Wrinkle Formation Characterisation During the Forming of Non-Crimp Fabrics

CIMComp EPSRC Future Composites Manufacturing Research Hub

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Aims / Objectives

Experimental Work | **Modelling Work**

1. To experimentally investigate the **relationship** between the **fibre strains** and **wrinkle formation** during the forming of a biaxial NCF with a pillar stitch pattern.
2. To develop a **FE model** that can **predict the fibre strains** in the NCF during forming and validate this model using experimental data.
3. To use experimental data and the FE model to **develop a Wrinkling Failure Limit Diagram (WFLD)** showing the failure strains at which wrinkles start to develop during forming.

Methodology

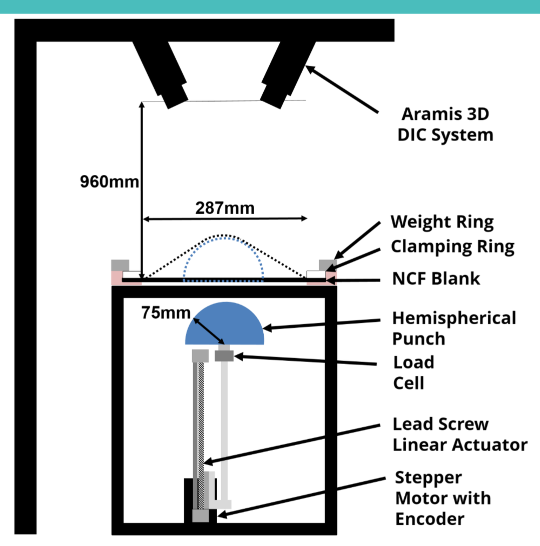

Figure 1: Experimental setup

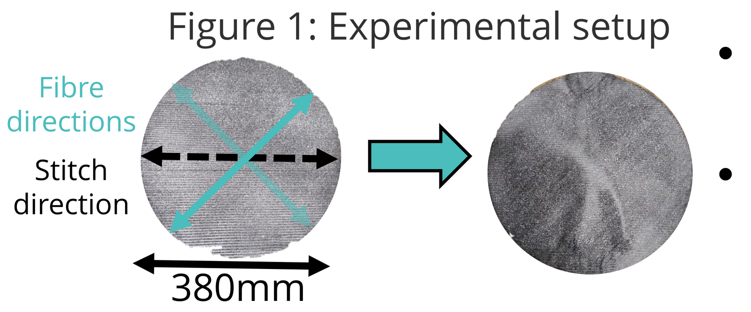

Figure 2: NCF before and after forming

- NCF sample (Hexcel FCIM359) is sprayed with graphite powder and flaw developer spray to obtain suitable **speckle** pattern [1].
- The **principal strains** during forming over hemispherical punch are obtained using **Aramis 3D DIC** system and custom built **forming rig**.
- Forming tests are repeated for different clamping conditions and sample geometries.
- **Process parameters**: Punch Speed=1mm/s, Maximum Punch Displacement (PD)=75mm, Blank Holder Force (BHF)=175N

- A phenomenological Abaqus ***Fabric material model** is used
- Non-linear anisotropic behavior with two fibre orientations.
- **Material Input Data**: Experimental tensile, shear & compression data. Shear data taken from [2].
- **Element type**: Membrane elements (M3D4R)
- **Mesh size**: Square elements of length 3-5mm
- **FE output**: Strains in fibre directions (E11, E22) & shear strain (EFABRIC12)
- **Geometry**: Outer Diameter=380mm, Inner Diameter=287mm, Punch Radius= 75mm
- **Boundary Conditions**: Constant Blank Holder Force (BHF=175N) and Coefficient of Friction (μ=0.4)

