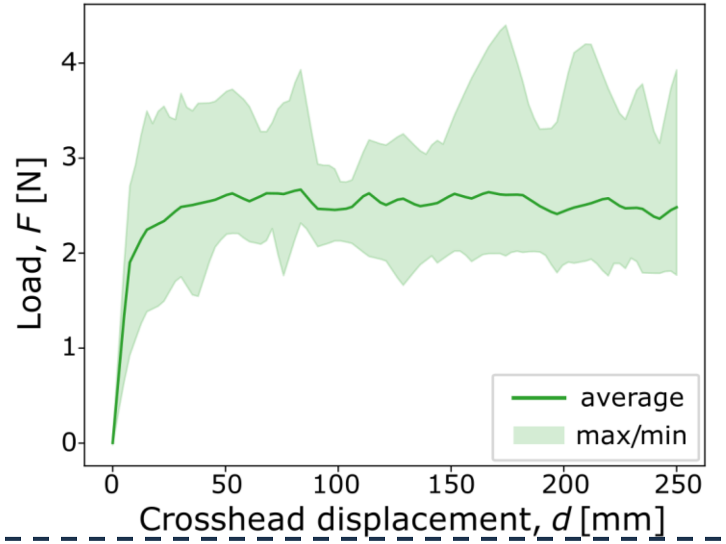


New methodology developed [10]



T-peel test





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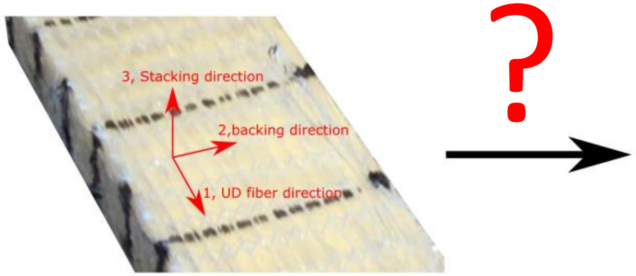
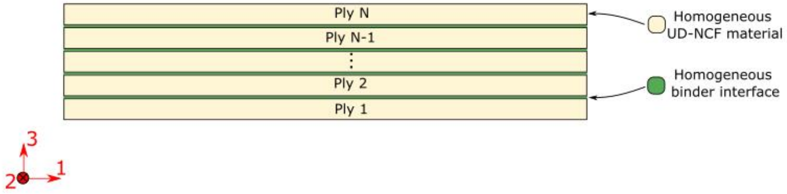
Modelling Strategy [8, 12]

Ply-by-ply macro-scale modelling approach

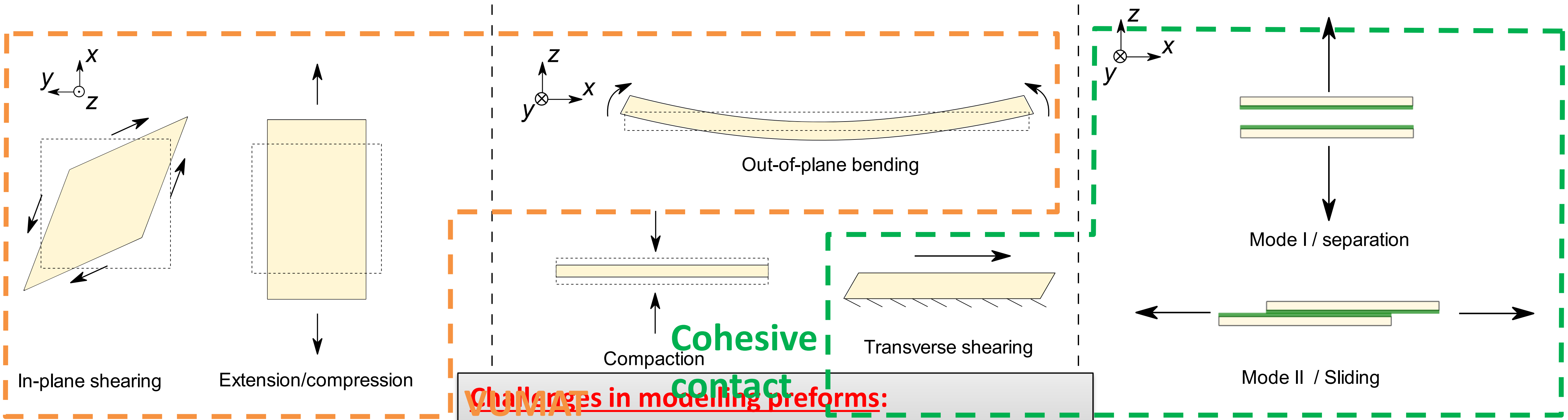


A 2D model is made in the 1-3 plane.



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

Deformation modes of the preform model

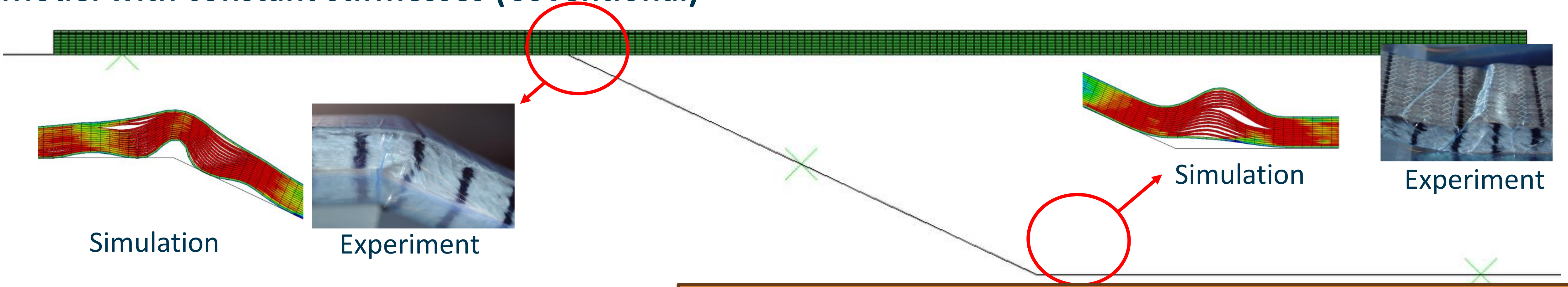


Challenges in modelling preforms:

- **Decouple the fabric stiffnesses**
- **Describe the material nonlinearities**

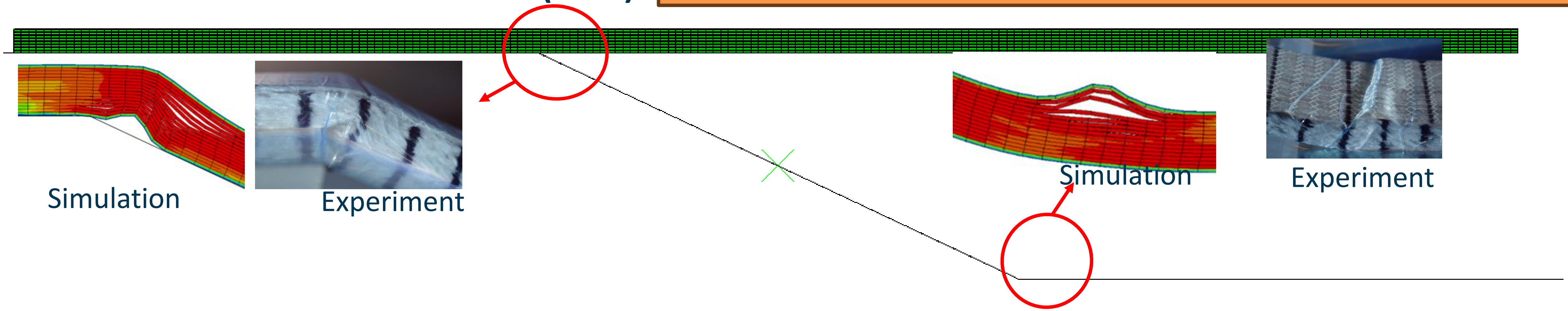
Simulation Results on Large Ramp

Model with constant stiffnesses (Coventional)



The new modelling framework improves the geometry of the predicted wrinkles by 35% to 94%!

Model with non-constant stiffnesses (New)



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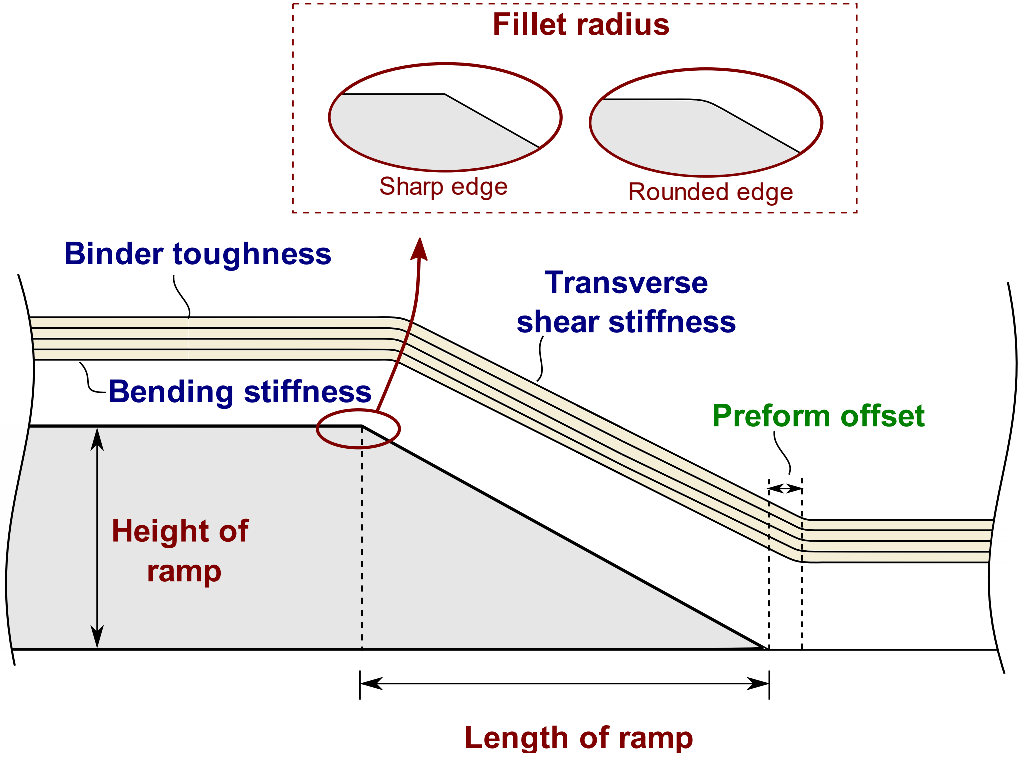
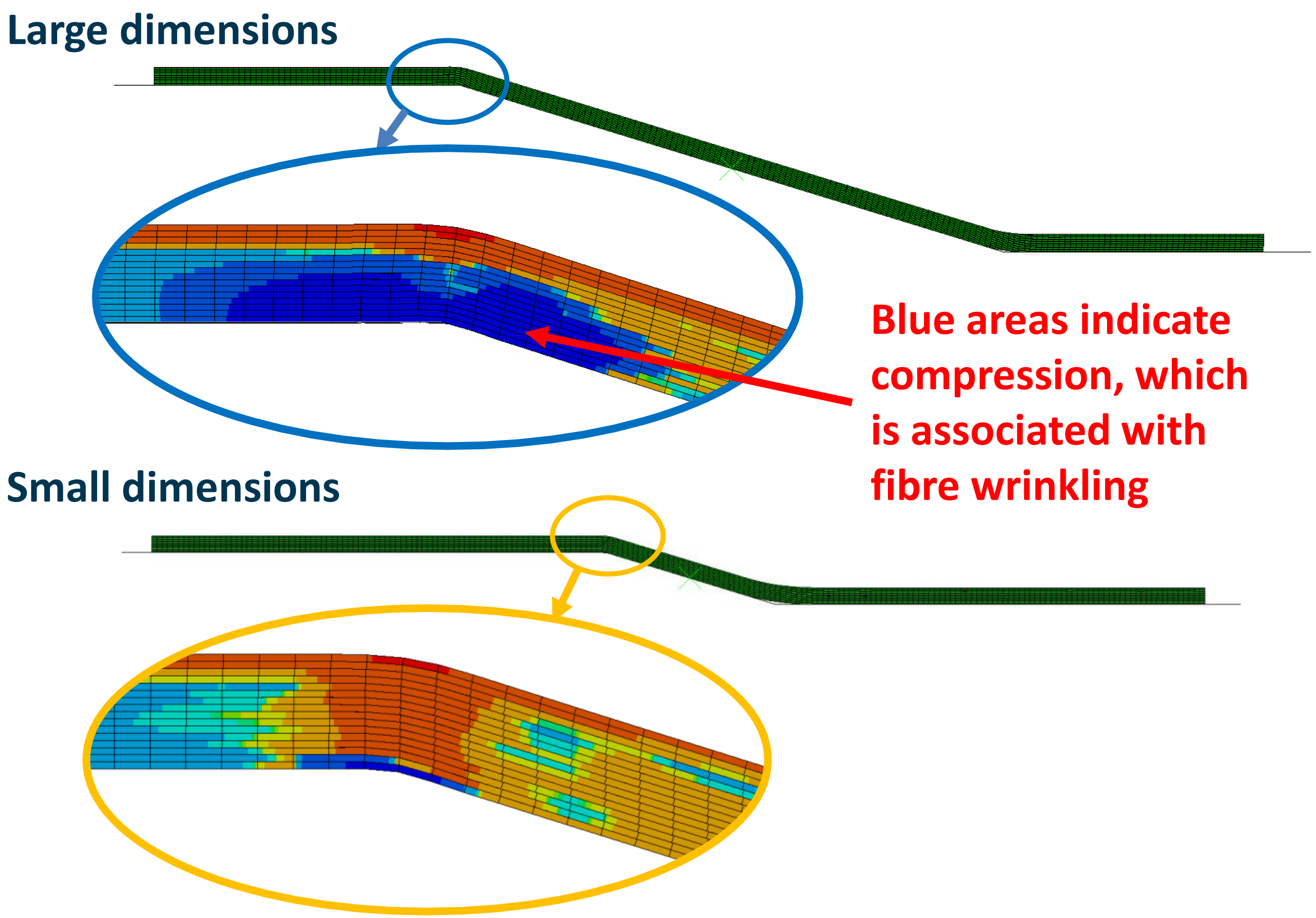
Parameter studies [13]



Parameter studies have been made considering variations in:

- **Ramp geometry**
- **Material properties**
- **Placement tolerances**

Small dimensions of the ramp enhance preform forming!



