DRAPABILITY EVALUATION OF ADHESIVE-BONDED NCF BY MEANS OF LOW-FIDELITY SIMULATION

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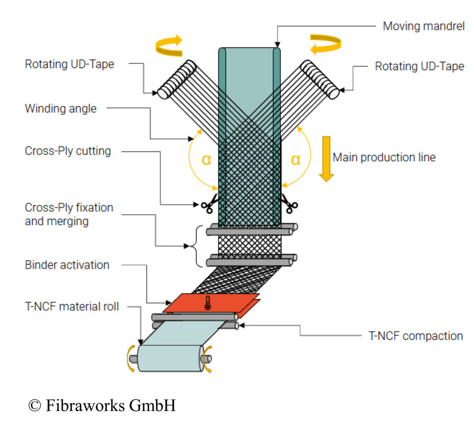
Forming simulation is a major part of process simulation for composite materials, as the occurrence of draping defects can significantly impact the mechanical properties as well as manufacturing properties of the part. The forming behaviour of dry fabrics has been studied extensively, with woven fabrics being in the focus. Non-crimp fabrics (NCF) are studied increasingly by now as the overall achievable mechanical properties and degree of tailoring are superior to woven fabrics. Focus has been laid on stitched-NCF, nonetheless the binding of layers can also be realized by adhesive binding techniques, applying thermoplastic adhesive webs or epoxy powder. Since this binding strategy underlies a different physical principal, the forming behaviour of adhesive bindered NCF is differing from the ones of woven or stitched NCF, which has not been described extensively yet. Aim of this study is to apply standard tests that are established for drapability characterization to chemically bindered NCF, to give a general description of the forming behaviour. Secondly the gained knowledge and mechanical characterisation will be used to simulate the draw-in behaviour of a four-layered adhesively bonded NCF. The simulation will be compared to experimental tests.

1. Chemically bonded NCF



- Scalable production street for NCF
- Large production volume for tailored semi-finished dry fibre products
- Increased mechanical performance by tailoring
- Omission of complex stitching machinery
- Supplementing stitching with adhesive binders

- Mechanical behaviour critically differs from stitched NCF and woven fabrics
- For process simulation drapability behaviour is of interest
- Investigation of shearing bending and overall drape properties relevant

Goal: experimental characterization of shearing and bending properties and modelling within a continuum approach in a forming simulation

