# MODELLING WRINKLING ONSET IN TEXTILE FORMING USING MEMBRANE ELEMENTS

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**Keywords:** Manufacturing, Draping, Numerical simulations, Defect formation

## ABSTRACT

Textile reinforcements have been used in automotive and aerospace industry. For the manufacturing of complex-shaped components, the most challenging step is forming, or draping, of the reinforcement with no defects. Forming of multi-layer reinforcements induces large shear deformation accompanied by friction between the layers can result in such defects as wrinkles. Numerical simulations have been employed for number of years to assess the design of the process and the part at early stages of the development and improve it before the production stage.

The paper employs the explicit finite element analysis and a model consisting of membrane elements to simulate forming of a two layer non-crimp fabric preform. The model is created using only standard material models available in Abaqus software. The wrinkling analysis is performed at the post-processing stage using an analytical model. The post-processing employs a 1D buckling model to analyse each element for wrinkling. The map of wrinkles obtained with the presented approach agrees with the experimental results obtained for forming of a hemisphere.

## 1 INTRODUCTION

Textile reinforcements are widely used in manufacturing of for composite components in automotive and other industries because of their superior drapability when compared to unidirectional multi-layer preforms and hence higher potential for manufacturing automatization. A particular type of textile reinforcements, non-crimp fabric (NCF), is successfully used in high-volume production of vehicles, owing to automatization of preforming and resin infusion. The forming process must produce a preform with as few defects as possible, to ensure good structural performance of the finished component, since wrinkles can lead to early failure [1]. Numerical simulations can be used to validate the component and process design and ultimately to avoid or reduce defects.

The simulation of textile draping processes is usually performed using either a continuum or a meso-scale approach [2]. The latter technique, based on detailed representation of the textile geometry, can provide a high fidelity tool for draping simulations, but the computational cost renders the techniques not feasible for simulations of draping of large components. In the continuum technique, a textile reinforcement is represented by a homogenised medium and can be efficiently simulated by a finite element (FE) code using solid, shell or membrane elements. While models composed of membrane elements proved to be efficient in draping simulations and require significantly shorter computation time than models which consist of solid or shell elements, membrane elements do not have a bending stiffness and hence cannot be used to predict the onset of the wrinkling and shape of defects [3-5]. However, when coupled with a physical-based criterion for the onset of the defects, the membrane element models may become a useful tool for the engineers.

The simplest mathematical model for wrinkling onset is a buckling model. Models of this type were widely applied to predict wrinkling onset in metal sheet forming. It was also shown that for complex geometries, these approaches can be coupled with membrane elements to predict local wrinkling [6]. This study presents an analytical model for prediction of the wrinkling onset in NCF and couples this model with an FE forming simulation which uses membrane elements. The approach enables the study of effects of process and material parameters on wrinkling during the draping process. The model, effectively a post-processing tool, can be used with existing codes and models to assess the likelihood of wrinkles.

## 2 FORMING SIMULATIONS

A validated framework for forming simulation is required before development of the post-processing tool for wrinkling analysis. A general purpose FE software, Abaqus, was chosen as it provides access to simulation with various types of elements (shell and membrane) unlike other commercial codes which may be restricted to shell elements. The Abaqus/Explicit solver provides an interface to a material model, keyword *FABRIC, designed for modelling textile deformation.

The continuum modelling technique requires the response of the reinforcement to be characterised prior the simulations. Typically, the response to shear deformation is measured through picture frame shear test [7]. This test was used by Chen et al. [8] to assess the behaviour of a NCF (Hexcel FCIM359, fibres are at 0°/90° and stiches at 45°) which is characterised by the shear curve shown in Figure 1. It was found that the shear curve is asymmetric owing to the different behaviour of stiches in tension or compression which correspond to positive and negative crosshead displacement, respectively. The response of the reinforcement in compression (shown as negative crosshead displacement) is of the same as for a conventional textile reinforcement, where the shear resistance is relatively low initially and increases following a power law at large crosshead displacements. On the other hand, when the stitches are in tension (positive crosshead displacement), the shear resistance is high at relatively low crosshead displacements which is followed by a reduction of the shear resistance after the stiches failure. The response of the reinforcement was assumed linear elastic in the yarn directions since the yarn crimp in NCF is negligible. The average experimental shear curve was used as input data for the *FABRIC material model. The Young's modulus along both fibre directions was assumed to be 138 GPa.