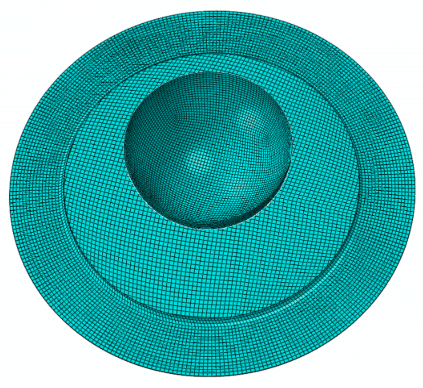
Figure 3: FE Model Geometry

Results

- Principal strains from DIC are transformed to determine **strains in the fibre coordinate system**:

$$\epsilon_f = \begin{bmatrix} \epsilon_{f11} & \epsilon_{f12} \\ \epsilon_{f12} & \epsilon_{f22} \end{bmatrix} = Q \begin{bmatrix} \epsilon_{11} & 0 \\ 0 & \epsilon_{22} \end{bmatrix} Q^T$$

$$where\, Q = \begin{bmatrix} \cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix}$$

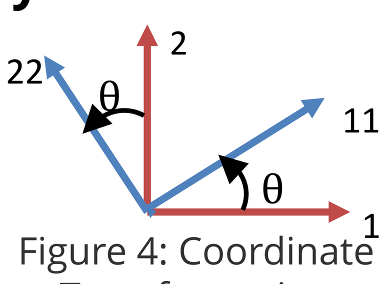

Figure 4: Coordinate Transformation

- The **fibre directions** are obtained through interpolation of the initial fibre direction using facet displacement data.
- **Wrinkle amplitudes** calculated by subtracting the smoothed displacement surface from the actual fabric surface.