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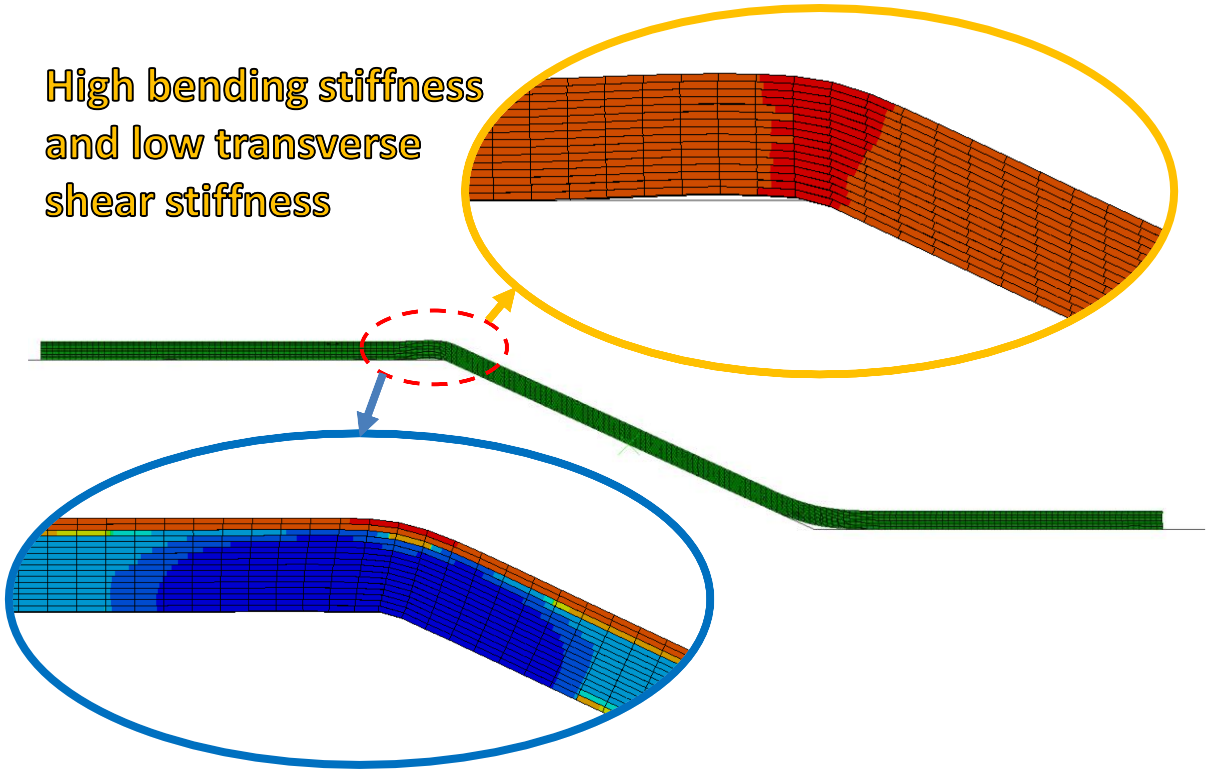
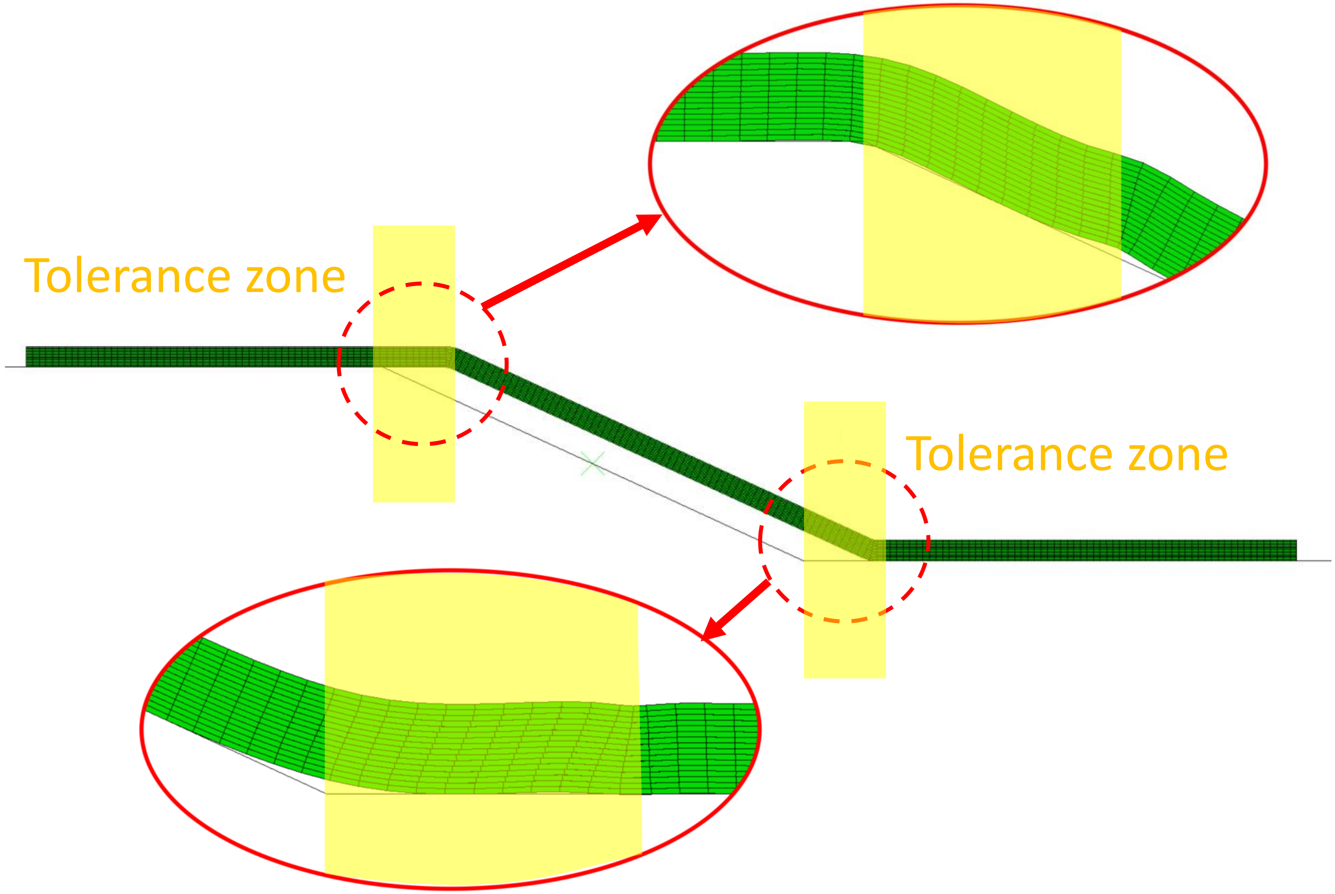
Parameter studies [13]

Large bending stiffness of the fabric and low transverse shear stiffness enhance preform forming!

High placement tolerances can be achieved by enabling preform to shear in tolerance zone!





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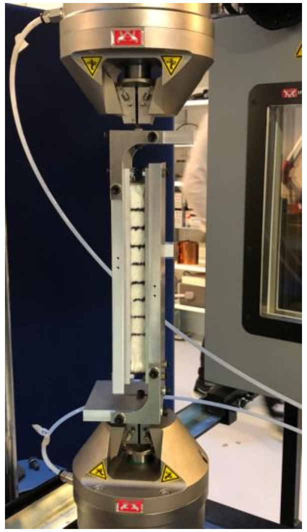
Conclusions and Impact

Simulation tool for predicting wrinkling in preforms during forming

Standardised characterisation for the industry to faster assess material quality

Modelling frameworks for use in aerospace and automotive sectors

Knowledge to enable faster and more reliable manufacturing of large wind turbine blades



[14]

[15]

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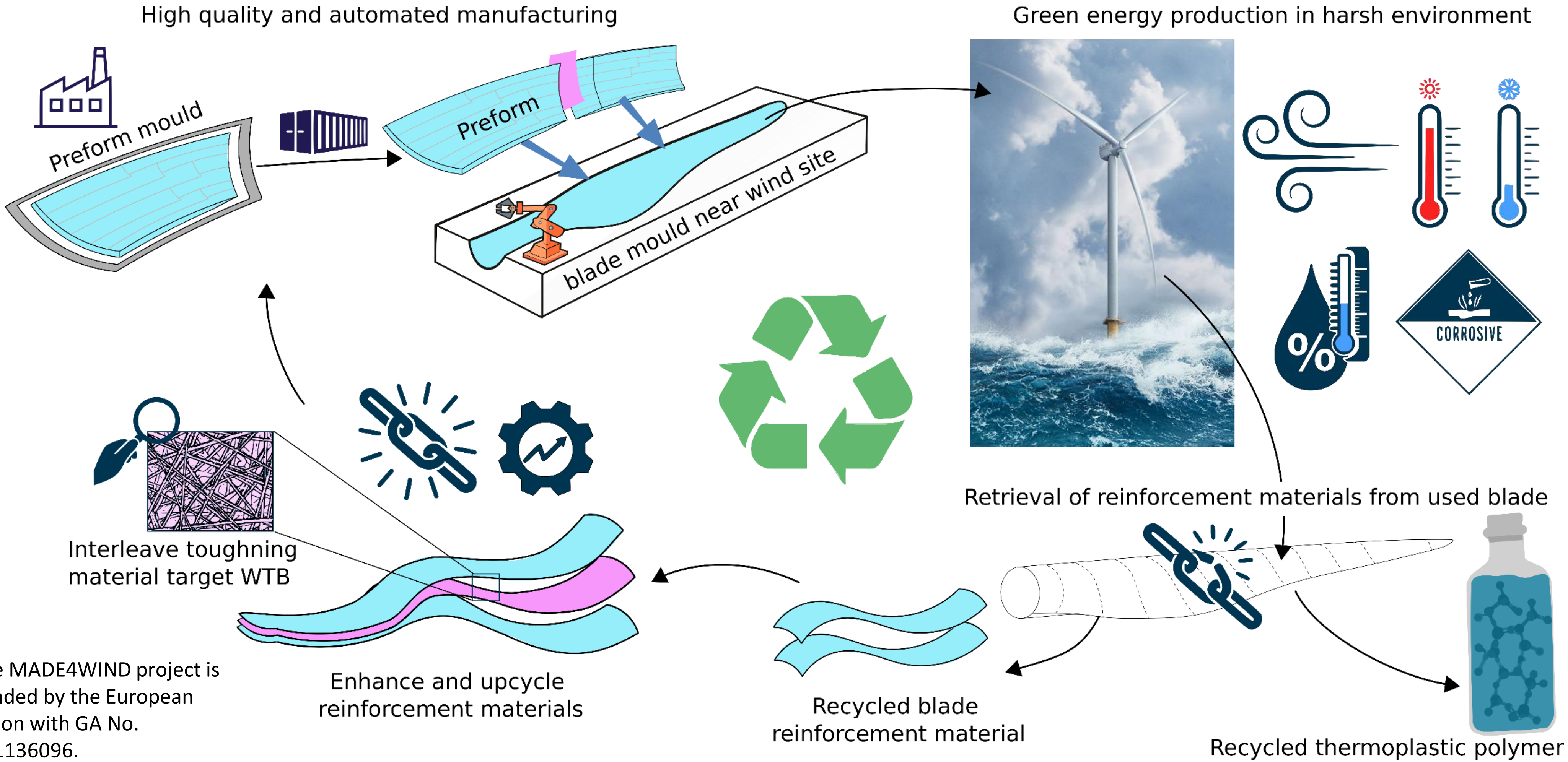
Future work: The MADE4WIND project!

The objective is to develop new blade technologies that will reduce blade production costs, increase reliability, reduce blade mass, and reduce waste through blade recycling



The MADE4WIND project is Funded by the European Union with GA No. 101136096.

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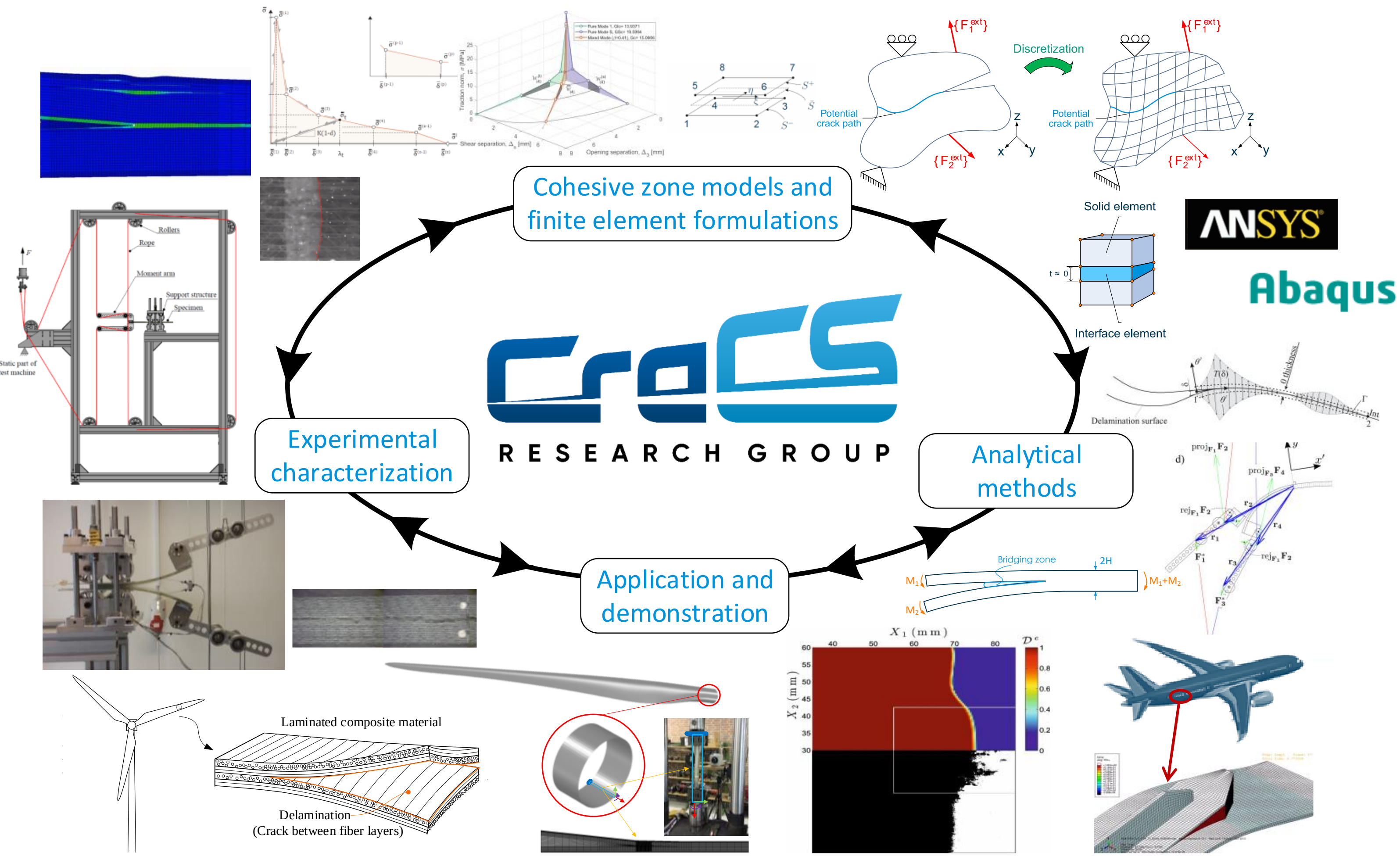
THANK YOU FOR YOUR ATTENTION



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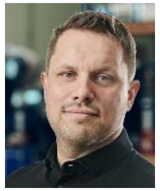
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[3] https://www.taipeitimes.com/News/taiwan/archives/2013/07/08/2003566614

[4] Bender, J. J., Hallett, S. R., & Lindgaard, E. (2019). Parametric study of the effect of wrinkle features on the strength of a tapered wind turbine blade sub-structure. *Composite Structures*, *218*, 120-129doi: 10.1016/j.compstruct.2019.02.065

[5] https://www.youtube.com/watch?v=S9_fwmdCyzo

[6] https://stateofgreen.com/en/news/the-worlds-first-wind-turbine-blade-beyond-100-meters/