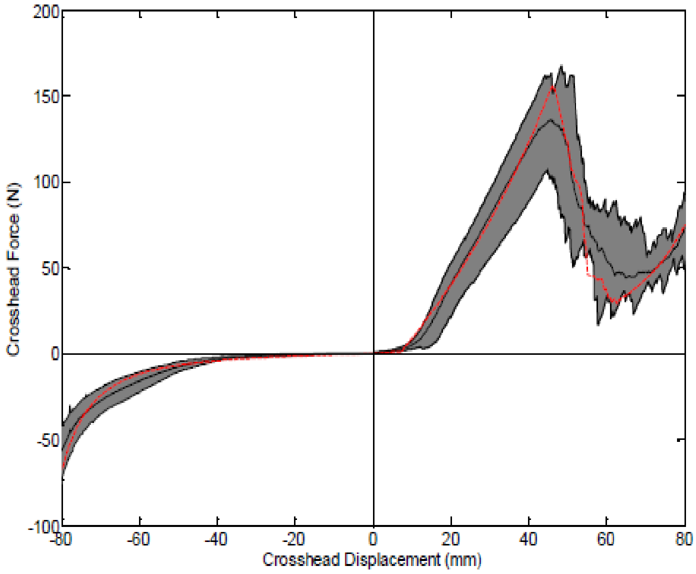
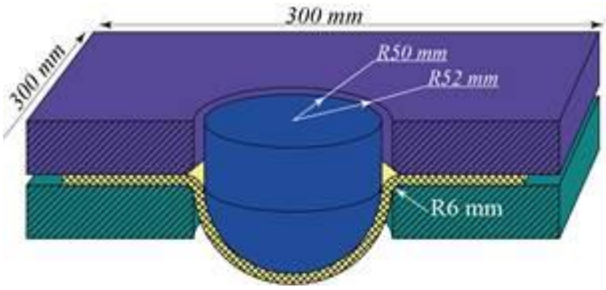



Figure 1. Shear curves for NCF [8] (black curve – average experimental response, grey shaded area – scatter of experimental results)

A model which replicates drawing of a reinforcement with a hemispherical punch (Figure 2(a)) was created in Abaqus using the dimensions shown in Figure 2(b). A square blank of dimensions 300 mm×300 mm is held by a blankholder with a normal force of 1200 N applied to it. The blank is composed of two layers of NCF. Each fabric layer consists of two orthogonal layers of yarns stitched at 45°. The blank is modelled using membrane elements. The friction coefficient between reinforcement and tools was set to 0.23, and the friction coefficient was 0.36 for contact between two layers of reinforcement.

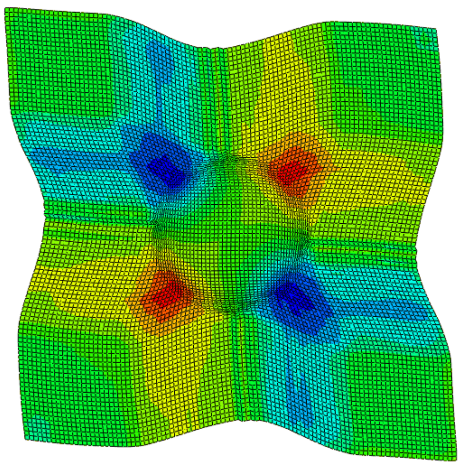
(a) Tool setup




(b) Dimensions

Figure 2. Hemisphere forming experiments setup (adopted from [8])

Results of the forming simulations are in good agreement with results of corresponding experiments and simulations presented in [8] for the same material but obtained using VFABRIC user subroutine. Shear angle maps are shown in Figure 3. The results show that the material model for textile deformation, implemented in Abaqus and called by *FABRIC keyword, can be reliably used instead of more complex VFABRIC or VUMAT user subroutines.



