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Formability optimisation of fabric preforms by controlling material draw-in through in-plane constraints

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ABSTRACT

A genetic algorithm is coupled with a finite element model to optimise the arrangement of constraints for a composite press-forming study. A series of springs are used to locally apply in-plane tension through clamps to the fibre preform to control material draw-in. The optimisation procedure seeks to minimise local in-plane shear angles by determining the optimum location and size of constraining clamps, and the stiffness of connected springs. Results are presented for a double-dome geometry, which are validated against data from the literature. Controlling material draw-in using in-plane constraints around the blank perimeter is an effective way of homogenising the global shear angle distribution and minimising the maximum value. The peak shear angle in the double-dome example was successfully reduced from 48.2° to 37.2° following a two-stage optimisation process.

1. Introduction

In the manufacture of composite components, draping of reinforcement fabrics can cause large local shear deformations (change in fibre orientations, fibre volume fraction, fabric thickness, etc.) to occur. For most fabrics, in-plane shear is the main deformation mechanism in drape, but excessive local shear can lead to wrinkling (i.e. out-of-plane buckling due to local compressive stresses) and fibre fracture [1]. To successfully drape a reinforcement without encountering unwanted wrinkles and defects, the main challenge is identifying optimum forming conditions. Among the processing parameters affecting fabric press forming, the distribution of the blank holder force (BHF) and the blank shape are two essential properties that should be optimised to improve the quality of the formed shape [2,3]. To optimise these parameters, efforts have been made to develop simulation tools to facilitate parametric studies.

Kinematic drape simulation codes [4,5] use a purely geometrical approach to compute fabric drape patterns, but whilst this method is computationally relatively inexpensive, there is no accounting for mechanical material properties or process conditions. Conversely, Finite Element (FE) simulations enable the physics of the forming problem to be modelled and are becoming a viable choice as computing resources improve. This approach enables the influence of process parameters, including contacts and friction between components to be studied, but more importantly can be used to indicate the likelihood of defects occurring during forming. To date, most FE forming studies have focused on capturing the deformation of fabrics accurately though implementation of suitable constitutive material models [6,7], rather than focusing on optimising the forming process.

Procedures for optimisation of the forming process can be classified as direct or indirect. Indirect methods refer to trial and error approaches, which require experience to interpret the results and can be time consuming. Nonetheless, they are likely to be used for optimising composite forming processes, since the complex relationship between wrinkling strain and clamping force does not need to be formulated. Indirect methods have previously been used to optimise fabric blank size [2] and BHF distribution [3], in order to minimise wrinkle formation. The probability for wrinkles to occur was shown to increase as the blank size is reduced relative to the size of the punch, since the tension in the blank is released during the latter stage of the forming process [2]. A uniform BHF distribution produced the least wrinkles in forming a hemisphere. However, it was concluded that a segmented blank holder is required to further reduce the level of wrinkling, to vary the local pressure distribution as a function of intra-ply shear and compressive forces [3].

Direct optimisation methods rely on mathematical relationships between the processing parameters (BHF, blank shape, fabric pre-shear) and the objective function (describing shear angle, wrinkling, etc.) to be formulated, and have been used extensively

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for optimising metal forming problems. They commonly employ Genetic Algorithms (GA) [8–11], which mimic natural selection processes to enable the strongest permutation of design variables to evolve, and inferior ones to fade out. GAs are not widely used for optimising composite forming problems, because they are computationally expensive. A GA was coupled with a kinematic drape model by Skordos et al. [5], where the drape start point, drape direction and the pre-shear angle of the fabric were defined as design parameters. Employing the GA reduced the CPU time to 30% of that required for an exhaustive search [5]. Alternatively, a simplified FE model was used in conjunction with a GA to optimise the BHF around the perimeter of the blank, with the objective of minimising wrinkling [12]. Results indicated that optimising the BHF successfully eliminated concentrated buckling of tows around the base of the hemisphere, without affecting the in-plane shear angle distribution.

This paper presents a GA coupled with a non-linear explicit FE model to optimise the draw-in of the blank during composite press-forming. Spring-loaded clamps are used to directly provide in-plane tension to the fabric, rather than applying a normal pressure (resulting in in-plane friction) through a blank holder. This technique has been discussed in the literature for thermoplastic forming [13,14] and is currently used in the automotive industry in preforming of non-crimp fabric. It enables the blank to be heated easily if the fabric is bindered or pre-impregnated, as the clamps are situated outside of the heated region of the press. This arrangement also offers more flexibility in terms of controlling material draw-in, as the spring-loading for each clamp can be controlled independently, but results in increased complexity. The optimisation procedure seeks to determine the optimum location and size of each clamp and the stiffness of each spring controlling the local draw-in. The objective is to minimise the global in-plane shear angle of the fabric.