[7] https://www.lmwindpower.com/en/stories-and-press/stories/news-from-lm-places/zebra-project-launched

[8] Broberg, P. H., Krogh, C., Lindgaard, E., & Bak, B. L. V. (2022). Simulation of Wrinkling during Forming of Binder Stabilized UD-NCF Preforms in Wind Turbine Blade Manufacturing. *Key Engineering Materials*, *926*, 1248-1256. doi:10.4028/p-165q46

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[11] Broberg, P. H., Lindgaard, E., Krogh, C., Thompson, A. J., Belnoue, J. P. H., Hallett, S. R., & Bak, B. L. V. (2024). That's how the preform crumples: Wrinkle creation during forming of thick binder-stabilised stacks of non-crimp fabrics. *Composites Part B: Engineering*, *273*, Artikel 111269. doi: 10.1016/j.compositesb.2024.111269

[12] Broberg, P. H., Lindgaard, E., Thompson, A. J., Belnoue, J. P.-H., Hallett, S. R., & Bak, B. L. V. (2024). An accurate forming model for capturing the nonlinear material behaviour of multilayered binder-stabilised fabrics and predicting fibre wrinkling. *Composites Part B: Engineering*, *274*, Artikel 111268. doi: 10.1016/j.compositesb.2024.111268

[13] Broberg, P. H., Lindgaard, E., Thompson, A. J., Belnoue, J. P.-H., Hallett, S. R., & Bak, B. L. V. (2024). Parametric study on the effect of material properties, tool geometry, and tolerances on preform quality in wind turbine blade manufacturing. *Submitted for review*

[14] https://www.airbus.com/en/products-services/commercial-aircraft/passenger-aircraft/a350-family

[15] https://reform-support.ec.europa.eu/what-we-do/green-transition_en

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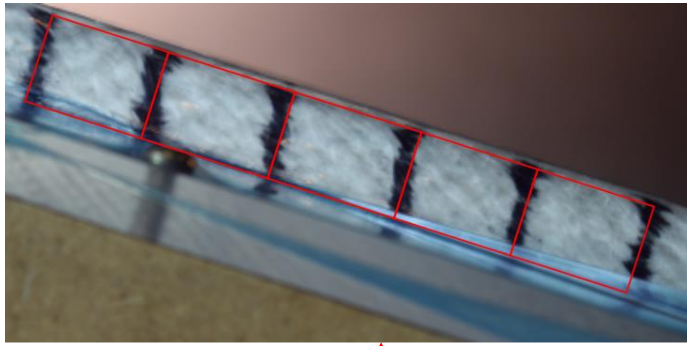
Bonus slides

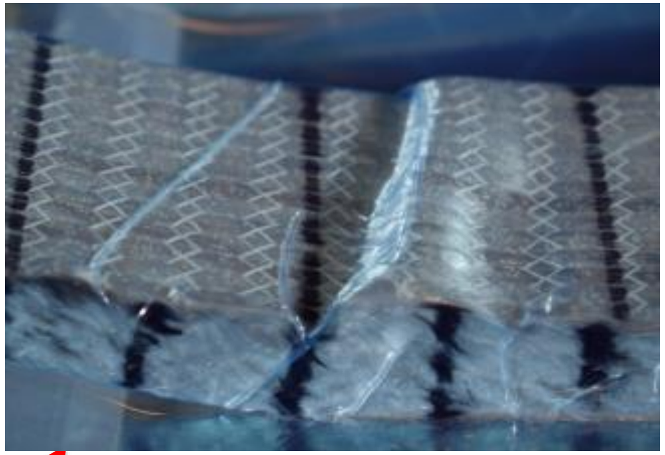
Results from Geometry 1 (Large Ramp)

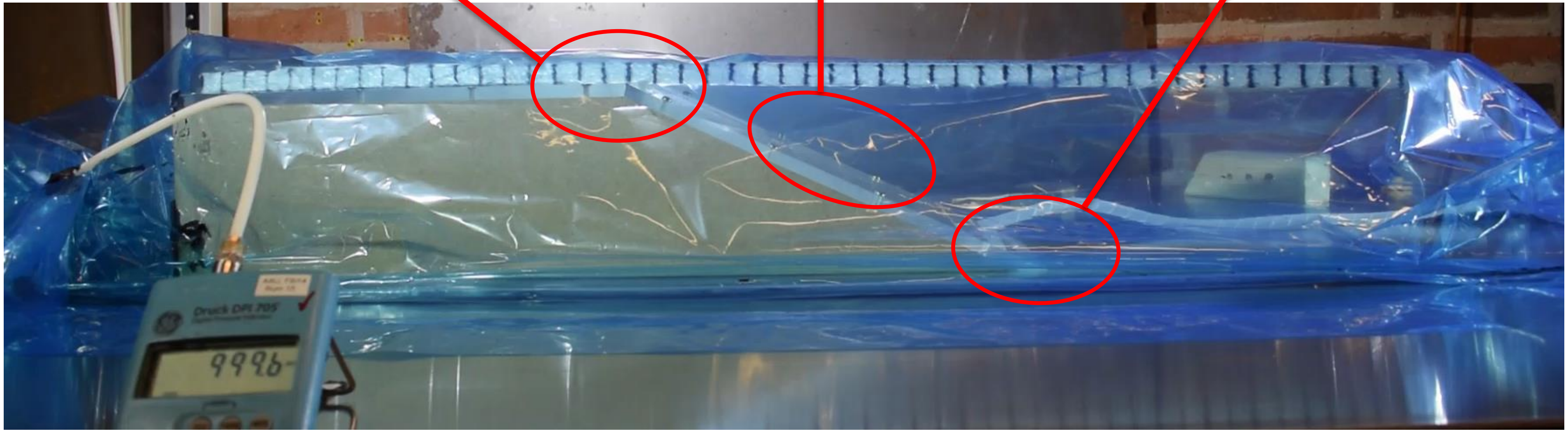
Top transition

Shear region



Bottom transition





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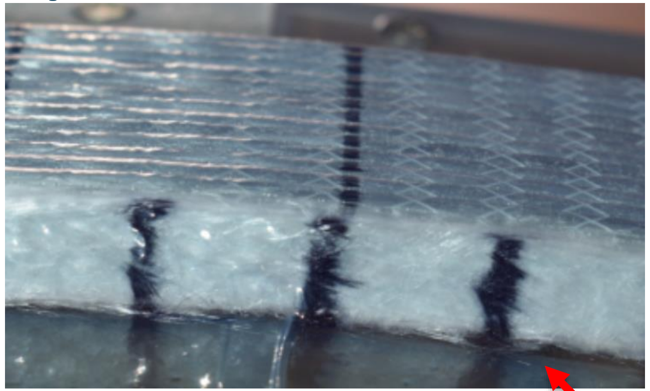
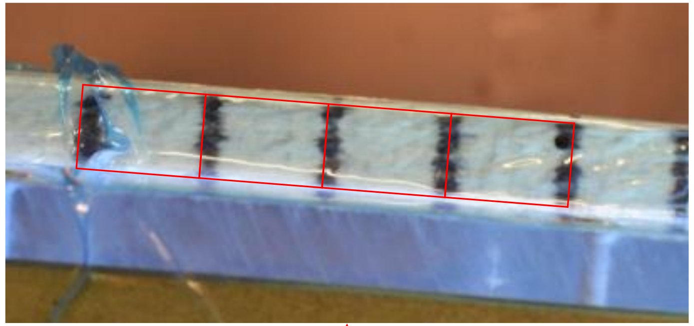
Results from Geometry 2 (Small Ramp)

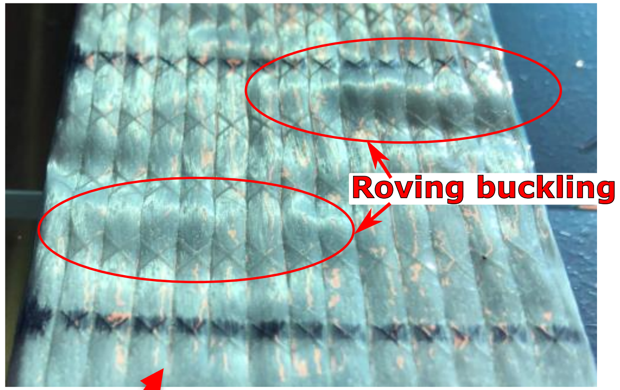
Top transition

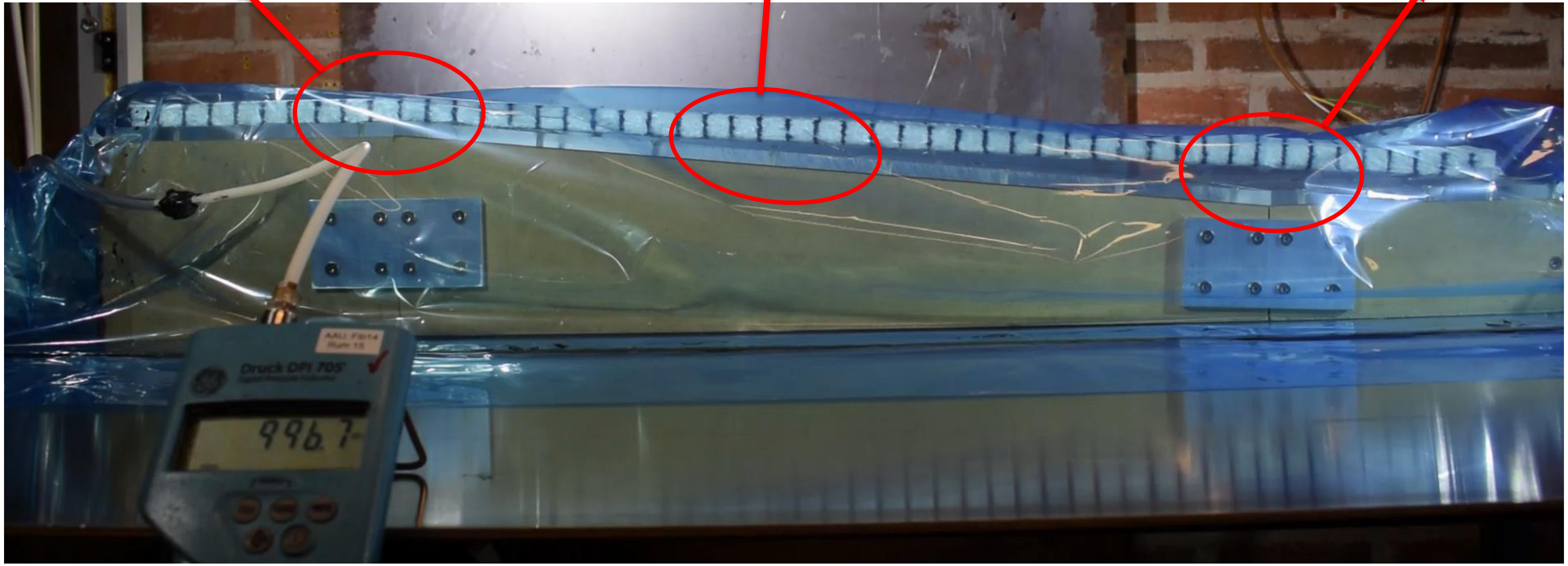


Shear region



Bottom transition





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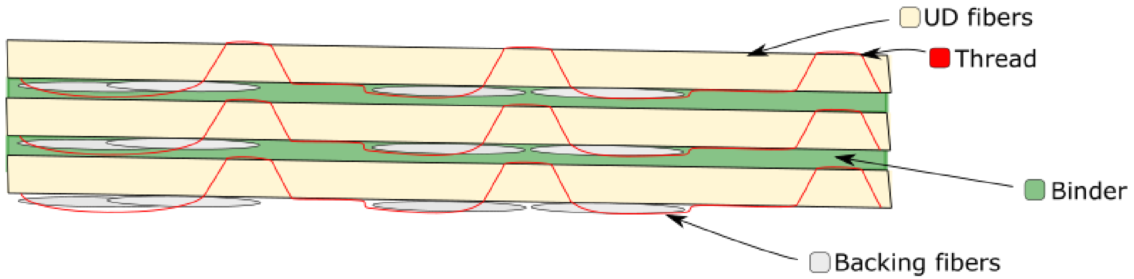
Wrinkle Mechanisms

Initial straight prefom with no loading



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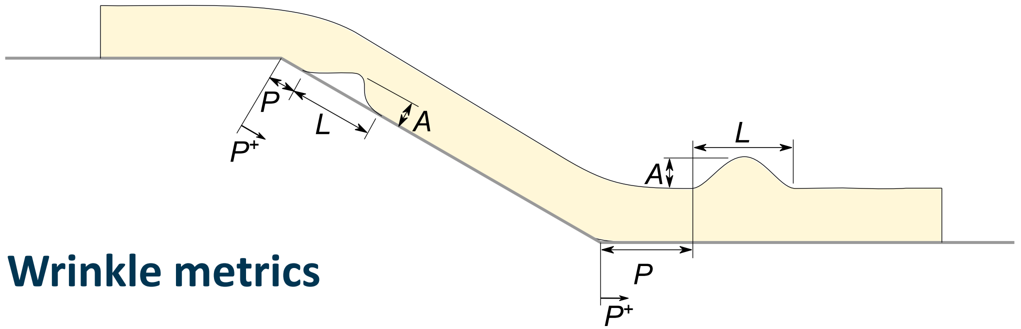
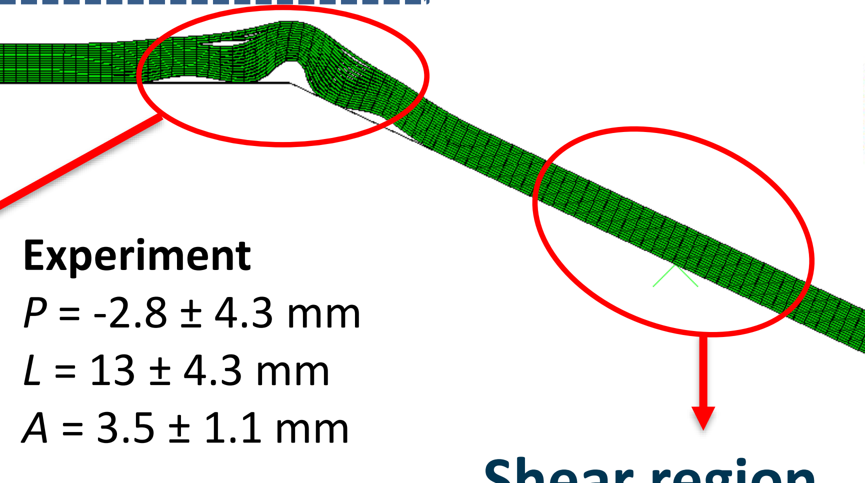
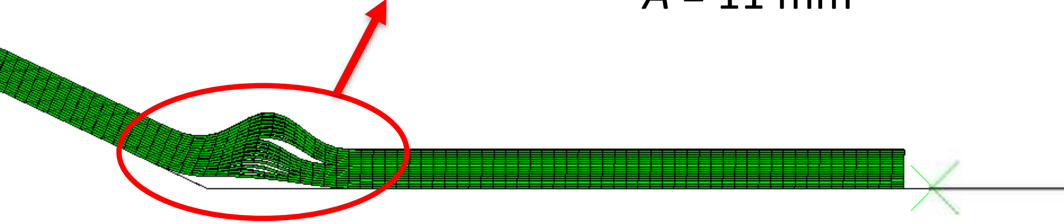
Comparison with the Conventional Model