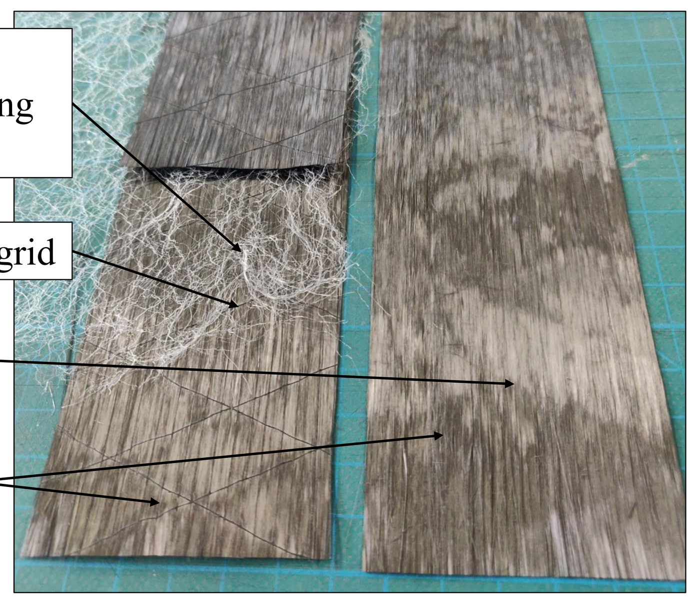
1.1 NCF description and manufacturing

Thermoplastic adhesive web (Spunfab) for in-plane bonding of layers

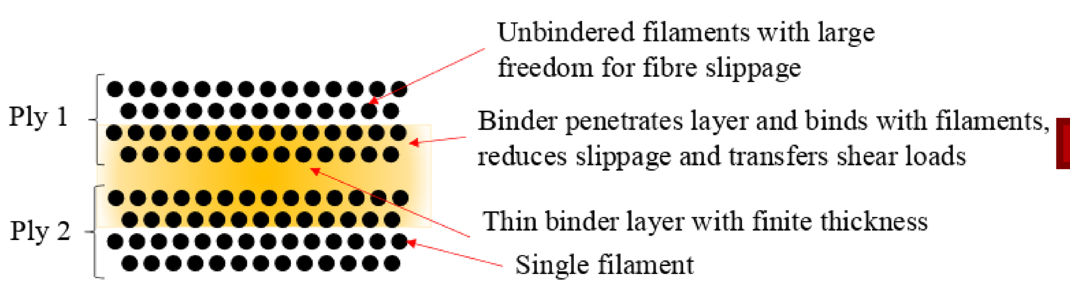
Top-side with thermoplastic grid

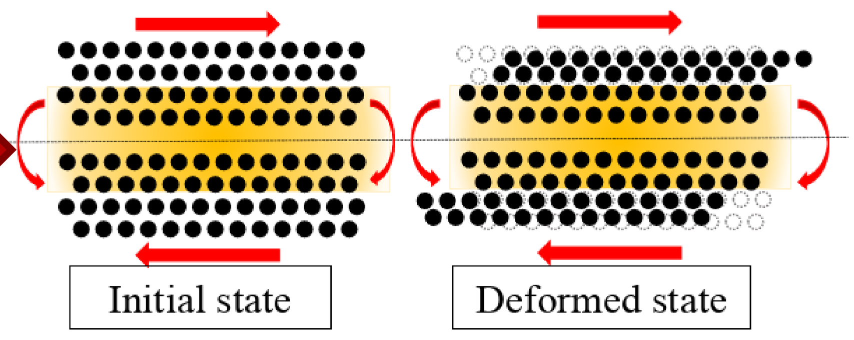
Back-side without thermoplastic grid

UD-Layer (Panex PX 35)

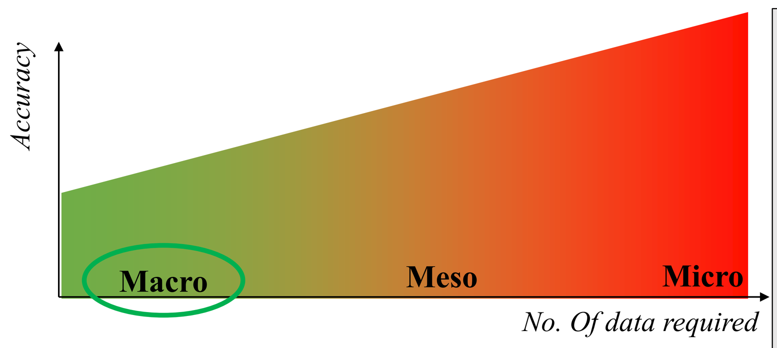


- Fiber layers bonded by adhesive web, which is thermally activated at 120°C and a defined pressure
- Liquification and compaction of the stack leads to a distribution of the thermoplastic
- After cooling layers are bonded leading to load transfer between dry fibre layers allowing for a handling of the stack
  - Questions arise concerning binder distribution
- Not all filaments in the layer are bonded
  - filaments with large freedom for slippage
- bending behaviour depends on quality of the fibre layer bonding
  - Production parameters such as applied pressure during activation lead to varying bending stiffness



