OPTIMISATION OF SHEET FORMING FOR TEXTILE COMPOSITES USING VARIABLE PERIPHERAL PRESSURE

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SUMMARY

This paper addresses optimisation of the sheet forming process for textile composites. A woven carbon/epoxy prepreg helicopter pilot helmet is used to demonstrate both experimental and numerical studies. A novel stamp-forming experimental procedure is developed, where a segmented blank-holder is used to control draw-in, facilitating process control and optimisation. A truss based finite element model, incorporating non-linear fabric shear properties and the occurrence of wrinkling due to tow buckling, is used to simulate forming. The simple basis of the model results in low computational times that allow its use within an optimization procedure. A genetic algorithm is used to solve the optimisation problem, minimizing the wrinkling in the formed component by selecting a suitable peripheral holding force distribution. Optimised designs resulting from the inversion procedure have significantly lower wrinkling than uniform peripheral force profiles.

1. INTRODUCTION

High performance composite components are produced traditionally by hand lay-up and autoclave curing of thermoset prepreg. However this technique relies on operator skill and offers limited scope for controlled or optimal forming. Hence manufacturers are investigating automated processes such as tape placement and diaphragm forming. An alternative approach is stamp-forming, where processes used for metal forming or plastics thermoforming can be adapted to form prepreg parts. This allows the process to be controlled, particularly if draw-in is controlled using a segmented pressure blank-holder. Such a process may allow an optimal forming strategy to be developed, for example to eliminate wrinkling or to achieve a structurally optimal fibre pattern.

Research on computational optimisation of composites manufacturing has focused on the impregnation and cure stages. Optimisation of the filling stage of liquid composite moulding with respect to the location of injection and outlet ports has been performed using cascade optimisation [1] and evolutionary algorithms [2]. Research on optimisation of the curing stage has addressed the problem of selection of cost effective thermal profiles [3] and specification of tool geometries that compensate for manufacturing distortion [4].

In an optimisation routine a forming simulation is executed iteratively and consequently it needs to be computationally efficient. A simplified finite element forming model has been developed to model forming of textile based thermoset prepregs [5]. This model simulates the woven material using stiff elastic trusses arranged in a lattice to represent the tows, and non-linear plastic diagonal members that incorporate the strain dependent shear behaviour of the reinforcement. Wrinkling due to tow buckling is incorporated by allowing tow elements to undergo only finite compressive deformation, below which they are deactivated [6]. This is fast enough to be suitable for use within an optimisation algorithm (for this study each run took 25-30 seconds on a P4 2.8 GHz PC).

The present paper addresses optimisation of the peripheral force distribution around the edge of the manufacturing tool during forming, with the objective of minimizing wrinkling. An experimental study is presented for forming of a helicopter pilot helmet from woven carbon/epoxy prepreg. This demonstrates the occurrence of wrinkling and also the effects of blank-holder pressure distribution on component quality. A numerical optimisation study is then presented, using the simplified finite element forming tool integrated with a binary genetic algorithm. This allows the pressure distribution to be determined for minimal component wrinkling.

2. FORMING EXPERIMENTS

Forming experiments for the pilot helmet were carried using a stamp-forming process with two matched moulds and a pressure blank-holder (Figure 1). The moulds were operated using a universal testing machine, so that forming rate could be controlled accurately. Draw-in of the prepreg was controlled using a segmented blank-holder, consisting of 16 spring-loaded feet mounted around a rectangular frame. The compression of each spring was set by tightening a bolt running through its centre, with each spring applying up to 27.5N. Prepreg sheet was placed on the lower mould, with a thin aluminium plate placed on top and the blank-holder mounted in place so that the feet transmitted the required force distribution to the plate.

