A comparison of simulation approaches for forming of textile composites

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ABSTRACT: This paper compares a number of approaches to simulate forming of textile composites. These include the traditional kinematic approach, a sequential mechanical simulation based on explicit finite element analysis, and two new models aimed to carry out detailed drape simulation while simplifying the FE analysis. These approaches are applied to the forming of a hemisphere and a helicopter pilot helmet geometry from a woven carbon/epoxy thermoset prepreg, laid up at various orientations. Predictions are validated using experimental measurements from a photogrammetry system, based on the deformation of a grid marked on the material prior to forming. This allows a quantitative comparison to be made for fabric shear angles, as well as fibre orientations and inter-tow slip. The results indicate the importance of accurate material properties and boundary conditions on the predicted fibre patterns, thereby highlighting the significance of the intermediate models presented here.

Key words: textile composites, forming, draping.

1 INTRODUCTION

A detailed understanding of the drape behaviour of woven fabrics is important to enable accurate predictions of the mechanical properties of complex-shaped composite structures and to optimise their manufacture. It has been established that pure shear is the main mechanism allowing a woven fabric to conform to double-curvature shapes. Accordingly most previous researchers have focused on studying the shearing of fabrics [1], and on developing kinematic models for fabric drape [2-4]. These kinematic models primarily take the shear deformation of woven fabrics into account and represent the fabric as a fishnet. A variation of the kinematic model is the energy approach [5] in which a mapping which minimises the fabric shear strain energy is sought.

The validity of these models depends on the following effects which are not accounted for:

- mechanisms apart from ‘pure shear’,
- local restraints such as tool friction,
- membrane forces developed in the fabric.

An alternative strategy used to model composite forming relies on comprehensive material models for the composite ply, tool and processing conditions [6]. These techniques are based on explicit finite element analysis of the draping process and require a comprehensive set of input parameters such as matrix viscosity, temperature, tool velocity, etc.

The work presented in this paper is part of a larger project which aims to provide the fundamental understanding and materials characterisation for the draping of fabric based composites (prepregs, thermoplastic composites and dry fabrics) and to provide the basis for developing a drape model intermediate to the above approaches. One such intermediate model, termed the progressive drape model [7-8], uses the kinematic model as the initial solution of the drape which is then updated with the inclusion of fabric stiffness and tool friction. The simulation starts at a point on the mould surface and the fabric progressively grows as new nodes are mapped using a kinematic model and updated with the help of FE analysis.

An alternative draping simulation strategy is also introduced here. This approach is similar to the comprehensive model but the FE mesh is greatly simplified by using 1D springs to represent the fabric shear stiffness. A marked saving in processing time is observed.
These various approaches are compared for processing speed and effectiveness when applied to the simulation of a hemisphere and a helicopter pilot helmet.

2 EXPERIMENTAL METHODS

This section describes the production of a helicopter pilot helmet component, and shear angle (change in included tow angle) measurements used for comparison with the drape simulation.

2.1 Component manufacture

The prepregs used to manufacture the helicopter pilot helmet had Tenax HTA fibres in a 5-harness satin weave, with Hexcel 6376 epoxy resin. The specimens were laid up by hand, vacuum bagged and then cured at 185°C for three hours. Three specimens were draped starting from the topmost point on the surface. Interestingly, it was found after curing that one of the two specimens with a bias-direction lay-up (i.e. the bias direction of the fabric mapped along the principal direction OA on the surface) had been pre-stretched such that the fabric near the starting point had +/-60 tows rather than +/-45, relative to the OA direction (figure 1). This specimen will be referred to as the ‘+/−60 specimen’. The other two layups were in +/-45 and 0/90 configurations. Figure 1 shows the +/-60 specimen in the final cured state. The grid lines are those marked on the flat blanks prior to the draping to aid the subsequent analysis using CAMSYS automated strain analyser.

2.2 Shear angle measurement

The measurements were made using the CAMSYS ASAME system; full details of the measurements are included in [9]. This system helps reconstruct the grid marked on the fabric in the form of a 3D mesh which can be used to determine the deformation pattern on the lamina. Angles and tow pitches were then measured from this reconstructed grid directly. The tow pitches were found to vary between +/-15% of the nominal pitch.