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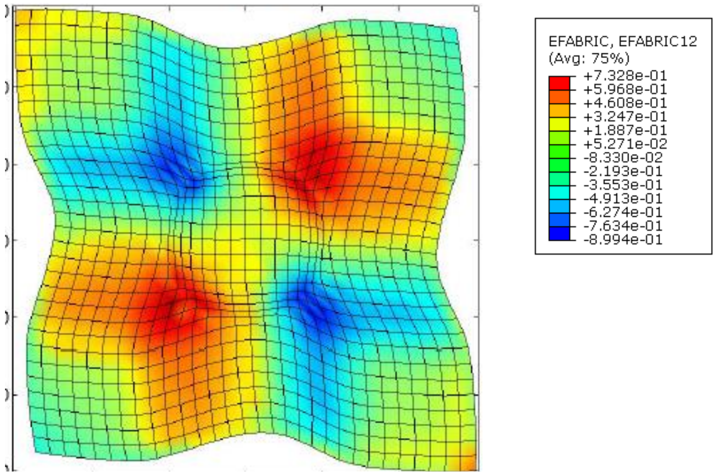


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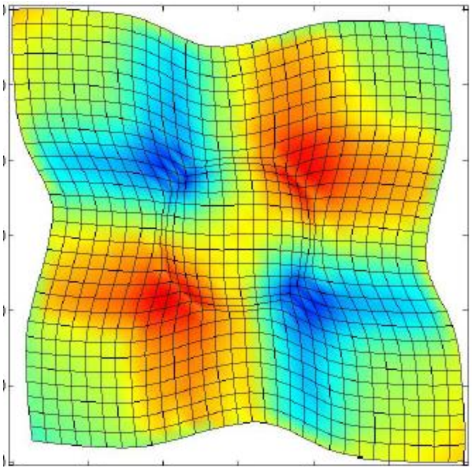

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Figure 3. a. Results of the present simulations; b. Simulation results by Chen et al. [8]; c. Experimental results from Chen et al. [8]

## 3 WRINKLING ONSET

Wrinkling during forming has been assessed by several energy-based criteria for sheet metal forming. In composite forming, the wrinkling is often assessed using a locking shear angle concept i.e. a critical shear angle after which a reinforcement cannot shear and wrinkles instead [9]. Alternatively, wrinkling can be postulated to occur after compressive strains in the material reach a critical threshold. Chen et al. [8] correlated experimental and numerical results and equated wrinkling onset strain to the critical value of 0.03. This criterion shows good agreement with the experimental results, but the critical value is not universal across different processing conditions, materials and contact behaviour.

The method proposed here considers a beam of infinite length which is pressed against a substrate by an evenly distributed pressure $q$ as shown in Figure 4. The friction coefficient between the beam and the substrate, which is considered to be independent of sliding velocity, is $\mu$. An axial compressive force is applied to the beam. When the force is increased above a critical value, the beam buckles with a buckling length $L$, and the slippage length is equal to $L_s$. It can be shown that the critical force, $P$, can be expressed as [10]

$$P = k\frac{EI}{L^2} + \mu q\left(\frac{L}{2} + L_s\right), \quad (1)$$

where $k$ is a constant which depends on the boundary conditions, $E$ is the beam's Young's modulus, and $I$ is the moment of inertia of the beam's cross-section. The slippage length, $L_s$, is found as explained in [10].