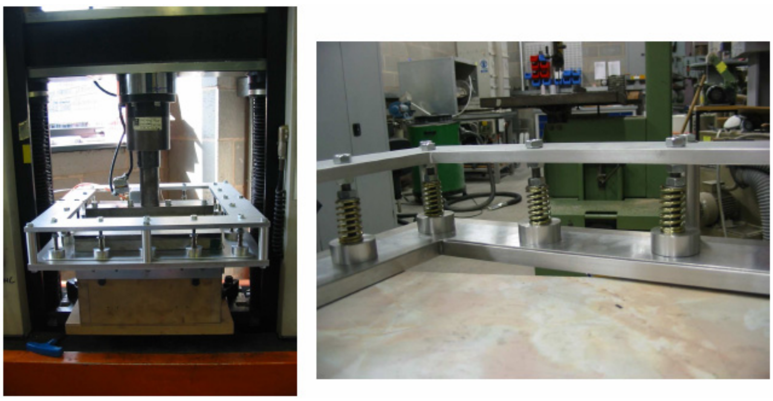

Figure 1: Forming apparatus for helicopter pilot mouldings, with (right) segmented blank holder.

Experiments were conducted using a plain weave carbon/epoxy prepreg. To evaluate the forming performance, prior to experiments white lines were drawn on the blank parallel to the fibres to form a grid, 10mm in grid size. In each case the shear angles and wrinkle locations were recorded after forming was completed. Further details of the experiments are included in [7].

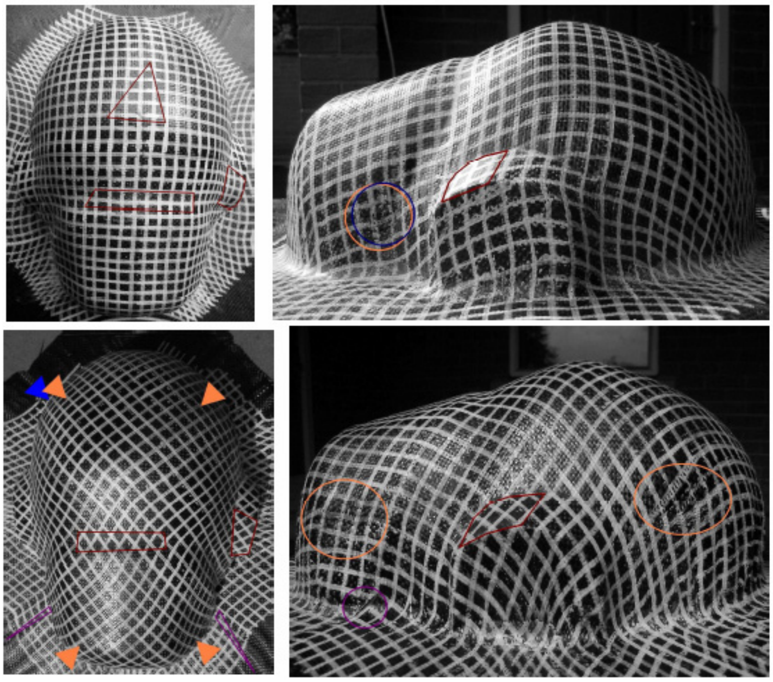

Figure 2: Prepreg helmets formed at 0/90° (top) and ±45° (bottom) orientations using a uniform blank-holder force distribution, with a total force of 300N.