2. Modelling of fabric preforming using in-plane constraints

2.1. Fabric material model

A non-orthogonal constitutive model is employed in this work to describe the fabric behaviour during preforming, which was previously derived by the authors [15]. This macro-scale model was shown to effectively capture the dominant factors in fabric forming, including in-plane shear, fibre elongation and inter-tow/intra-ply slipping. This kind of non-orthogonal model is considered to be more accurate than an orthogonal model, because it appropriately describes the anisotropic behaviour of biaxial materials under large shear deformation [16,17]. A VFABRIC subroutine was developed in Abaqus/Explicit to implement the mechanical constitutive relations for woven fabrics. Comparisons against experimental data [15] indicated high levels of accuracy for the simulation results, which was not significantly compromised by time-scaling or mass-scaling employed to reduce CPU time.

2.2. Validation for forming model using in-plane constraints

Numerical tests have been performed to validate the material model against experimental data for the case where in-plane constraints are used to provide tension in the fabric to control draw-in [13,18], rather than out-of-plane blank-holders. Material parameters were consistent with the values in the literature [19–22] for a balanced plain weave glass fibre/polypropylene commingled fabric. The value of Young's modulus was taken to be 35.4 GPa in each fibre direction and the shear modulus was described by a polynomial:

$$G_{12} = (6.7135|\gamma_{12}|^4 - 9.8228|\gamma_{12}|^3 + 6.3822|\gamma_{12}|^2 - 1.5928|\gamma_{12}| + 0.1948)\ \text{MPa} \quad (1)$$

where γ_{12} is the in-plane shear angle in radians.

Validation was conducted using the same geometry and material properties as in the literature [13,18]. The blank was a single 0°/90° ply at a thickness of 0.4 mm. The optimised blank shape described by Harrison et al. [13] was employed, and the ply was modelled using quadrilateral membrane elements (M3D4R). Tooling was considered to be rigid; Coulomb friction was adopted for both tooling-material and material-material contacts, with a coefficient of 0.2; displacement boundary conditions were applied to the punch, whilst in-plane spring elements were used to connect the edge of the blank to a rigid frame, in order to control blank slippage. The stiffness of the elastic 1D spring elements was 0.20 N/mm on the short edges and 0.27 N/mm on the long edges of the rectangular frame [13].

A comparison of the shear angle distributions is presented in Fig. 1. Qualitatively, the outline shape of the final formed part from the simulation is in very close agreement with experimental data [13]. A quantitative analysis was performed by comparing the local shear angle at 20 discrete locations (Table 1). Two experimental repeats were performed [13], and the measurements from each of the four quadrants were averaged for each repeat. Fig. 1 indicates that the predicted shear angles from the numerical solution fall within the range of the experimental values, with deviations of generally less than 2° according to Table 1.

3. Methodology of in-plane constraint optimisation

3.1. General strategy

The initial blank size for the double-dome forming study discussed here was 470 mm × 270 mm with a thickness of 0.4 mm, and the ply was discretised into 5076 square membrane elements (M3D4R). The initial fibre orientations in the blank were at 0°/90°.

Springs are arranged around the perimeter of the preform to control material draw-in, providing in-plane constraints during draping. The optimum design of this system is dependent on the geometrical arrangement (number, position and size) of the springs and their mechanical properties (stiffness). The optimisation procedure is split into two stages as shown in Fig. 2: (a) Step I: Clamping arrangement optimisation, (b) Step II: Spring stiffness optimisation. The first step determines sensible clamping positions to improve formability, by reducing the maximum global shear angle in the model. Compromises have to be made however, as it is not practical to constrain every position. The second step determines optimum spring stiffnesses for the derived spring arrangement, therefore the final solution may not be the global optimum, but near-optimal.

This multi-stage approach makes the procedure independent of specific geometrical parameters, thus providing the flexibility for application to a variety of test geometries. Simultaneous optimisation could potentially be more cost-effective computationally and produce a more efficient solution, but only if a suitable mathematical description could be derived. However, this would require a specific new formulation of the optimisation problem for each forming task and would not enable routine application of the method.

3.2. Step I: Clamping arrangement optimisation

Each node around the perimeter of the blank is initially constrained by an individual spring element with the same initial stiffness (see Fig. 2a). The other end of the spring is fixed to a fully