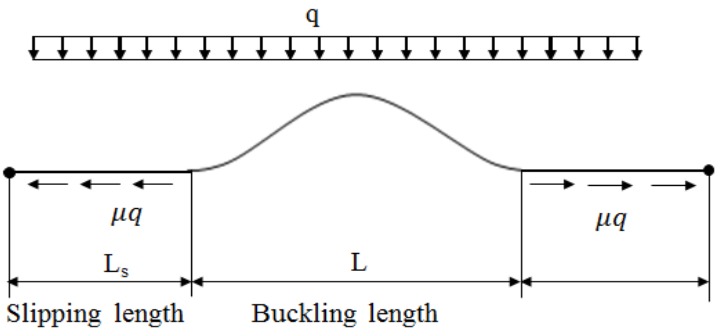



Figure 4. Buckling model

It can be seen that the first term of the solution is equal to the classical Euler buckling solution, and the second term is the contribution of the frictional forces. The effect of the additional term on buckling is shown on Figure 5. Obviously, an increase of the friction coefficient results in an increase of the buckling force for a particular buckling length. However, the most important is that the friction introduces a certain critical buckling force below which no buckling is possible at any length.

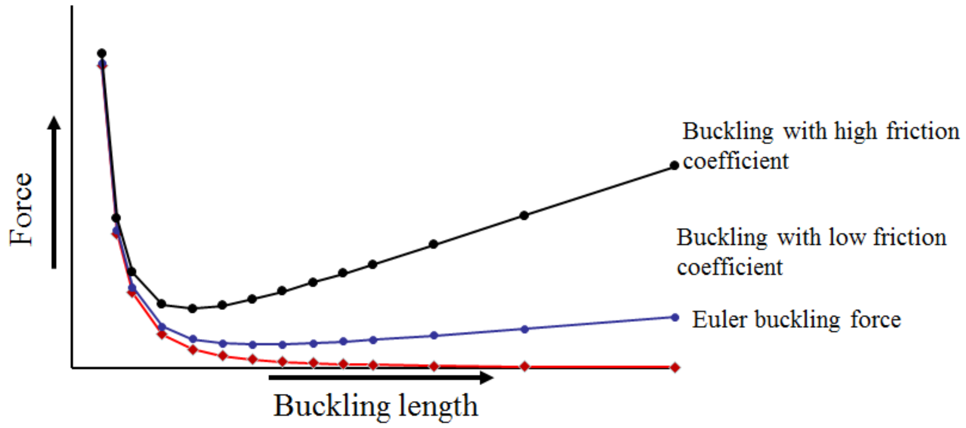



Figure 5. Effect of substrate friction on buckling of a beam

Wrinkling in the model described in Section 2 was analysed with a Python script which iterates though all the finite elements of the model. The normal pressure at each element was used to calculate the critical force using equation (1). The moment of inertia of the section was assumed to be 0.041 of the moment of inertia of a solid beam of the same dimensions following experiments performed by Wong [11]. The map of the elements which are wrinkled according to the presented approach is shown in Figure 6. The map of wrinkles agrees with the experimental observations shown in Figure 7. The flanges of the hemisphere, where the blank is compressed between the blankholder and the die, exhibit in-plane wrinkling. The radius between the flanges and the hemisphere and the areas slightly above exhibit out-of-plane wrinkling of yarns.