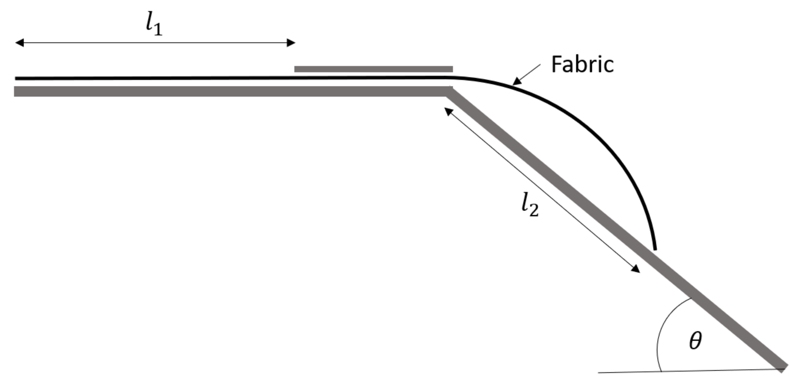


2. Material characterization and modeling approach

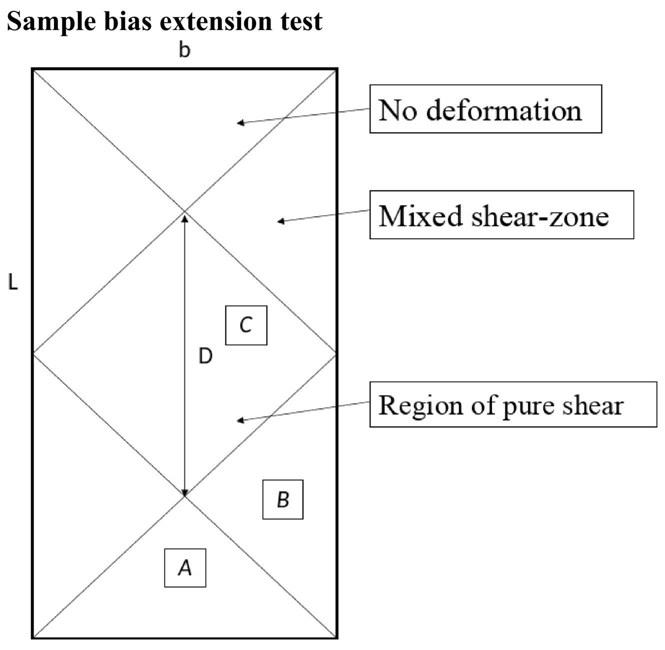


- Little knowledge of forming behaviour and mechanism
- Many influences from binder quantity and processing parameters
- General material characterisation necessary
- Macroscopic approach in form of continuum sheet model to investigate here

Cantilever test stand

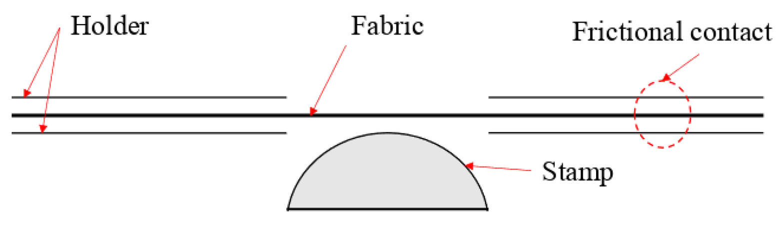


Sample bias extension test



Material characterization for orthotropic continuum model

- $E_{1,2}$ – tensile test or theory
- G_{12} – Bias extension test
- ν_{12} – tensile test



Stamp forming simulation

- Explicit simulation
- Forming speed u=10mm/s
- Layup: [0/90]s, Binder: Thermoplastic adhesive web (6g/m²)
- Comparison between **membrane** and **preintegrated shell elements,** with decoupled membrane and bending stiffness

3. Experimental characterization results

3.1 Characterization of bending stiffness

$$G\ [Nmm] = \omega * \left(\frac{l_1^3}{8}\right) * \left(\frac{\cos\left(\frac{\Theta}{2}\right)}{\tan(\Theta)}\right) \quad [1]$$

$$G\ [Nmm] = l_2^3 * \left(\frac{P}{3l_2} + 0{,}13 * \omega\right) * \left(\frac{\cos(\Theta)}{\Theta}\right) \quad [2]$$