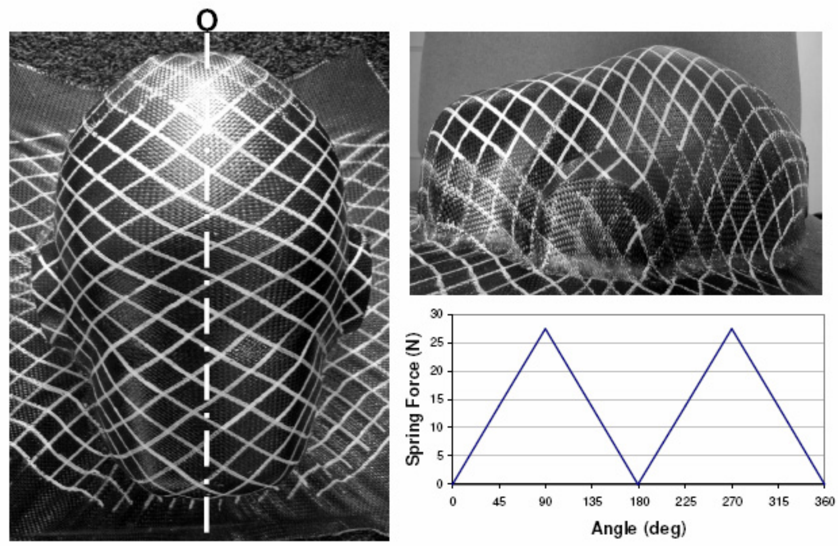

Figure 3: Prepreg helmet formed at ±45° orientations using a variable blank-holder force distribution (bottom right, where x-axis refers to position around the periphery relative to the point **O** on left-hand image).

Initial experiments were conducted using a uniform blank-holder force around the perimeter. Typical results are included in Figure 2 for 0/90° and ±45° orientations with respect to the axis of symmetry. Generally less wrinkling was observed for the 0/90° case, where wrinkles were present at the top of the “ears”, top of the “head” and in the four highly sheared corners. For the ±45° case severe wrinkling/folding occurred below the ears and on top of the head.

The effects of varying the blank-holder pressure distribution are illustrated for the ±45° case in Figure 3. Here the blank-holder force was varied between minimum and maximum force around the periphery. Comparison with Figure 2 shows that this had a significant effect on the formed fibre pattern. The material was sheared preferentially across the component, with more material drawn in from the top and bottom. However whilst wrinkling was largely eliminated around the ears, defects were still present particularly at the top and bottom of the component. This experimental study demonstrates that the blank-holder can control the fibre pattern, but that it is difficult to achieve an optimum fibre pattern using experiments alone.

3. FORMING OPTIMISATION

The optimisation scheme used here is based on a genetic algorithm (GA) operates on the peripheral force profile and interacts with the MSC.Marc implementation of the forming model [6]. The objective is to minimise total wrinkling strain (defined as Green-Lagrange strain below –0.01%). To avoid pressure profiles involving unrealistically high force gradients the profile is regularised as follows:

$$F(\theta) = A_o + \frac{C}{cosh[\sigma_1(\theta - \varphi_1)]} + \frac{C}{cosh[\sigma_2(\theta - \varphi_2)]} \qquad (1)$$

Here θ is the angle from the positive x-axis (dashed line in Figure 3) to the point on the periphery, and A_o, C, σ_1, φ_1, σ_2 and φ_2 are constants. This functional form includes two peaks or troughs depending on the sign of C. The position of the peaks or troughs is controlled by φ_1 and φ_2, whereas their height and breadth are controlled by σ_1, C and σ_2. A_o controls the level of the force profile, which here is adjusted so that the total force applied to the prepreg is constant over all possible process designs. The pressure distribution is thus characterised by five independent variables (C, σ_1, φ_1, σ_2 and φ_2), which are optimised by the genetic algorithm.

Two different forming orientations were considered, with tows at either 0/90^o or ±45^o to the x-axis. The parameters of the GA and the search space of the five parameters for the two optimisation runs are given in Table 1.

The convergence of the genetic algorithm and evolution of the peripheral force distributions for the two optimisation runs are illustrated in Figure 4. The algorithm converged within 75 generations for the 0/90o orientation and within 38 generations for the ±45 ^{o} case, corresponding to 1500 and 760 forming model runs respectively. The decrease in total wrinkling achieved in comparison to the uniform force profile is about 30% in the 0/90 ^{o} forming case and 50% in the ±45 ^{o} case. The optimum force profile for 0/90o involves two peaks of approximately 7 N magnitude at about 55o and 155 ^{o}. The process design for the ±45^o forming also involves two peaks of similar magnitude at 90 ^{o} and 175 ^{o}.

Table 1: Design space and parameters of the GA.