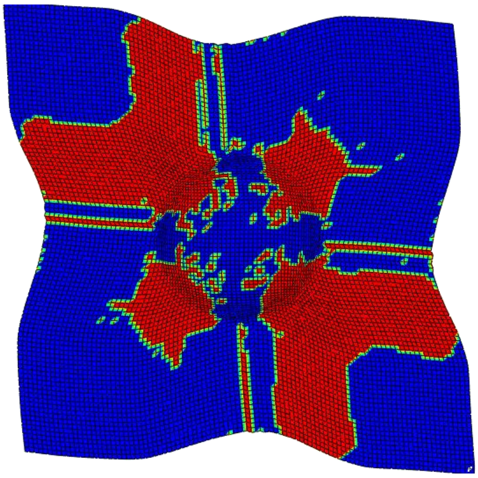
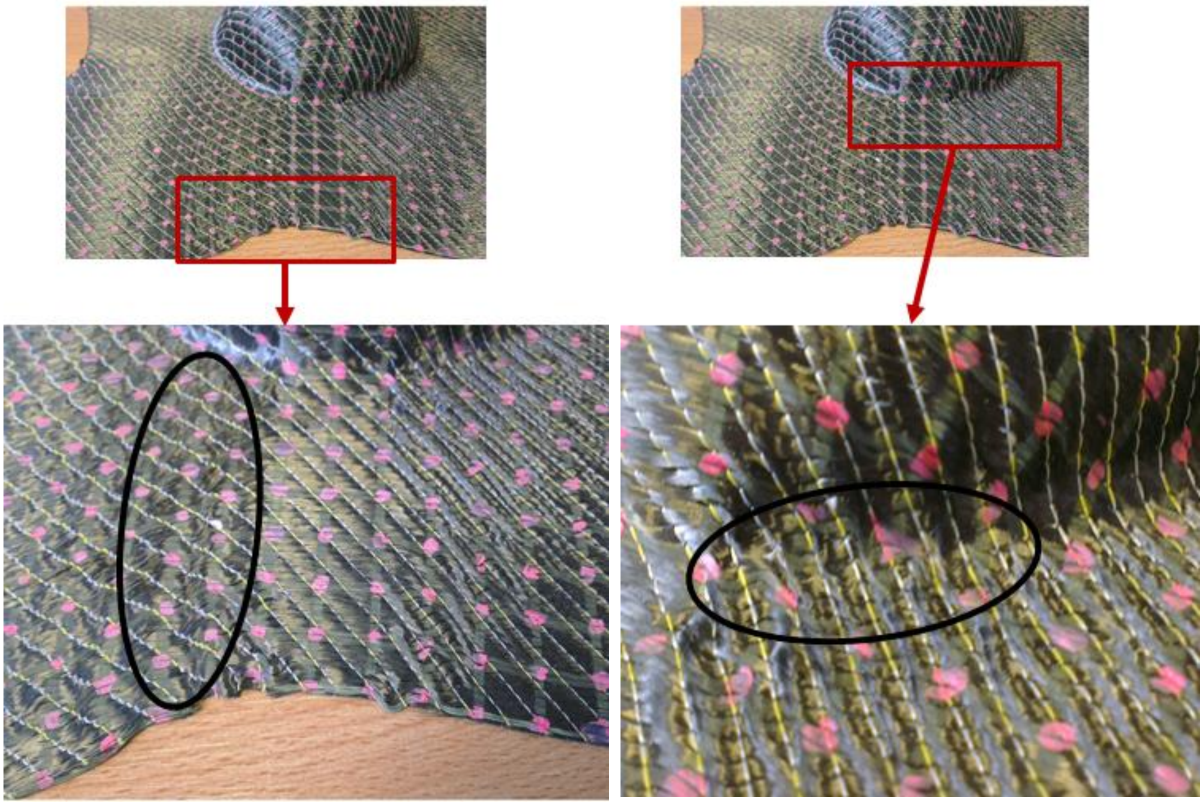


Figure 6. Map of wrinkles



a b

Figure 7. a. In-plane wrinkles; b. Out-of-plane wrinkles

## 4 CONCLUSIONS

It was shown that fabric forming simulation can be performed with Abaqus/Explicit using a standard material model and membrane elements. The forming simulations captured asymmetry of the material behaviour in shear and predicted the shear angle map which agrees well with the experimental results. Occurrence of wrinkles is assessed in post-processing where a Python script is used to analyse the strain and local pressure for every element. A critical strain is computed for every element using a 1D buckling model and then compared to the actual strain. The model predicted wrinkling locations which agree with the experimental observations.

The presented approach can be extended towards prediction of the type of buckling in order to distinguish in-plane or out-of-plane wrinkling. Furthermore, validation of the approach for more complex cases is required.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance of the Engineering and Physical Sciences Research Council (EPSRC) for supporting the present work under grant Ref. EP/K032798/1 (Friction in Composites Forming). Dr Shuai Chen and Dr Oliver McGregor are acknowledged for access to their experimental data.

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