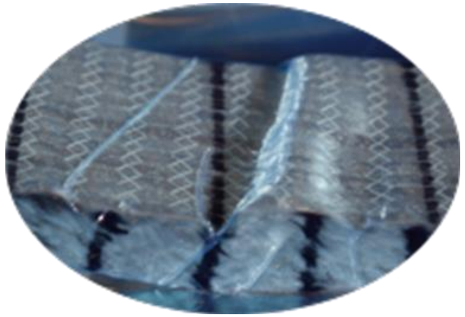


Wrinkle metrics

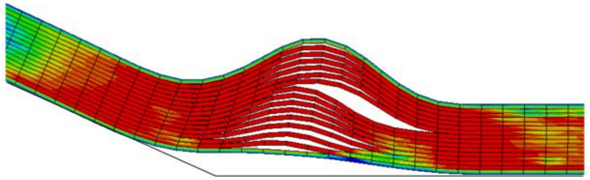




Bottom transition



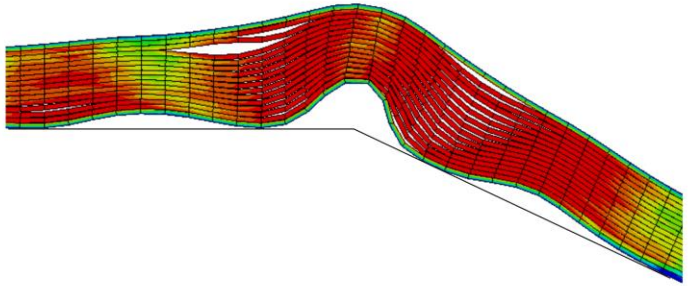
Experiment
P = +29 ± 28 mm
L = 37 ± 8.6 mm
A = 4.6 ± 1.4 mm



Simulation
P = -2 mm
L = 54 mm
A = 11 mm

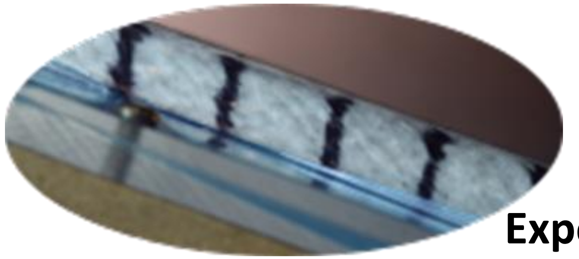
Top transition

Experiment
P = -2.8 ± 4.3 mm
L = 13 ± 4.3 mm
A = 3.5 ± 1.1 mm

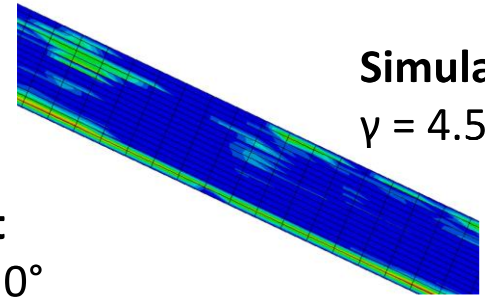


Simulation
P = -17 mm
L = 30 mm
A = 12 mm

Shear region



Experiment
γ = 7.1° ± 1.0°



Simulation
γ = 4.5°

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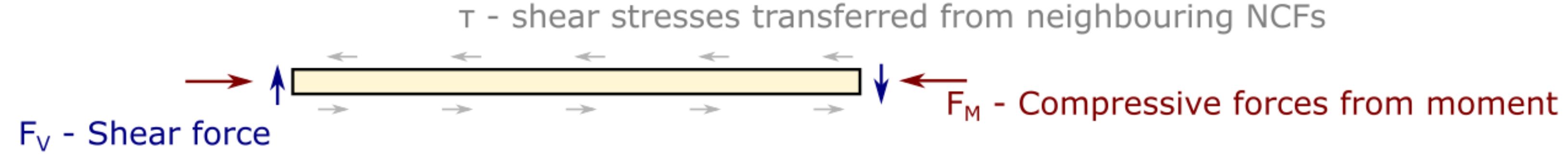
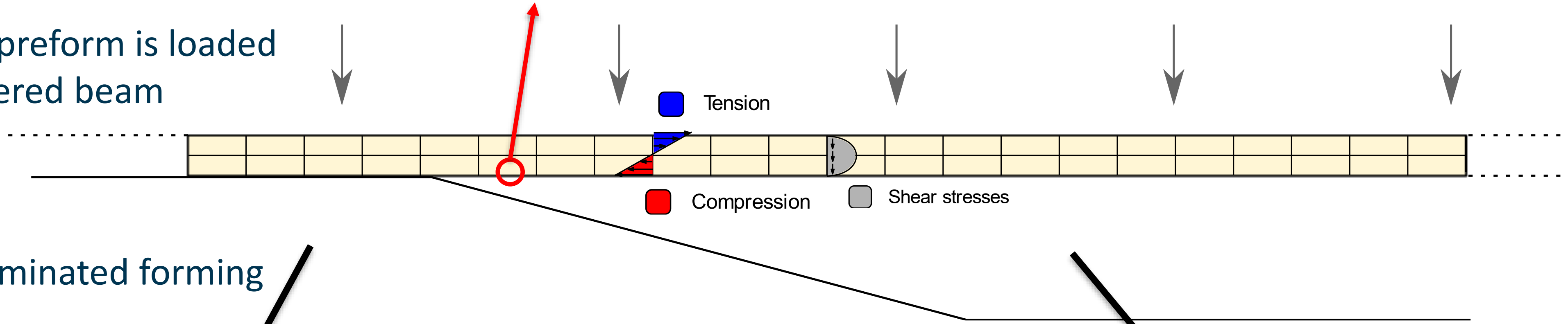
Governing Deformation Modes

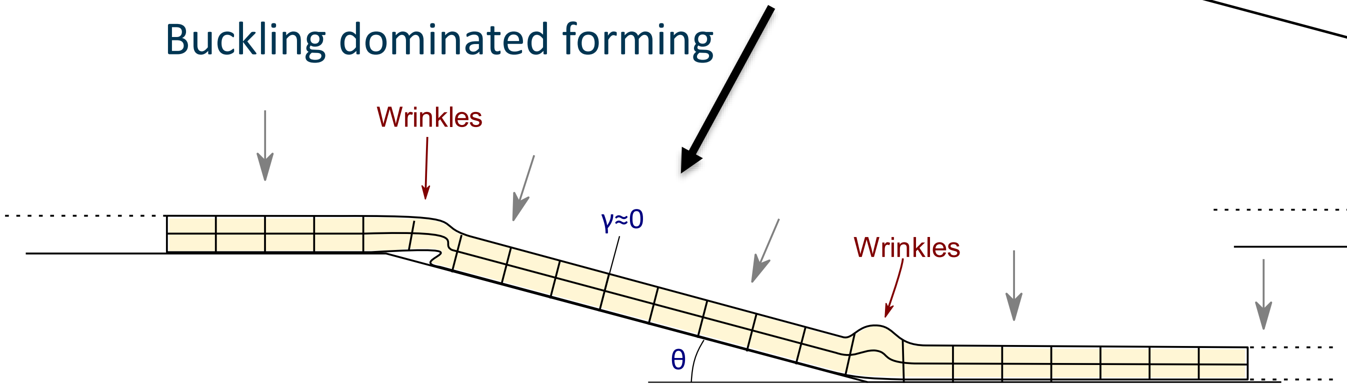
Loads on UD-NCF on compression side



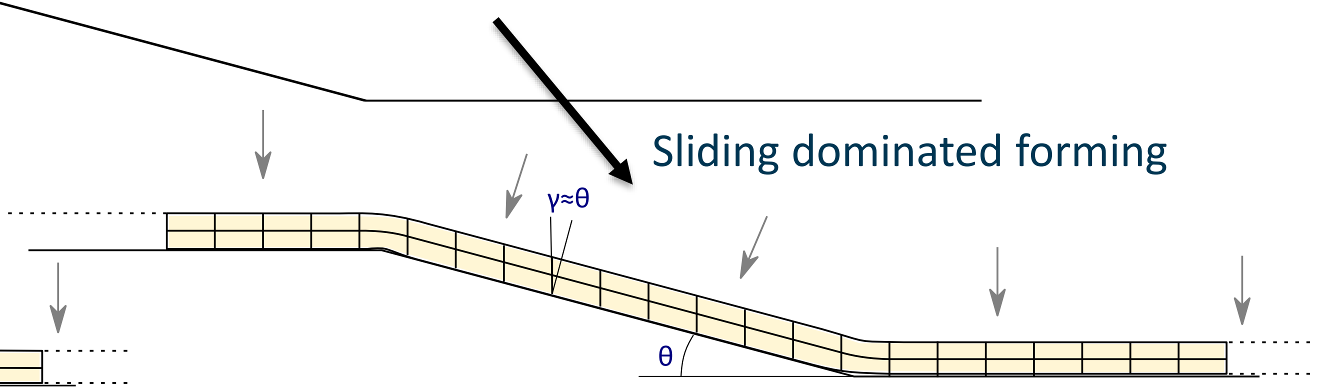
During forming the preform is loaded similar to a cantilevered beam



Buckling dominated forming



Sliding dominated forming



Non-optimal forming

Optimal forming

<u>Important deformation modes:</u>

- Bending of NCF → Wrinkling/Fibre instabilities
- Transverse shearing of preform → Fibre sliding
- Decohesion of binder → Onset of wrinkles

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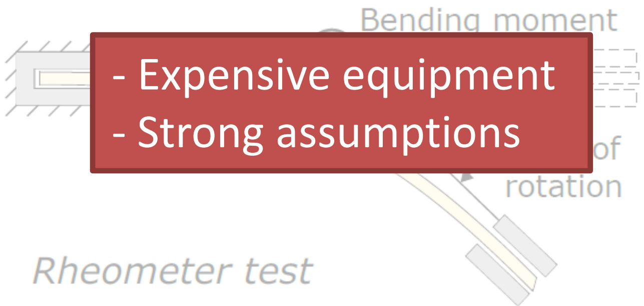
Paper B

Title:

One-click bending stiffness: Robust and reliable automatic calculation of moment-curvature relation in a cantilever bending test

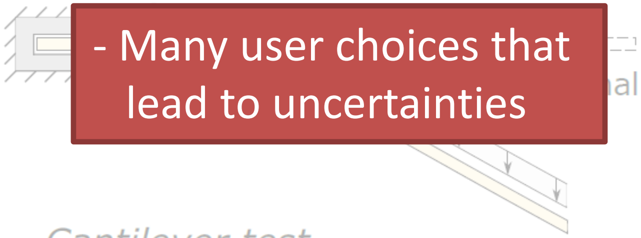
Direct methods



- Expensive equipment
- Strong assumptions

Rheometer test

In-direct methods



- Many user choices that lead to uncertainties

Cantilever test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One-click bending stiffness: Robust and reliable automatic calculation of moment–curvature relation in a cantilever bending test

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ARTICLE INFO

Keywords:
A. Fabrics/textiles
D. Mechanical testing
Bending stiffness
Smoothing spline
Cross-validation

ABSTRACT

The cantilever bending test is one of the simplest and most widely used methods to estimate the bending stiffness of textile materials. A nonlinear moment–curvature relationship can be computed from a single image of a cantilevered textile specimen. However, the calculation of curvature involves second-order differentiation of noisy data, which leads to noise amplification. Traditionally, this is handled by subjectively choosing one of many functions to fit the data or by manual tuning of fitting parameters. The user choices ultimately lead to uncertainties in the data fit. This paper presents a novel automatic data processing method for the cantilever test using smoothing splines with automatic parameter selection through cross-validation. The method is verified on a simulated deflection curve with known bending stiffness and then used to characterise real textile specimens. Finally, the method is validated by simulating the deflection curve using the computed stiffness. This method makes it possible, for the first time, to accurately predict the textile curvature even in the presence of severe noise, without needing user inputs prone to human error. The code used for this paper is freely available with sample data on the repository at https://doi.org/10.5281/zenodo.7376939.

1. Introduction

The stiff and strong behaviour of fibre composite materials makes them attractive in many applications where lightweight structures are desired. This includes the aero-space, automotive, and wind energy industries. The desirable material properties of fibre composites come with the cost of complex manufacturing. To accommodate this, process simulation models may be used to predict the occurrence of manufacturing defects and final fibre orientation of composite parts [1–5]. Simulation of composite manufacturing processes is often done on a macro-scale, assuming homogeneous properties of the textile, to make them computational efficient [6]. The early models neglected the out-of-plane properties of the textiles and primarily focused on the in-plane shear behaviour. However, more recent literature shows that the bending stiffness of textiles plays a huge role in the manufacturing process, especially in the formation and size of wrinkles [7]. It is known that wrinkles may be critical for the structural strength of fibre composite laminates [8,9], which makes the correct characterisation of textile bending stiffness important.

The bending behaviour of textiles is much different from homogeneous materials as the textile structure consists of thin fibres that can move relative to each other. Effectively, this means that textiles subjected to bending kinematically behave very differently than described by classical beam theories, like Bernoulli–Euler and Timoshenko [10]. Despite this, the bending stiffness, B, for textile materials is often defined as the relation between the moment, M, and the curvature, κ, of the textiles' midline, $M = B\kappa$. The effect of transverse loads on the specimen is also often neglected. Classical beam theories define the bending stiffness as $B = EI$, where E is Young's modulus of the material and I is the area moment of inertia. Because of relative fibre movement during textile bending, the macro-scale bending stiffness should be decoupled from the membrane stiffness in textile modelling [11–13]. This means that the bending stiffness needs to be characterised separately. Moreover, textiles typically have a highly nonlinear bending behaviour with higher bending stiffness at lower curvatures [14–16].