C	-100 -100
σ_1	0.005 - 0.16
φ_1	0 - 90
σ_2	0.005 - 0.16
Φ_2	90 -180
Elite size	2
Reproduction population size	14
Uniform crossover probability	0.5
Mutation probability	0.104
Chromosome size	5
Generation size	20

Figures 5 and 6 compare the fibre patterns and wrinkling strain distributions with uniform peripheral pressure to the optimised conditions in each case. Maximum shear occurs at diagonal positions near the base in the 0/90^o case using uniform pressure (Figure 5a). The fibre pattern for the optimised force profile is very similar to that for the uniform profile (Figure 5b). For the ±45° case, maximum shear occurs at normal positions near the base of the geometry, and again fibre patterns for the uniform and optimised force profiles are very similar (Figure 6). Concentrated wrinkling occurs near the base at locations where one set of tows runs parallel to the periphery of the helmet. Thus, buckling of tows occurs at positions normal to the symmetry axis of the geometry in the 0/90 ° case (Figure 5a), and at angles of 40° and 145° in the ±45 ° case (Figure 6a). This is similar to experimental observations (Figure 2). The use of the optimised profile achieves partial elimination of concentrated buckling (Figures 5b and 6b). In the 0/90° case, maximum wrinkling strain decreases from 20% to 14 % when the optimised pressure profile is used. The corresponding improvement for the ±45° case is from 15% maximum wrinkling strain to around 8%.

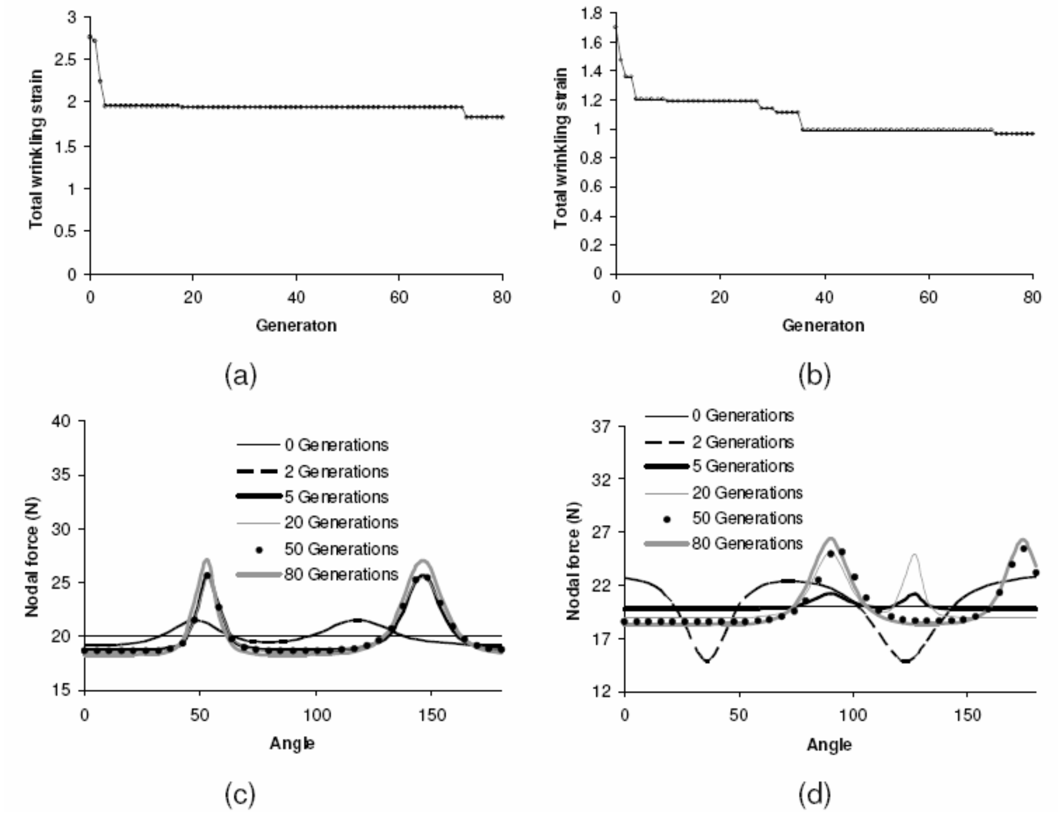

Figure 4: Convergence of the genetic algorithm: Evolution of total wrinkling strain for (a) 0/90° forming and (b) ±45° forming; evolution of peripheral force distribution for (c) 0/90° forming and (d) ±45° forming