G – flexural rigidity [Nmm]
ω – areal weight of fabric [N/mm²]
θ – Inclination angle of plate [rad]
P – additional weight added at free end of fabric [N/mm]
l_1 - free sample length [mm]
l_2 - projected length [mm]

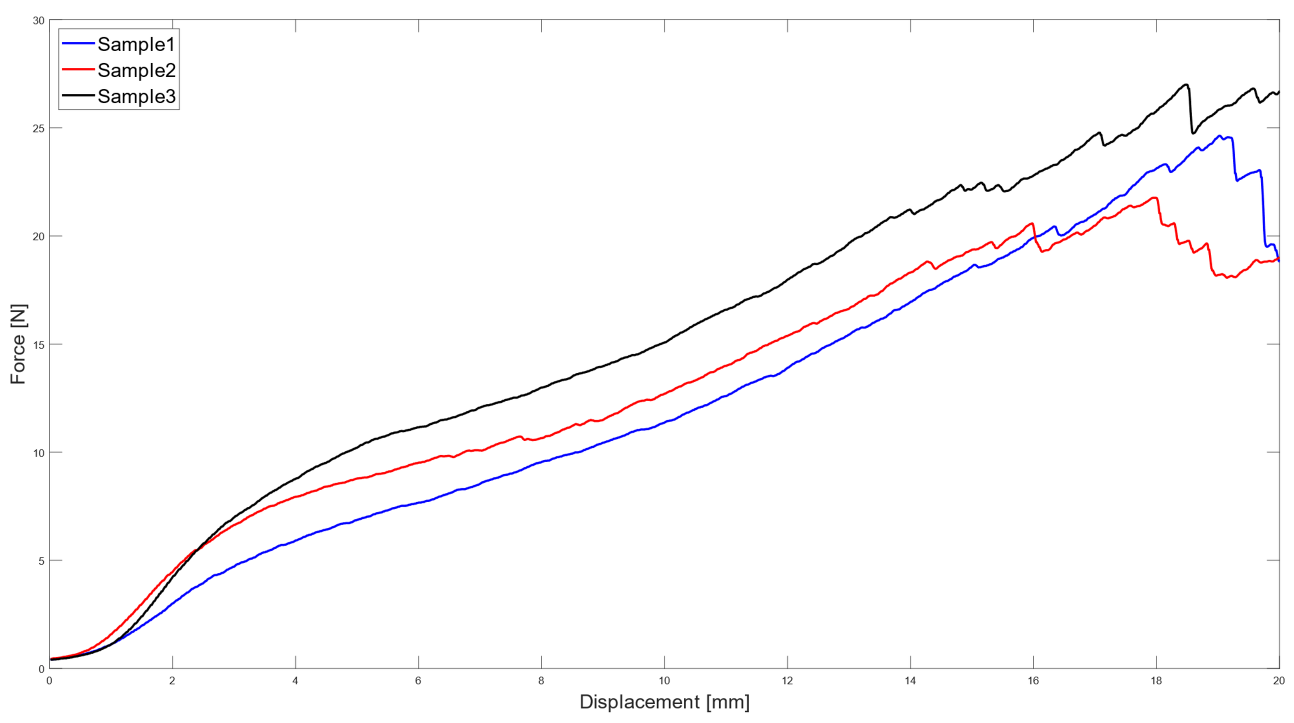
Binder amount/pressure	[0/0/0/0]	[0/90/90/0]	[90/0/0/90]
6g/m², 34hPa	14600±1700	3300±100	4000±500
6g/m², 67hPa	13700±1200	3700±300	4300±200
6g/m², 950hPa	13300±1100	5100±800	5400±600
12g/m², 34hPa	17700±1600	3400±100	3500±500
12g/m², 67hPa	17800±1000	3700±300	3600±200
12g/m², 950hPa	25100±3200	7600±1200	8300±1300