Different methods for characterising textile bending stiffnesses have been proposed in the literature. One of the first and most simple

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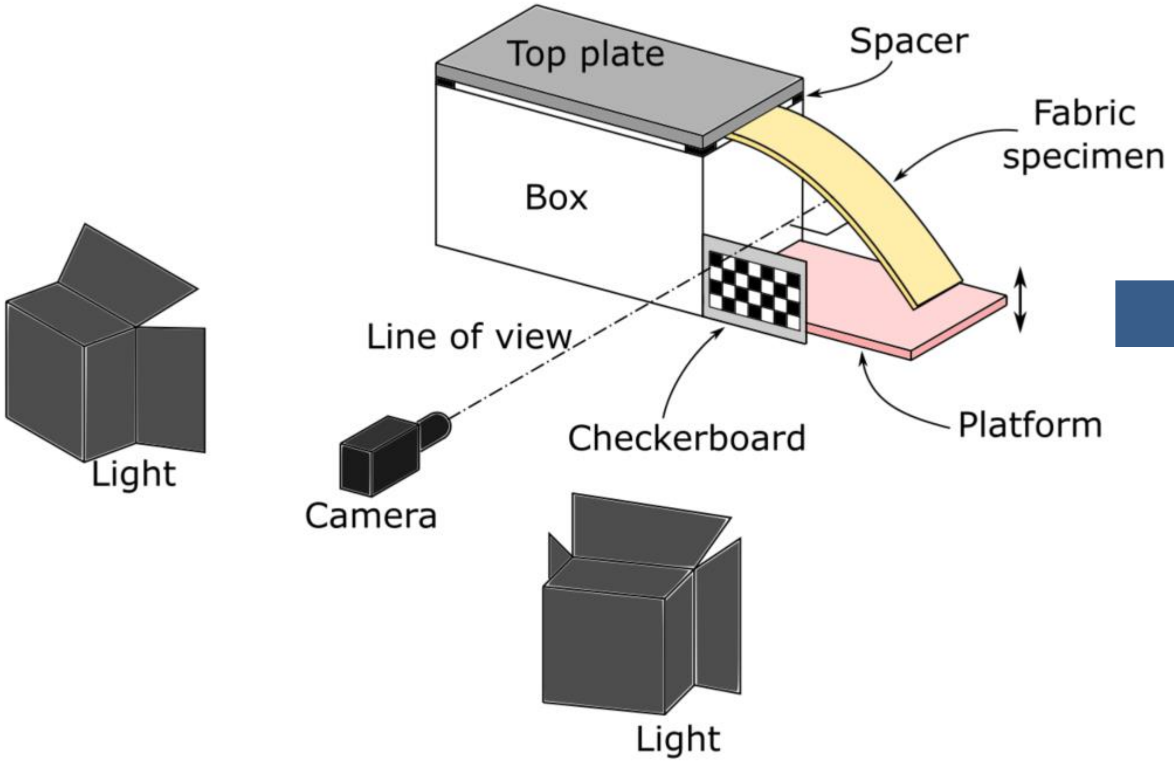
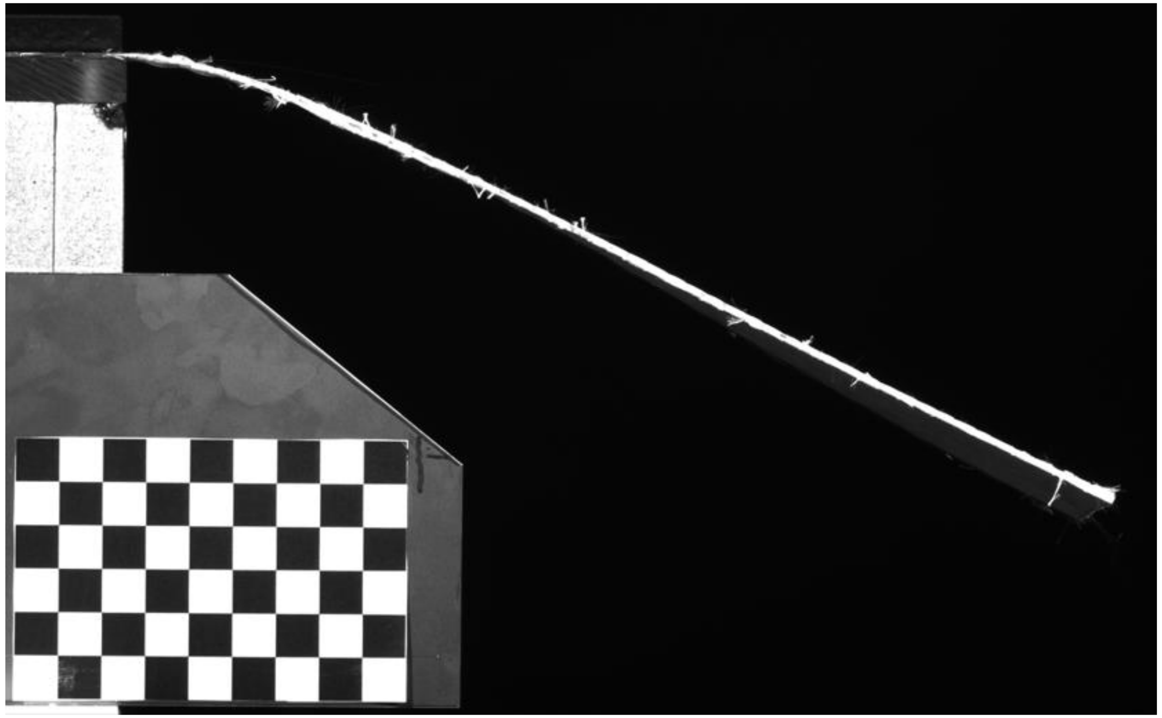
Available online 28 April 2023

Paper B: Methodology - Experimental Setup

Experimental setup



Input image



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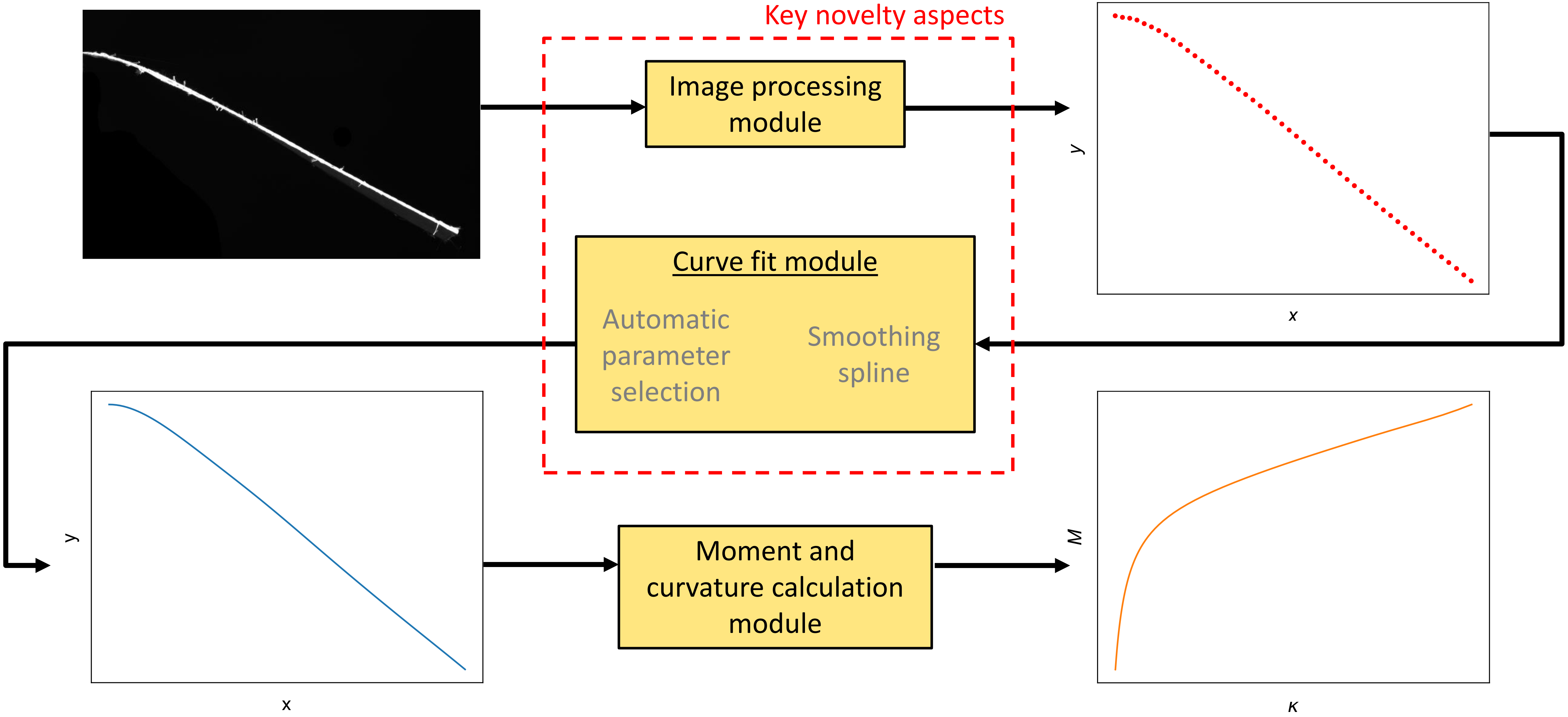
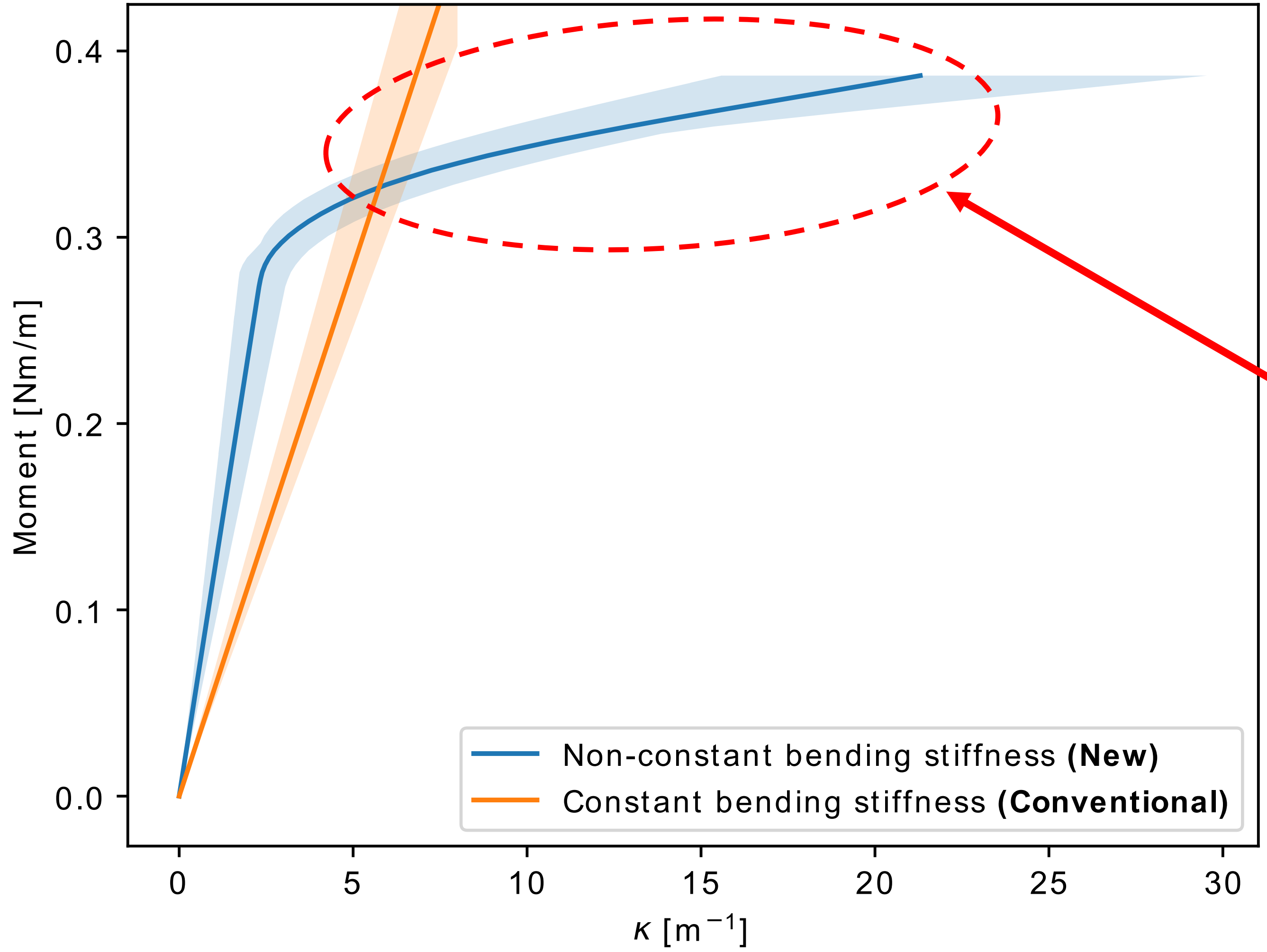
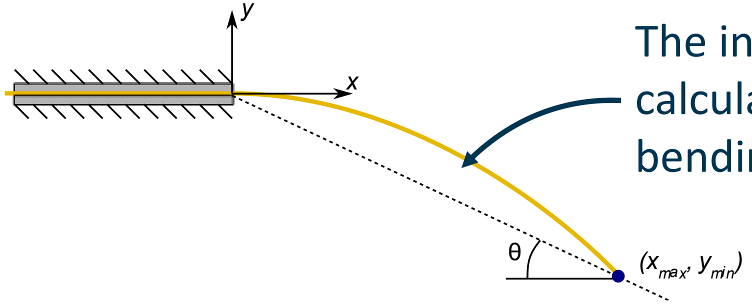
Paper B: Methodology – Data Processing



Paper B: Results



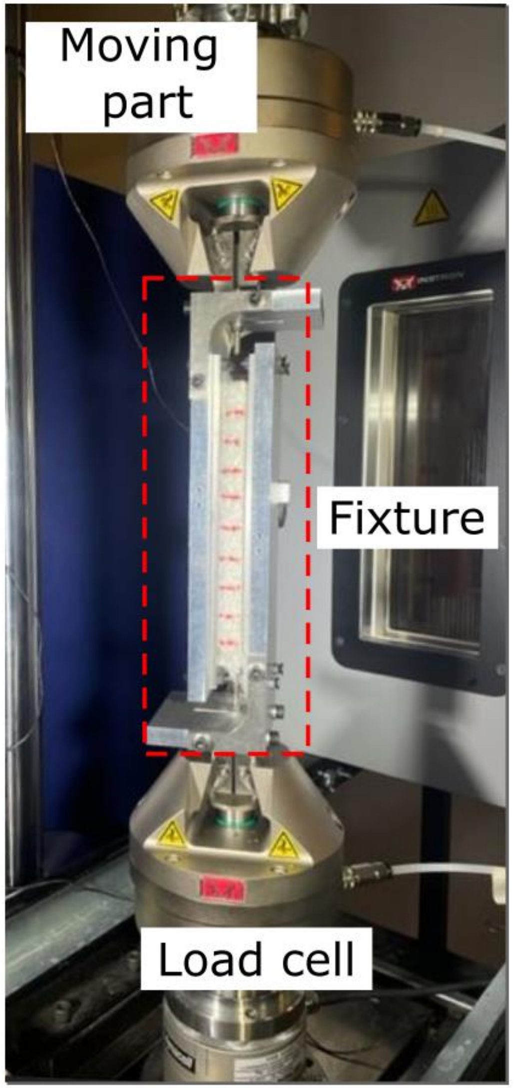


The inclined plane used to calculate the constant bending stiffness

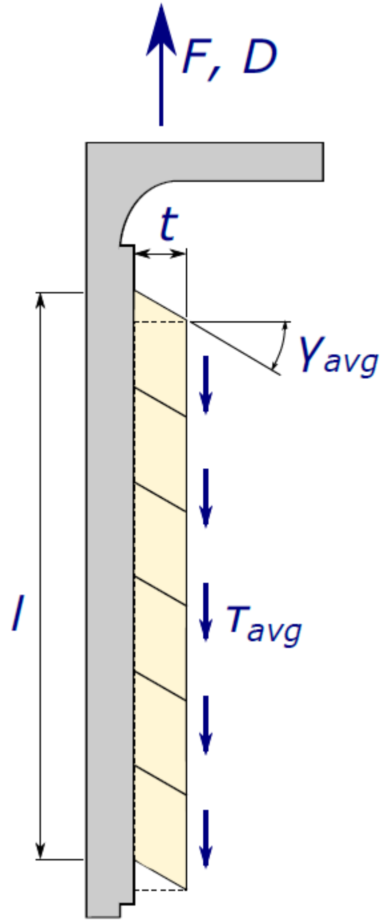
Wrinkles are associated with high curvatures!