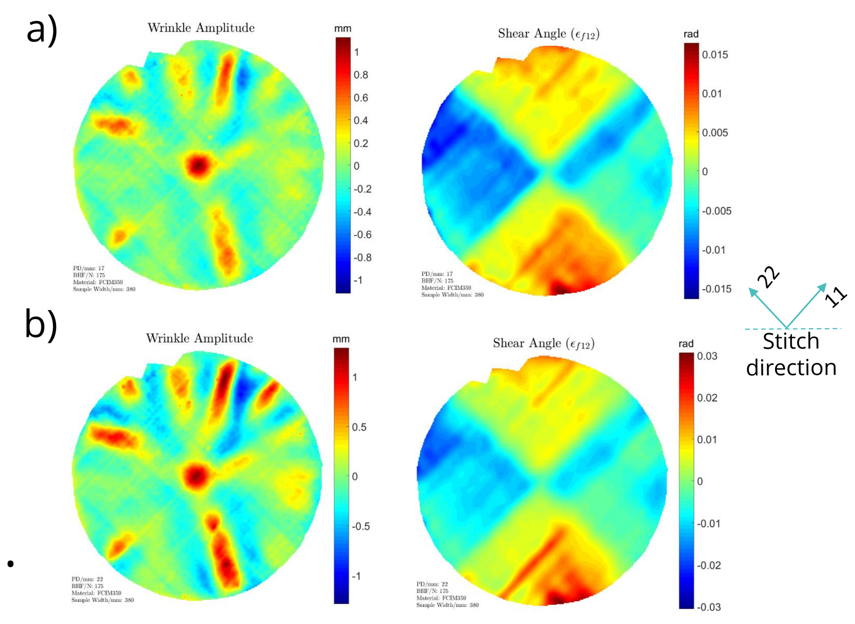

Figure 5: Wrinkle Amplitude and Shear Angle at a) PD =17mm and b) PD=22mm

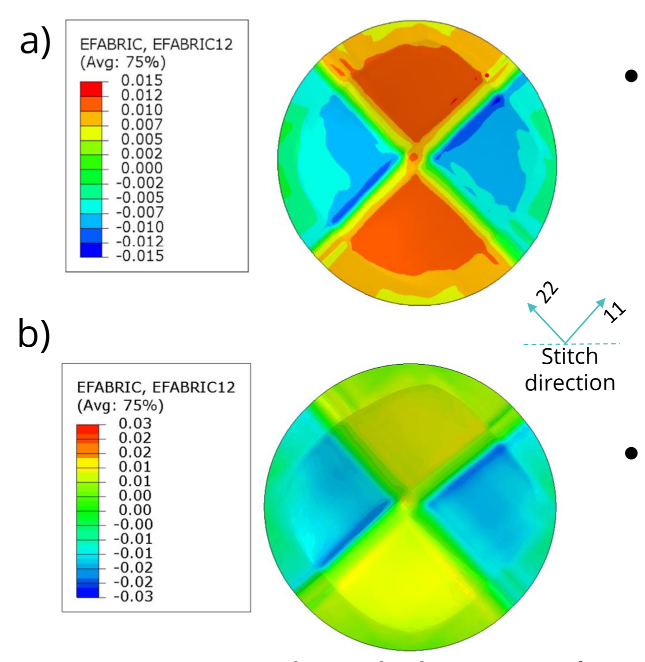

Figure 6: Predicted Shear Angle at a) PD =17mm and b) PD=22mm

- Experimental conditions are replicated in the model and **predicted shear angles compared** against experimental results.
- Model is then altered to consider alternative sample geometries.

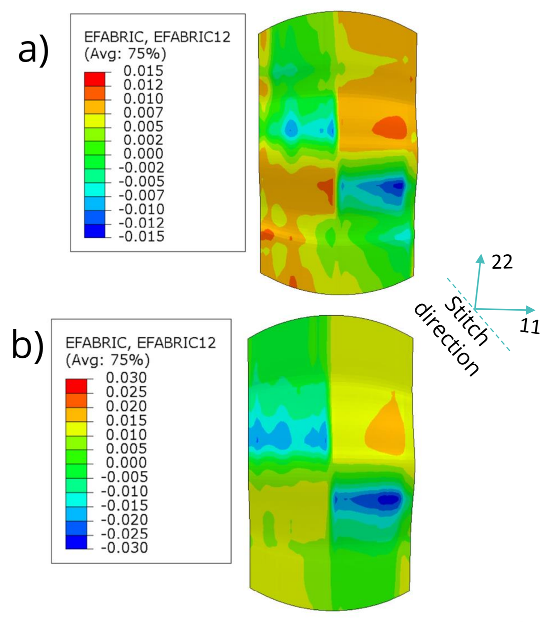

Figure 7: Predicted Shear Angle for BHF=175N at a) PD =17mm and b) PD=22mm (150mm wide sample)

Key Findings

- **Increasing BHF** significantly **reduces** the amplitude of **wrinkles** produced.
- For uniformly applied BHF, there is **a general correlation** between the **locations of wrinkles and maximum shear angles**.
- For non-uniformly applied BHF and non-circular geometry, there is less agreement between location of wrinkles and maximum shear angles, suggesting that **another mechanism** other than shear lock up, is causing those wrinkles.
- It is hypothesised that **compressive radial strains** that are inherent to the forming process contribute to the onset of these wrinkles.

- The shear angle distribution predicted by the model (Figure 6) **shows good correlation** with experimental results (Figure 5) for a circular sample under the same conditions.
- The validated model can thus be used to obtain strain distributions for alternative sample geometries and punch shapes.
- Using the strain distributions, the **wrinkling patterns can be inferred** given the general correlation between strains and wrinkles.
- Thus FE model can be used to interpolate and extrapolate **a WFLD** from a limited set of tests for a particular NCF.

Research Impact

- The experimental rig enables for the wrinkle development and surface strains to be **tracked continuously** during forming allowing for improved understanding of mechanisms involved.
- The **forming limit diagram** provides a methodology to relate a limited set of forming experiments performed with a given material to **forming of complex parts** using the same material.
- Understanding of wrinkle formation and a way of determining wrinkle formation allows **development of a standardised way of testing and representing fabric behavior,** which can be by end-users in design of components and manufacturing routes.

References

[1] P. Harrison et al. *Int. J. Solids Struct.*, vol. 0, pp. 1–17, 2016.
[2] S. Chen et al. *Compos. Part A Appl. Sci. Manuf.*, vol. 91, pp. 156–167, 2016.

Acknowledgements

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DASSAULT SYSTEMES HEXCEL

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