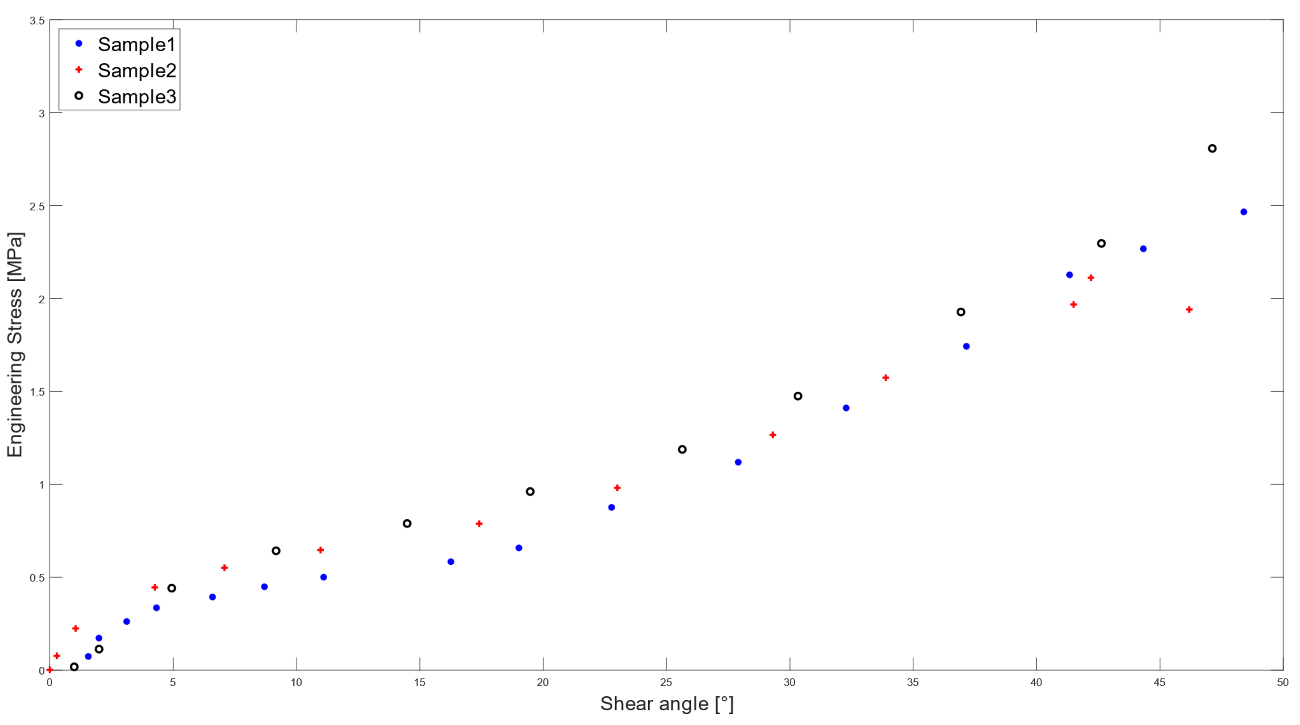
Measured **flexural rigidity in *mNmm*** for fabric samples with varying stack-up, binder amount and consolidation pressure

- Investigation of influence of:
  - stacking-sequence; [0/0/0/0], [0/90/90/0], [90/0/0/90]
  - Binder amount: 6 g/m² and 12 g/m²
  - Consolidation pressure: 34hPa, 67hPa, 950hPa
- Measurement of flexural rigidity with Peirce-Cantilever test

- Significant influence of binder amount for unidirectional stack
  - Influence not significant for orthotropic stack-up
- Flexural rigidity by tendency higher for [90/0]s than [0/90]s
  - Larger bonded surface of inner 0°-plies for [90/0]s
- Insignificant difference in flexural rigidity for lower consolidation pressures (33hPa, 67hPa)
- Larger data scatter for unidirectional NCF, microscopic evaluation of binder distribution needed