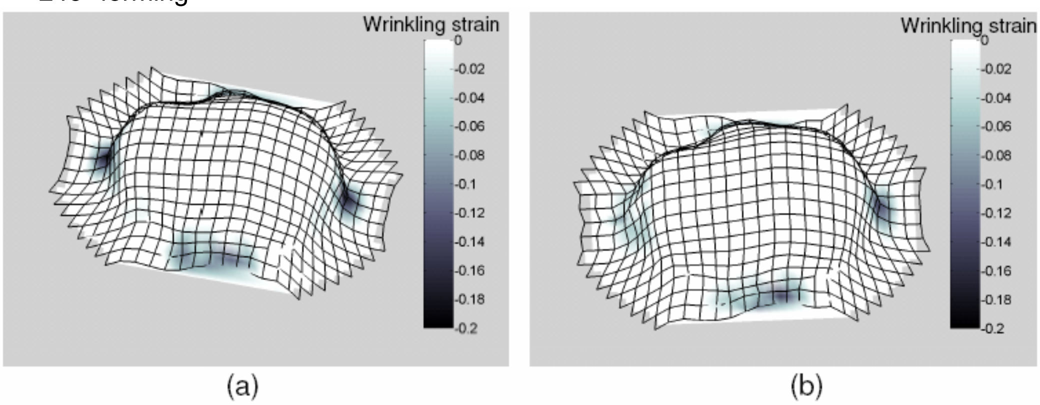

Figure 5: Optimisation results for 0/90° forming: Wrinkling strain distribution for (a) uniform force profile and (b) optimised force profile.

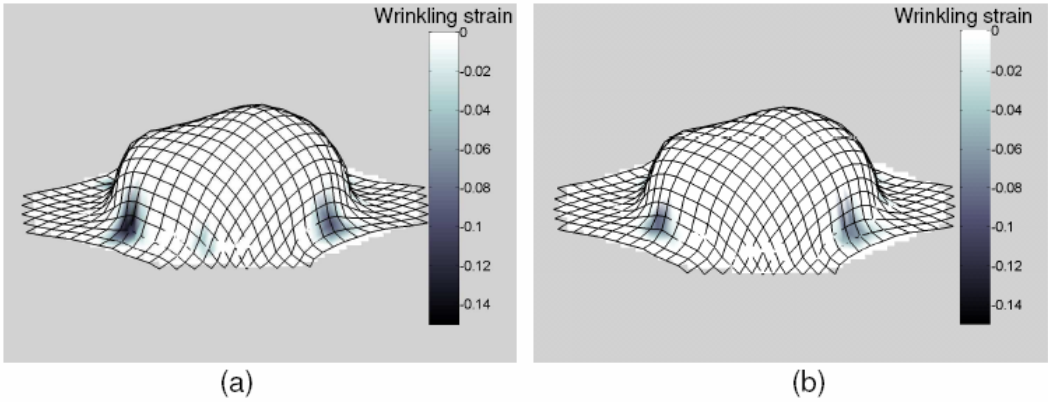

Figure 6: Optimisation results for ±45° forming: Wrinkling strain distribution for (a) uniform force profile and (b) optimised force profile.

4. CONCLUSIONS

This paper has described both experimental and numerical studies of forming for a complex component. An automated stamp-forming process with a segmented blankholder has been developed, and the potential of this for control and optimisation demonstrated. Selection of an appropriate peripheral force distribution can allow wrinkling to be reduced. To facilitate this, a numerical optimisation procedure based on a simplified finite element forming simulation and genetic algorithm has been implemented. This suggests that an improvement in total wrinkling strain of between 30% to 50% can be achieved. Optimised blank-holder force profiles involve increased peripheral pressure at positions diagonal to the locations of concentrated buckling. The next stage in the work will be to evaluate the optimised force profile within the experimental set-up.

5. ACKNOWLEDGEMENTS

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