Paper C: Methodology

Test setup



Data processing



$$\gamma_{avg} = \tan^{-1}\left(\frac{D}{t}\right), \tau_{avg} = \frac{F}{l\,w}$$

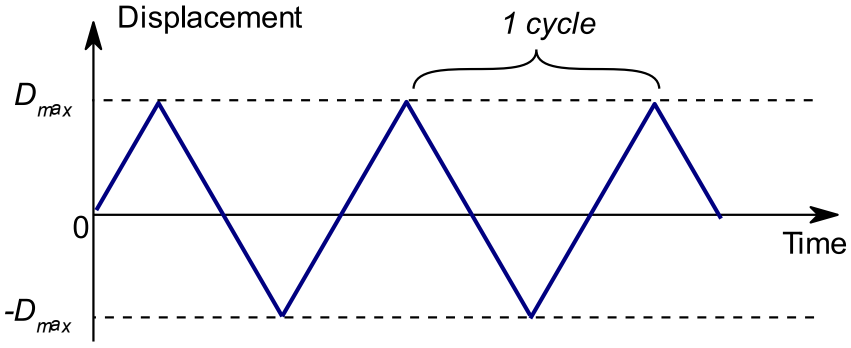
Test campaigns

Monotonic campaign:

- Deformation rates:
  - 2 mm/min
  - 20 mm/min
  - 60 mm/min

Cyclic campaign

- Deformation amplitude
  - 0.5 mm
  - 4.0 mm
- 20 cycles



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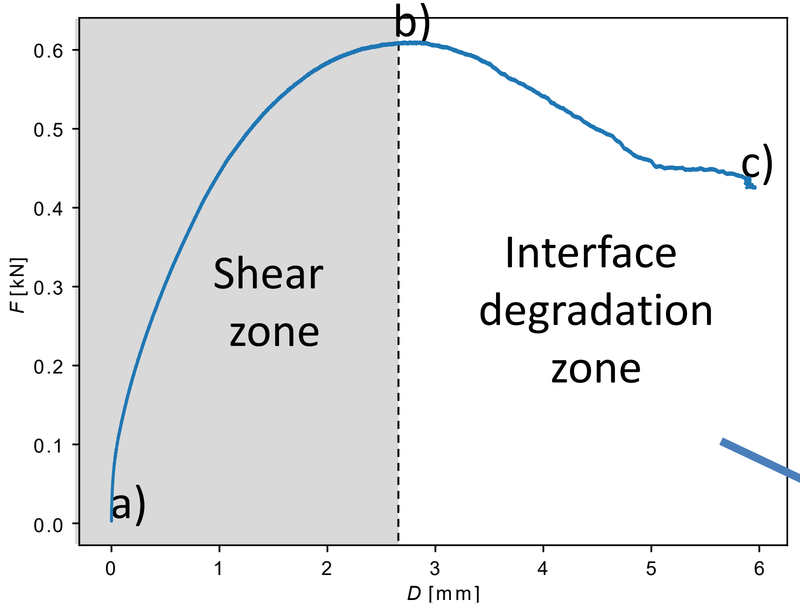
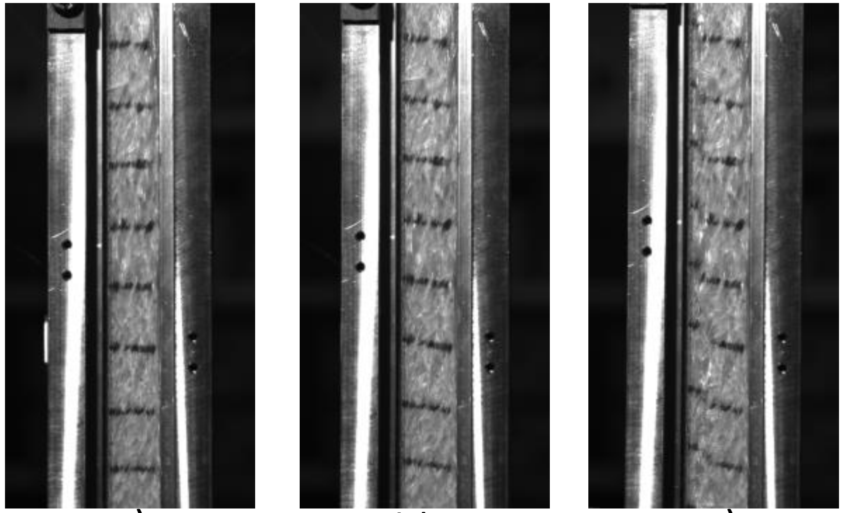
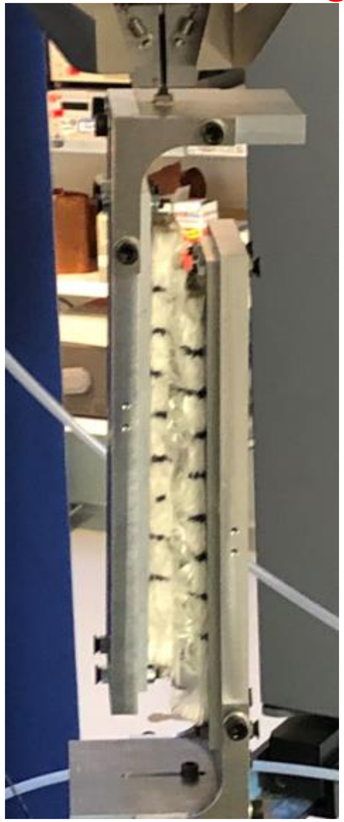
Paper C: Results from Monotonic Tests



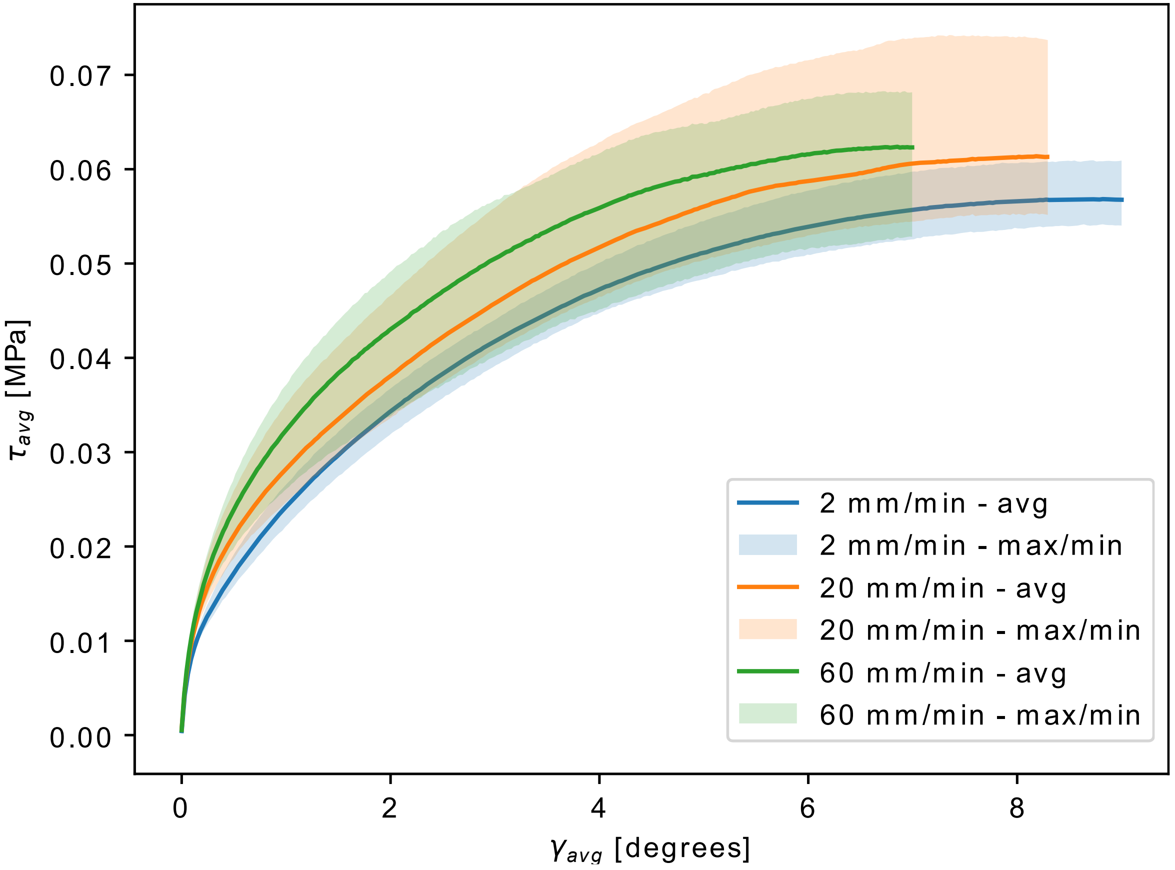


a) b) c)

The interface degradation zone should not be reached during manufacturing



Different deformation rates



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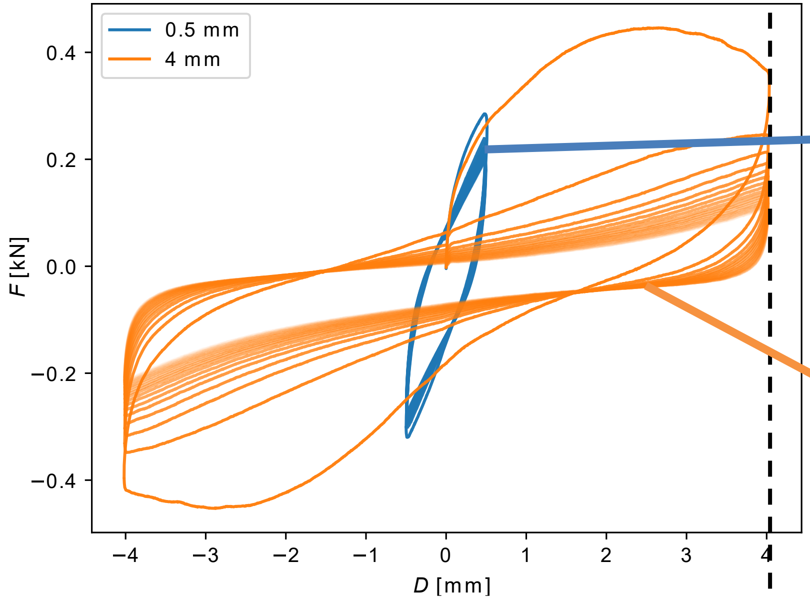
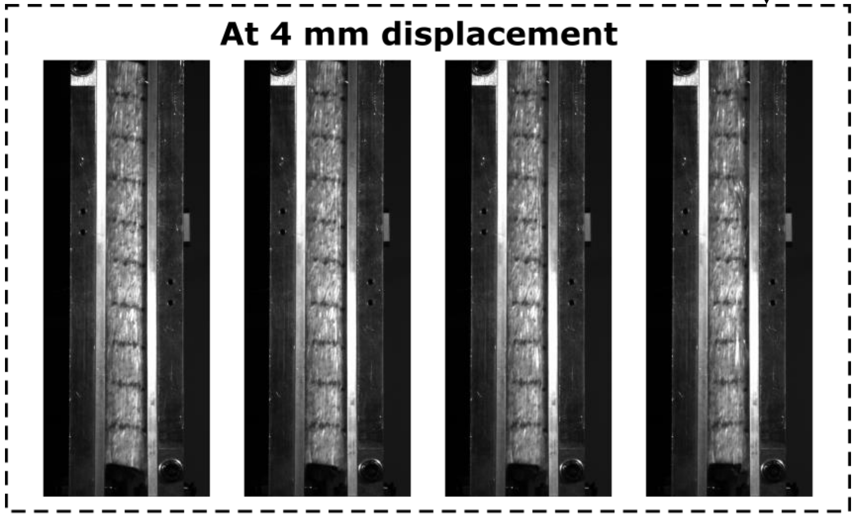
Paper C: Results from Cyclic Tests