3.2 Characterization of shearing behavior





$$\gamma\ [°] = \pi/2 - 2 * \arccos\left(D + d/(\sqrt{2} * D)\right) \quad [3]$$

$$\sigma_y = \frac{F * \left(\cos\left(\frac{\gamma}{2}\right) - \sin\left(\frac{\gamma}{2}\right)\right)}{\sqrt{2} * e * l_s} \quad [4]$$

γ – shear angle [°]
D – vertical length of shear zone [mm]
d – displacement [mm]

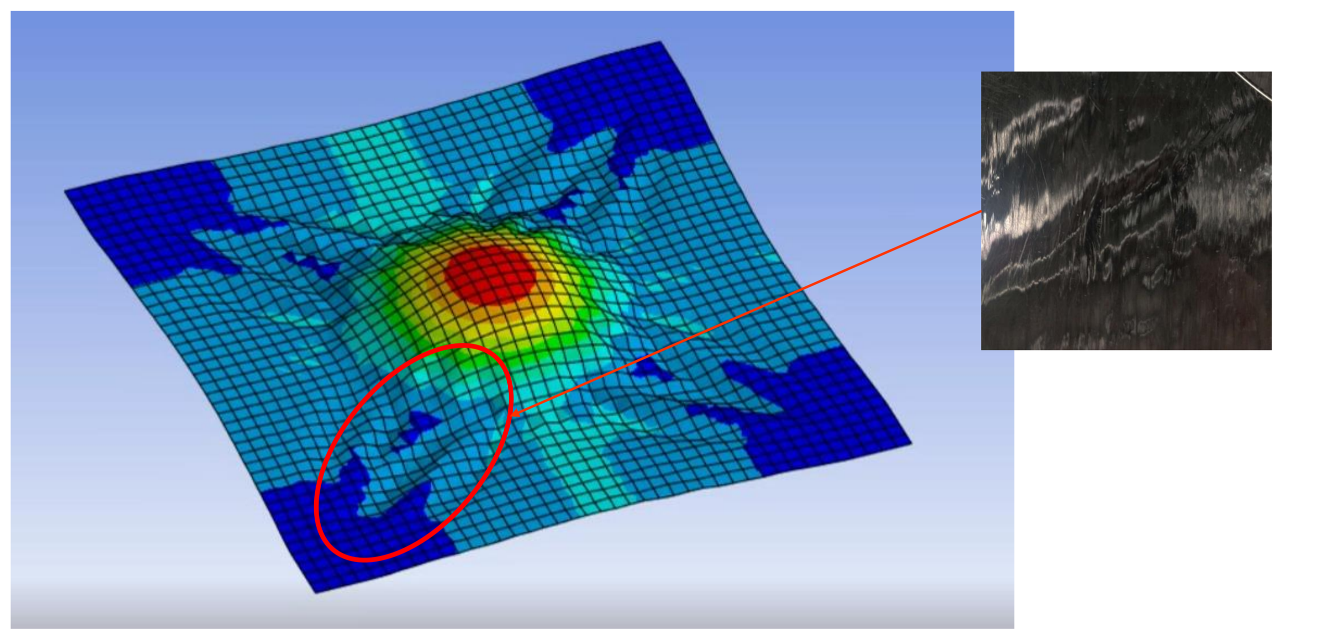
F – measured axial force [N]
e – sample thickness [mm]
l_s - initial sample width [mm]