3 KINEMATIC MODEL

MSC Patran Laminate Modeler drape simulation is based on the kinematic fishnet approach. This software was used for obtaining the results of draping for the different configurations and to compare with the experimental measurements.

3.1 Model result

Figure 2 shows the drape simulation results with the fabric draped with the +/-45 configuration. The topmost point was taken to be the starting point of the drape, with the inward normal vector as the application direction. Two reference yarns on the fabric were aligned on the surface so that the desired layup configuration was achieved. The fabric was assumed to have orthogonal tows.

Results were also obtained for the 0/90 layup. In order to simulate the +/-60 drape, a feature of Patran which allows a non-orthogonal fabric to be draped was used (inter-tow angle was 60°).

3.2 Comparison to experiments for +/-45, +/-60, and 0/90 layups

In order to compare the drape output against the experimental measurements, specific representative curves on the surface were chosen and measurements were made along them. The most
important of these were the curves that followed the diagonal (bias direction) of the draped fabric. For the drape layups chosen here these were curves OA and OB as shown in Figure 1.

To start with, the +/-45 layup is considered, and the measurements along curve OA are compared with the predicted values as shown in Figure 3.

The comparisons with the kinematic model thus confirm that shear is the dominant mechanism of deformation, but that it is necessary to know the exact initial condition of the drape. For example the forces required to produce the pre-stretched (+/-60) specimen cannot be predicted. Membrane forces applied at points on the fabric away from the starting point will further affect the drape. No fabric stiffness is taken into account, so the effects of an unbalanced fabric or blank holder cannot be determined.

4 EXPLICIT FE MODEL

ESI PAM-FORM is a commercial software package for comprehensive analysis of forming, taking material behaviour and processing parameters into account [6]. The material model used for each composite ply is described as a thermo visco-elastic matrix with elastic fibre shell element. Normally one would model the displacement of a punch through several composite plies supported by a pressure blank-holder. However to simulate the hand lay-up process used to manufacture the helmet, a combination of gravity, applied normal (vertical) pressure and in-plane membrane forces was used.

An extreme example of how initial stretch of the fabric causes a very different mapping was observed in a specimen draped in the +/-60 configuration. The overall draping was better than in the previous case, and this was inadvertently achieved by forcing the change of initial conditions at the starting point. The +/-60° fabric definition used in Patran showed a good match with the experimental results, as shown in Figure 3. Note the shear angle changes sign between points O and A.

A good match with the kinematic model was found for the 0/90 mapping (Figure 5). A wrinkle-free component with moderate shear was achieved.

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5 INTERMEDIATE DRAPE MODELS

Two models have been proposed during the course of the present work. The aim is to utilise the effectiveness and simplicity of a kinematic model while combining the advantage of an FE analysis
which can take forces and fabric stiffness into account.

The first of these, the progressive drape model, utilises also the effectiveness of the kinematic model to provide a good ‘first order’ approximation. Figure 7 illustrates a typical result applied to the helmet using this approach, wherein nodal forces are applied to the edge of the material. These forces modify the deformation predicted from the kinematic model; this process can be progressively applied to cover whole of the mould surface.

![Fig. 7 Progressive Drape Model applied to a helmet.](image1)

An alternative intermediate model involves a complete drape simulation within FE, but uses a simplified unit cell model for the fabric which contains a spring to provide the material shear stiffness, as shown in Figure 8.

![Fig. 8 Unit cell for intermediate drape simulation.](image2)

The intermediate drape models took less than a minute to map a hemisphere with tool, fabric, and blank holder interaction included in the analysis (Figure 9).

![Fig. 9 Hemisphere drape using Intermediate Drape Model.](image3)

6 CONCLUSIONS

The kinematic model is the fastest method for fabric drape simulation, but has limited accuracy due to the omission of fabric and processing parameters. The explicit FE analysis is time consuming, but effective for a complete analysis of material behaviour and processing conditions. The intermediate model introduced here is able to strike a compromise between the two extremes of these available models. This model is very promising for a comprehensive drape analysis without the overhead of high processing time. None of the existing models are capable of handling tow slippage explicitly; work is underway to include this mechanism in the intermediate drape model.

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REFERENCES