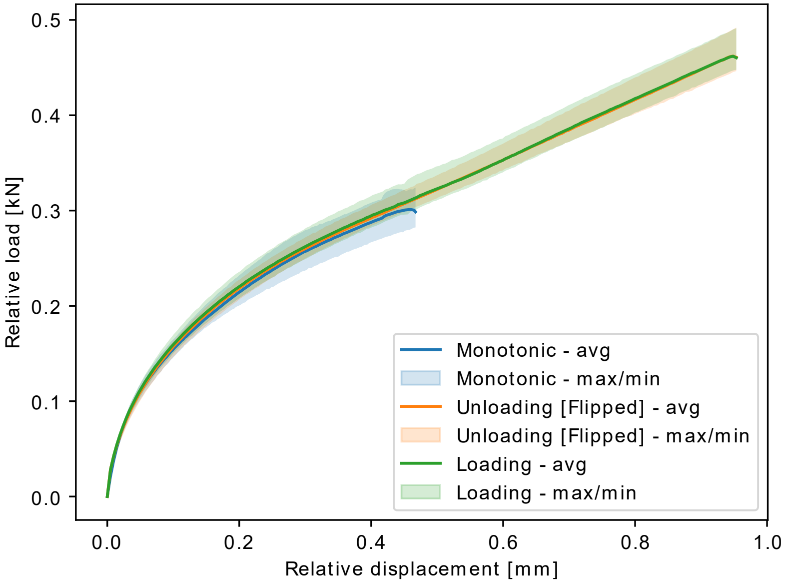


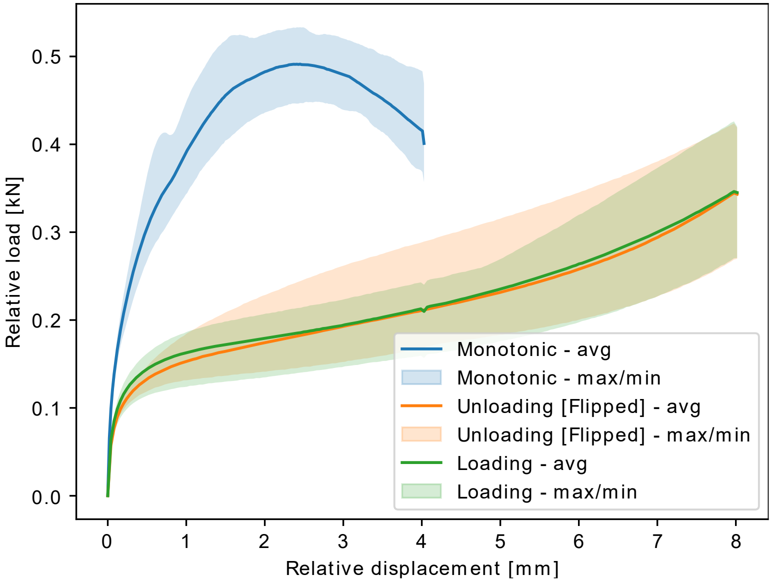
Repeated loading in the shear zone

Repeated loading in the interface degradation zone



0st cycle 1st cycle 4th cycle 19th cycle





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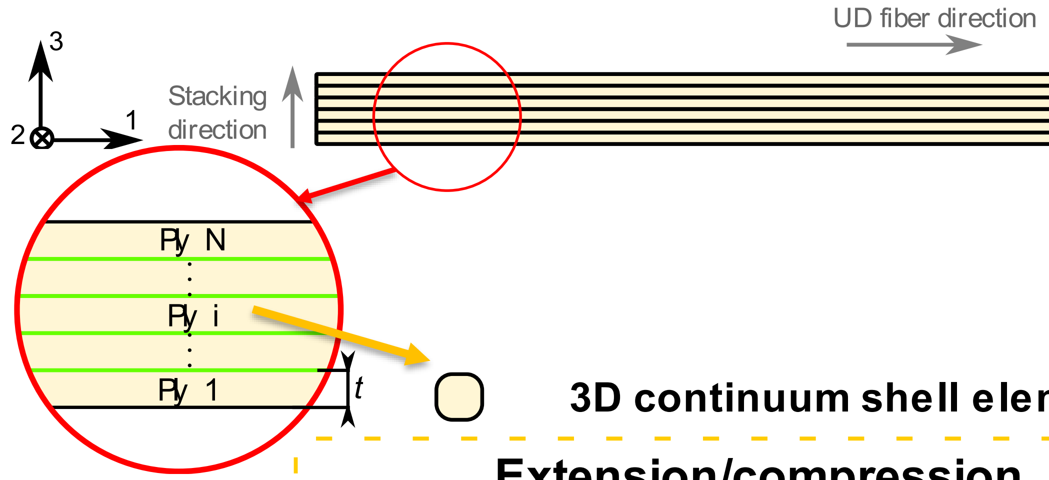
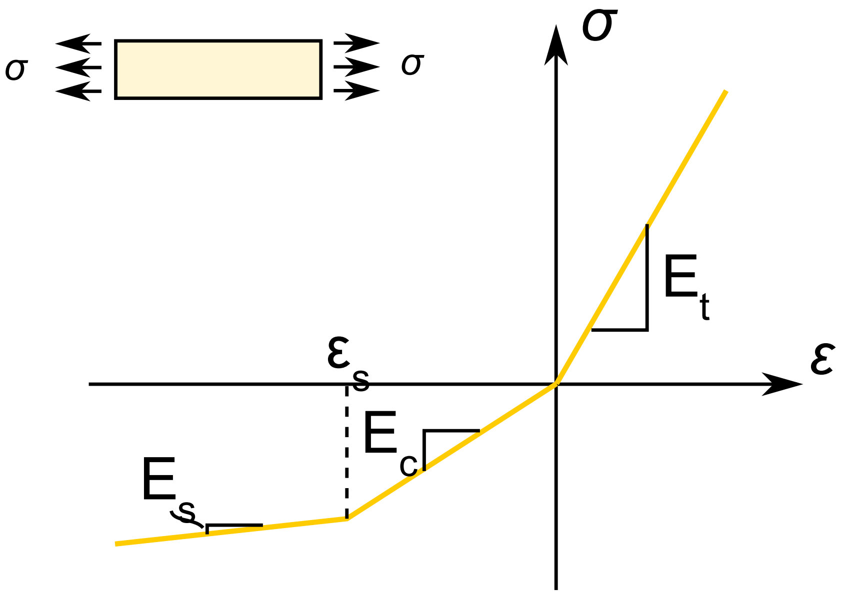
Modelling of NCF and Interface

2D model of fiber-binder preform

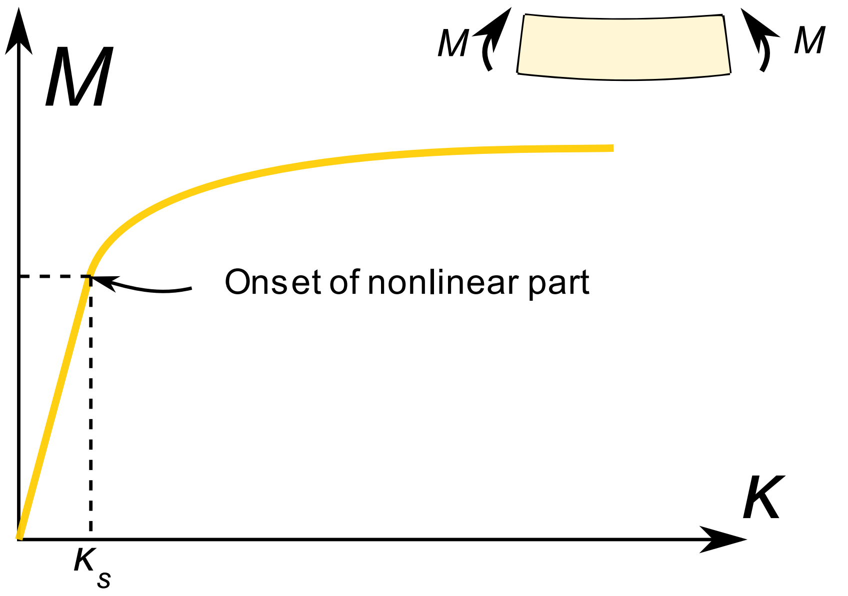
3D continuum shell element (SC8R) with VUMAT



Extension/compression



Out-of-plane bending



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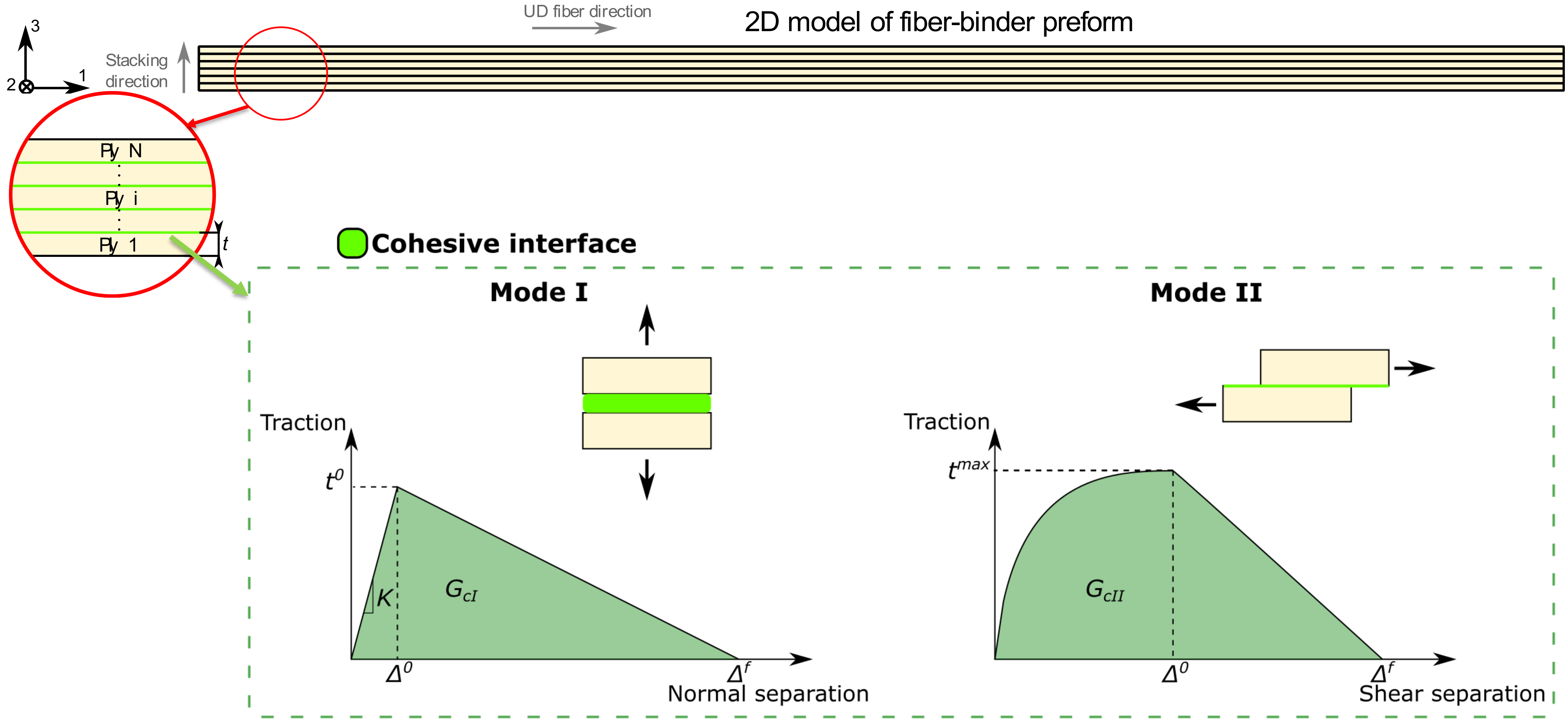
Modelling of NCF and Interface



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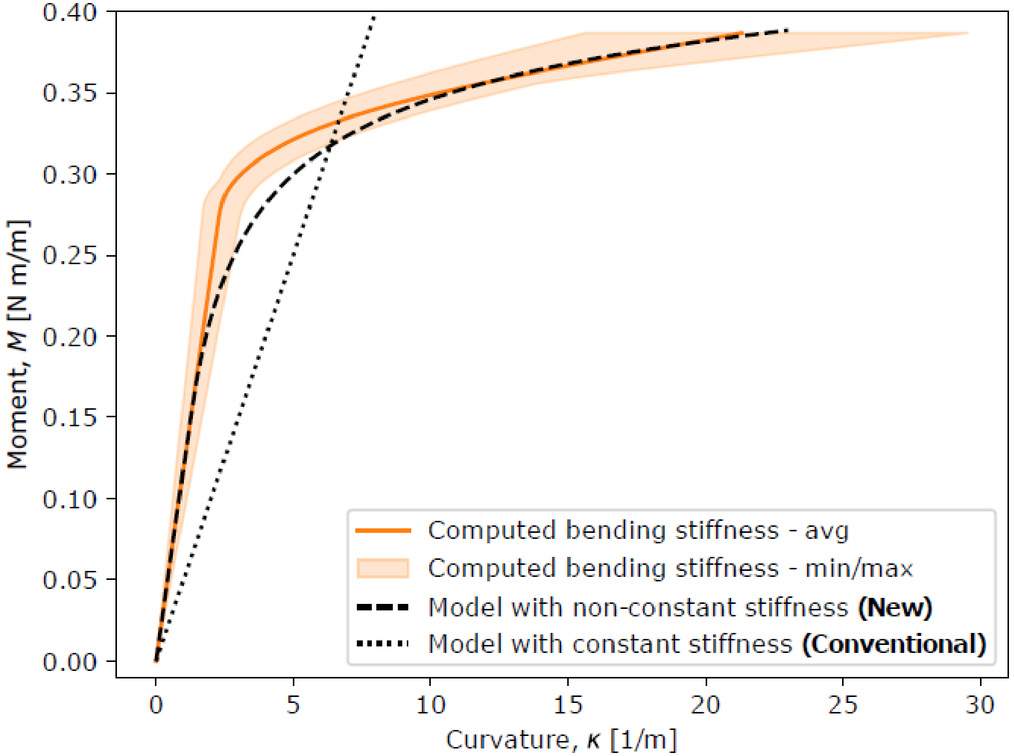
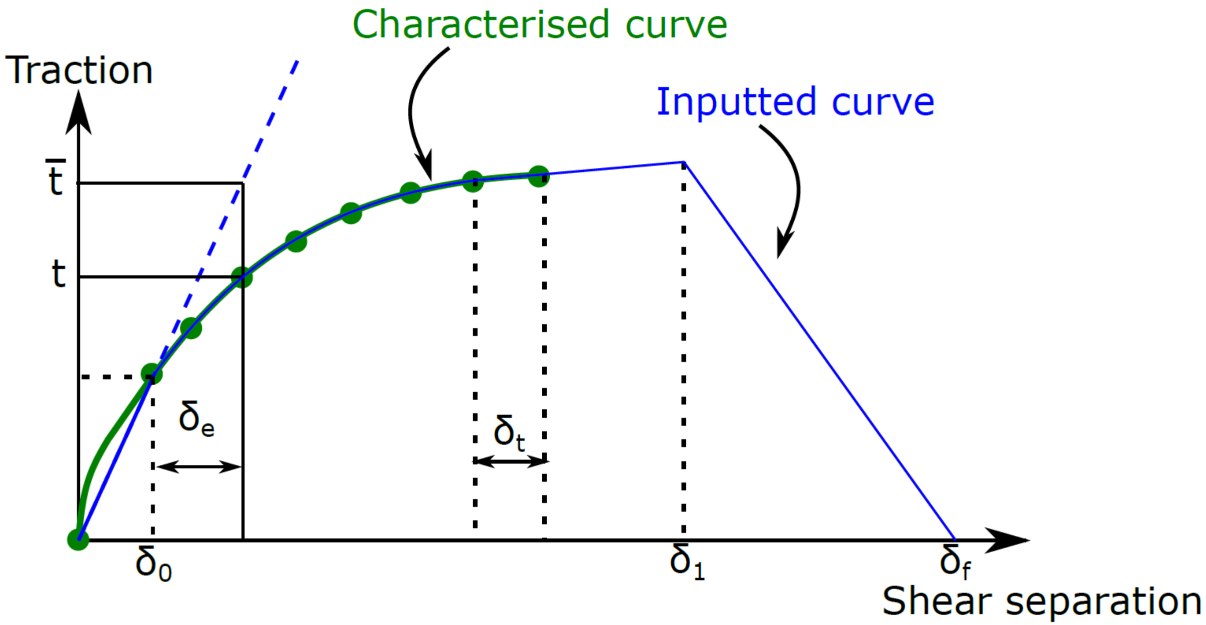
From Experiments to Simulation Model

Bending model



Transverse shear model (CZM)

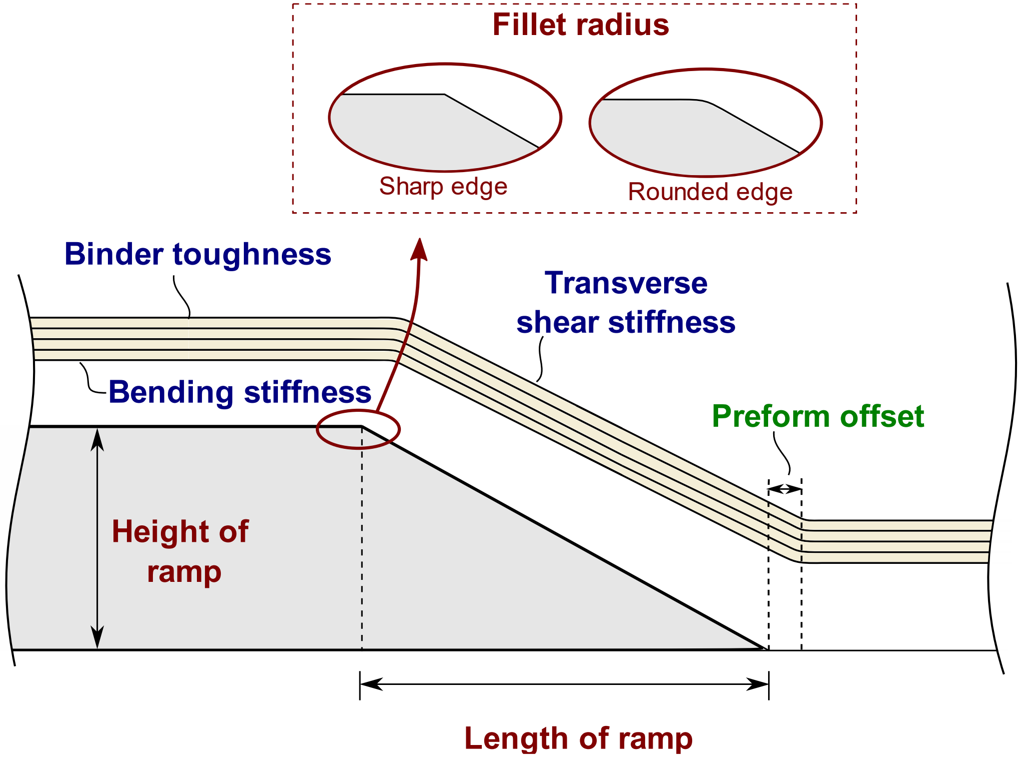


Parameter Studies - Intro

Parameters to be varied:

The parameters are divided into 3 categories

- Ramp geometry
- Material properties
- Tolerances



Variations:

Ramp geometry

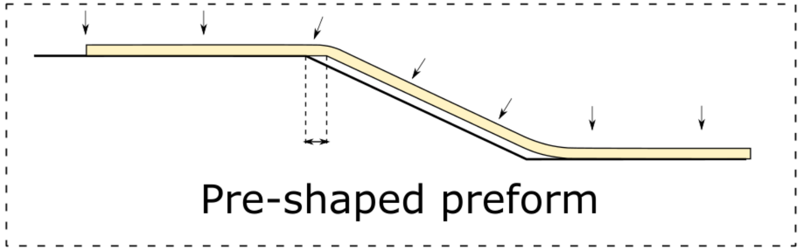
PARAMETER:	REF VALUE	1ST VARIATION	2ND VARIATION
FILLET RADIUS	0 [mm]	2 [mm]	20 [mm]
TRANSITION LENGTH	320 [mm]	160 [mm]	480 [mm]
TRANSITION HEIGHT	150 [mm]	100 [mm]	50 [mm]

Material properties

PARAMETER:	REF VALUE	1ST VARIATION	2ND VARIATION
BINDER TOUGHNESS	x1	x0.5	x2
TRANSVERSE SHEAR STIFFNESS	x1	x0.5	x2
BENDING STIFFNESS	x1	x0.5	x2

Placement tolerances for preshaped preform

PARAMETER:	REF VALUE	1ST VARIATION	2ND VARIATION	3RD VARIATION	4TH VARIATION
PREFORM OFFSET	0 [mm]	-50 [mm]	-10 [mm]	10 [mm]	50 [mm]



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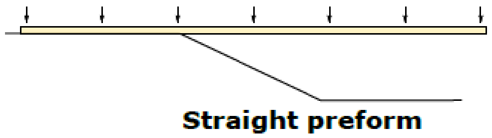
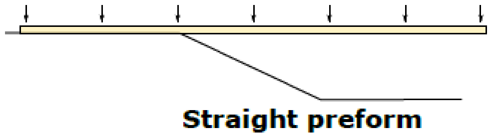
Parameter Studies - Intro

Study 1: 27 simulations



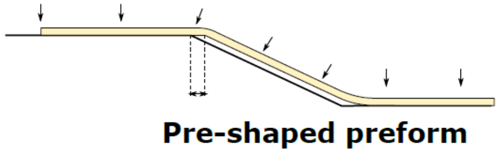
Ramp geometry: Full factorial
Material: Reference
Offset: N/A

Study 2: 27 simulations



Ramp geometry: Reference
Material: Full factorial
Offset: N/A

Study 3: 5 simulations



Ramp geometry: Reference
Material: Reference
Offset: Full factorial

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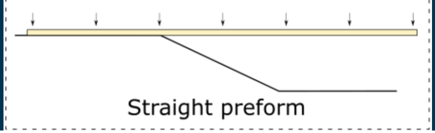
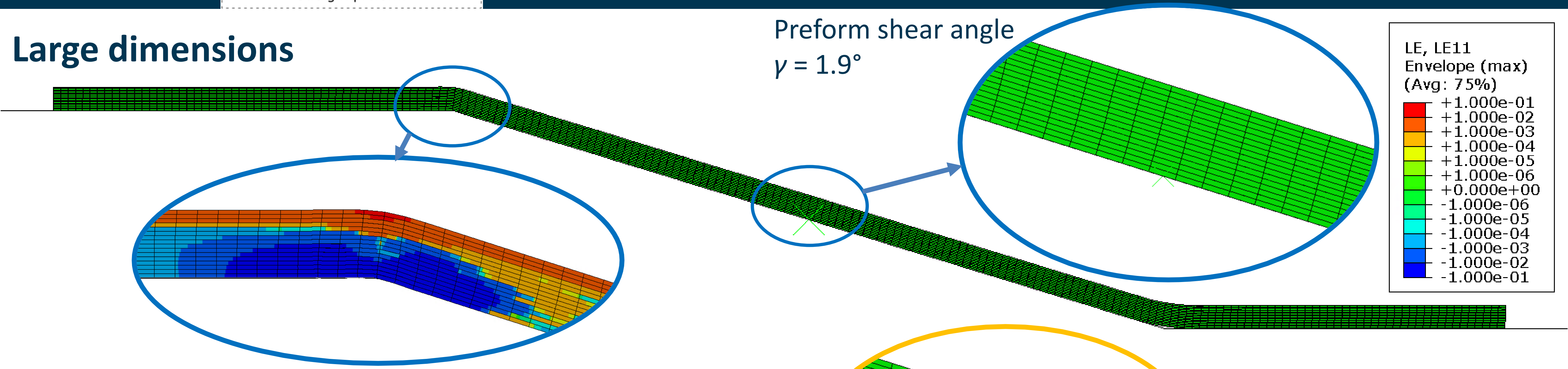


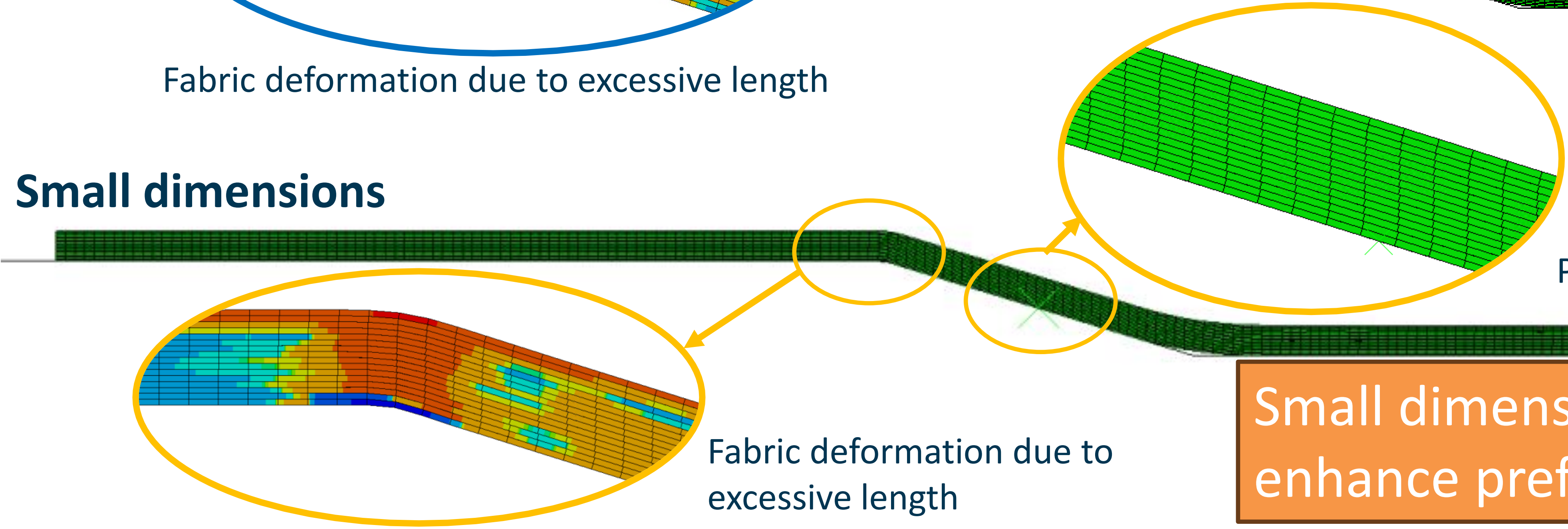
Large dimensions

Preform shear angle
$\gamma = 1.9°$



Fabric deformation due to excessive length

Small dimensions



Preform shear angle $\gamma = 14°$

Fabric deformation due to excessive length

Small dimensions of the ramp enhance preform forming!

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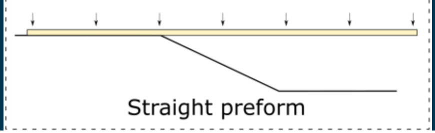
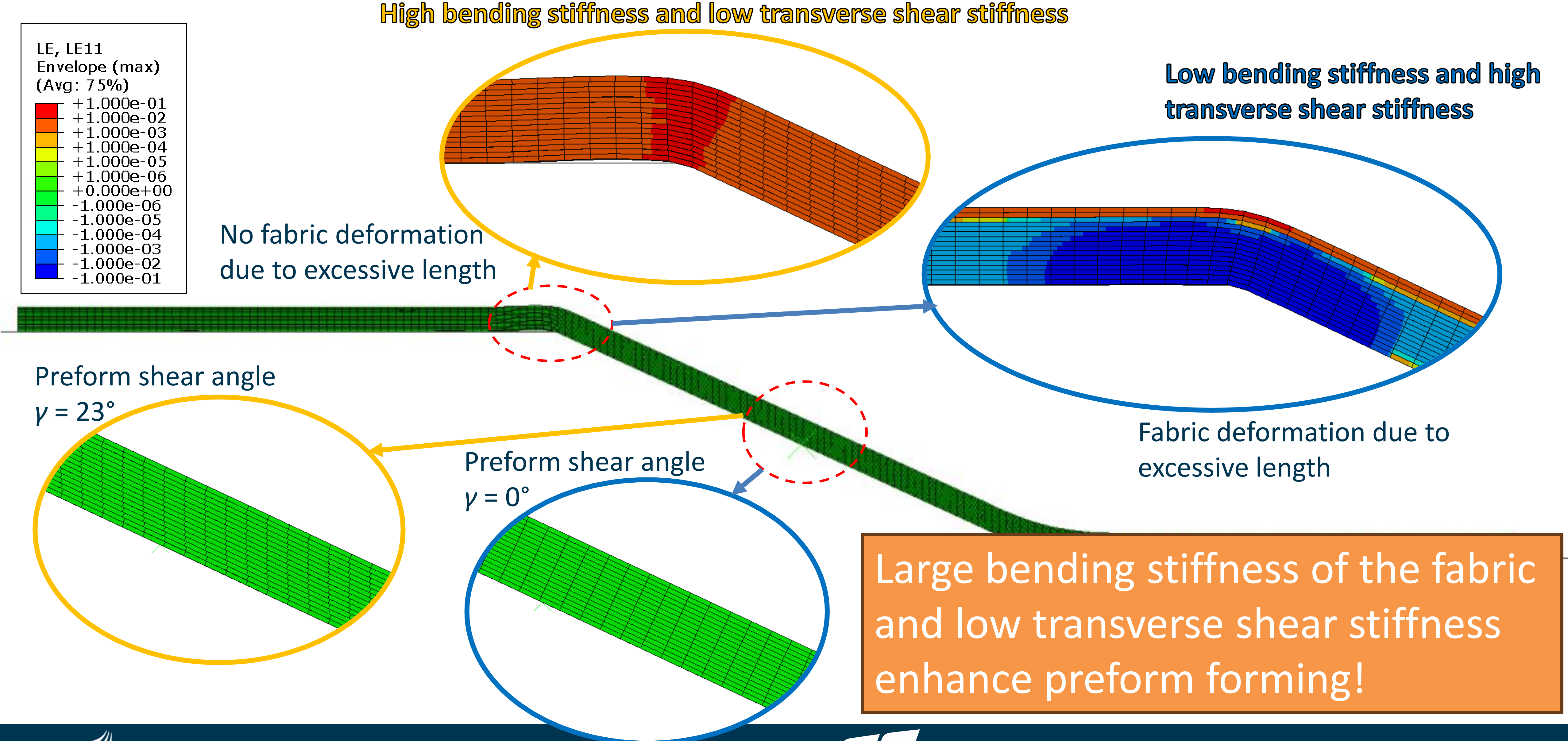
Study 2





Large bending stiffness of the fabric and low transverse shear stiffness enhance preform forming!

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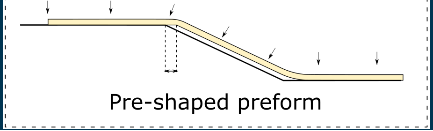
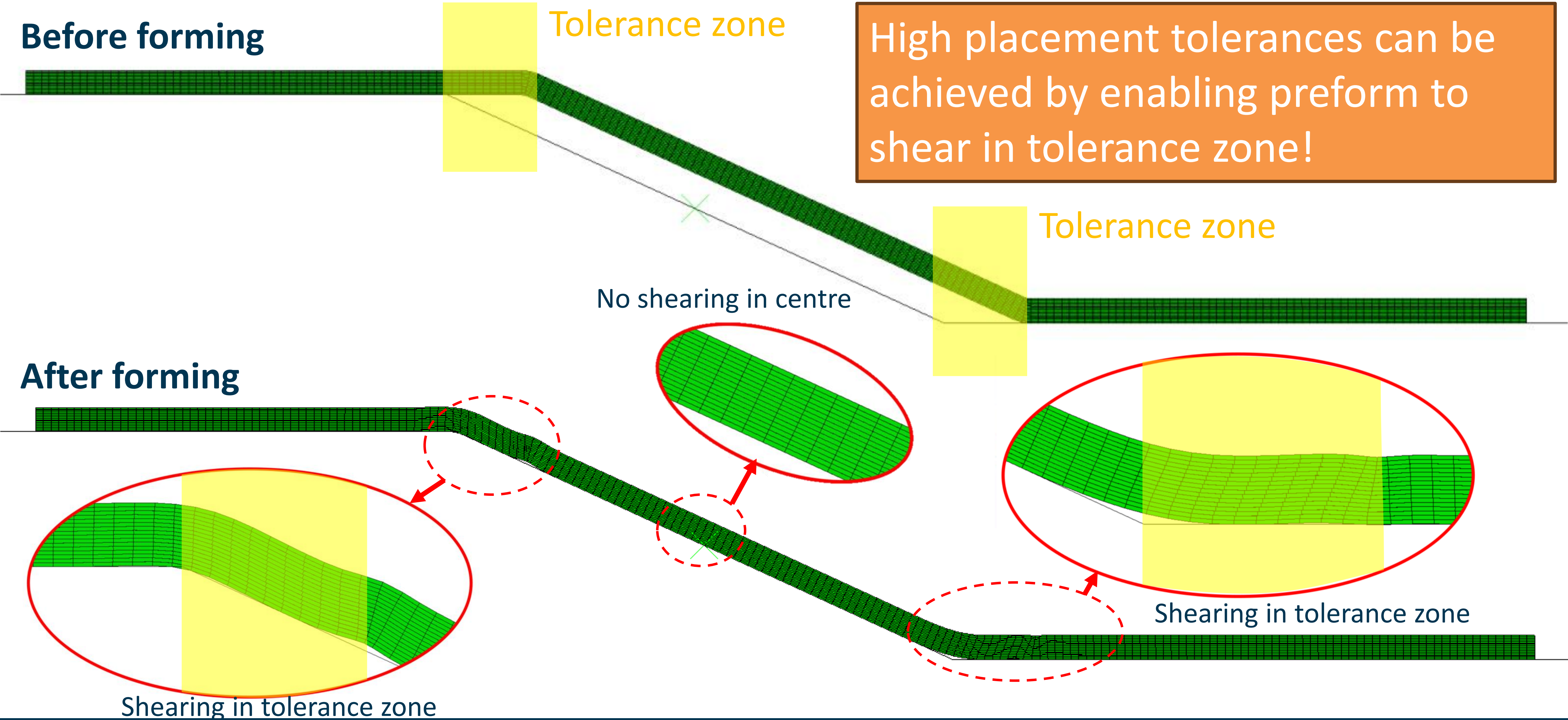
Study 3



High placement tolerances can be achieved by enabling preform to shear in tolerance zone!



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