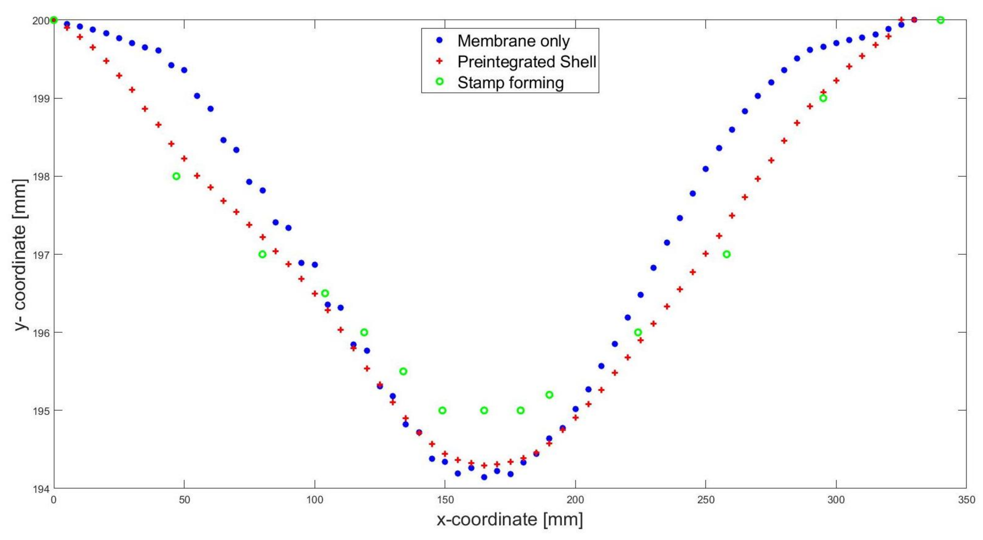
- Rather specific shearing behaviour
  - Initial shear stiffness reduces at low shear angles
  - Audible binder separations
  - Lower shear stiffness until larger shear angles (>25°)
- Forming of out-of-plane waviness of non-bonded filaments

4. Draw-In Simulation

E_1 [GPa]	E_2 [GPa]	G_{12} [MPa]	ν_{12}
121	121	2,8	0,22

Material parameters for [0/90]s





- Pre-integrated shell model with better approximation
- Same max. draw-in for membrane and shell
  - Slightly overpredicted compared to stamp forming experiment
- Accurate wrinkle prediction for pre-integrated shell

Conclusion

It was shown that the binding strategy differs greatly from the ones applied for stitched NCF, since the binding is achieved in-plane with varying through-thickness effects, largely depending on the manufacturing parameters of the NCF. The cantilever tests proved to be applicable for the testing, though care must be taken when manufacturing and handling the specimen to achieve reproducible results and to reduce data scatter. Also, the bias-extension test was applied successfully, with optimization being possible for the sample geometry and measurement method. While bending and shearing behaviour were derived macroscopically, the study of microscopic effects seems to be relevant to get deeper insight into material deformation mechanism and influencing parameters, with respect to through-thickness binding. The draw-in experiment and FE-simulation need to be adapted for larger deformations in order to get a better idea of the achievable accuracy. While wrinkles were predicted with acceptable accuracy, the draw-in was slightly overestimated. The approach using measured fabric stiffness values in the simulation proved to be more accurate than the approach using only membrane elements. If the deviations for FE-model to experiment remain similarly small for larger deformations, the preintegrated shell FE-approach can be seen as a suitable low-fidelity method. If this is not the case, the implementation of updating material models considering change in shear stiffness with increasing shear angle could be a suitable adaptation to increase accuracy.

References

[1] Boisse, P., Hamila, N., Guzman-Maldonado, E., Madeo, A., Hivet, G., and dell'Isola, F. 2017. The bias-extension test for the analysis of in-plane shear properties of textile composite reinforcements and prepregs: a review. Int J Mater Form 10, 4, 473–492

[2] Bilbao, E. de, Soulat, D., Hivet, G., and Gasser, A. 2010. Experimental Study of Bending Behaviour of Reinforcements. Exp Mech 50, 3, 333–351.

[3] LIANG, B. and BOISSE, P. 2021. A review of numerical analyses and experimental characterization methods for forming of textile reinforcements. Chinese Journal of Aeronautics 34, 8, 143–163.

[4] Pourtier, J., Duchamp, B., Kowalski, M., Wang, P., Legrand, X., and Soulat, D. 2019. Two-way approach for deformation analysis of non-crimp fabrics in uniaxial bias extension tests based on pure and simple shear assumption. Int J Mater Form 12, 6, 995–1008.