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Double diaphragm forming simulation for complex composite structures

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ABSTRACT

A finite element (FE) model has been developed to simulate the double diaphragm forming (DDF) process, to identify potential defects when forming complex 3D preforms from 2D biaxial non-crimp fabric plies. Three different metrics have been introduced to predict and characterise defects, which include local shear angles to determine ply wrinkling induced by over-shear, compressive strains in the primary fibre directions to determine bundle wrinkling, and tensile stresses in the primary fibre directions to determine fabric bridging. The FE simulation is in good agreement with experiments performed on a demonstrator component. Results indicate that fabric bridging occurs in large-curvature regions, which is the dominant defect in DDF, as wrinkling is generally lower than in matched-tool forming due to relatively low forming pressures (up to 1 bar). The axial tensile stress in fibres has been used as a measure to identify suitable positions and orientations for darts, to alleviate fabric bridging and improve surface conformity, whilst minimising the effect on the mechanical performance of the component.

1. Introduction

Diaphragm forming (also referred to as hot drape forming) is one potential method for automating the production of low cost preforms for high volume applications (30,000+ ppa), due to lower capital investment compared to matched-tool forming. In the forming process, a hydrostatic pressure is applied to a dry fabric stack via a diaphragm to produce the final preform, similar to the commonly employed preforming step of prepregs for autoclave processing in the aerospace industry [1]. It used to be mainly associated with thermoplastic composite materials [2–4], but more recently has been used to process thermoset prepregs [1,5–7] and produce binder-stabilised dry fabric preforms for liquid moulding routes [8–11].

There are two diaphragm forming options; using either a single diaphragm (Single Diaphragm Forming, SDF) or two diaphragms (Double Diaphragm Forming, DDF). In DDF, material plies are sandwiched between two deformable diaphragms, which are deep-drawn over a rigid tool by applying a pressure differential normal to the surface. Multi-axial in-plane tension is applied to the plies through friction on the diaphragm surfaces, which can be controlled by adjusting the pressure between the diaphragms to avoid fibre wrinkling and buckling and control in-plane shear. DDF is limited to forming the full ply stack in one operation, as layer-wise forming of multi-ply preforms is prevented by the presence of the lower diaphragm which would separate adjacent layers. SDF offers more process flexibility, enabling the preform to be constructed from multiple plies which can be formed sequentially. However, the single diaphragm does not constrain the ply stack relative to the tool, which can result in greater variation particularly for complex geometries.

Defects in the fibre architecture caused by diaphragm forming are different to those caused by matched tool forming. At the end of the stroke of a matched tool process, both sides of the preform are in contact with tool surfaces. Therefore, any local changes in thickness are smoothed out, as the material undergoes transverse extension (UD materials), inter- and intra-ply slip and inter-ply rotation. Comparison of matched tool forming and DDF [12] shows that DDF constrains the material movement much less and allows some thickening of the material as it shears, which may cause out-of-plane buckling. The quality of the formed component is also influenced by the tool design, depending on whether the fabric is draped over a male tool, or drawn into a female tool [13]. The shape of the tool controls the magnitude of the compression force during diaphragm forming, and therefore in-plane fibre tension. The clamping forces and the forming forces are independent for a matched tool process, and are provided by the blank holder and the punch/die respectively. However, both of these functions are provided simultaneously by the diaphragms in diaphragm forming, which results in reduced process control. For a male tool, the diaphragm/preform initially makes contact with the highest point of the tool and tension is generated, stretching the diaphragms. Compressive stresses transverse to the stretch

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direction occur due to the effect of Poisson's ratio, resulting in severe out-of-plane buckling in the diaphragms. For a female tool, the diaphragm/preform initially makes contact with the flat region typically surrounding the perimeter of the tool, creating a frictional force which affects the tension in the preform. This can help to prevent compressive stresses (hence wrinkling) from occurring, but can also cause fabric bridging. The forming forces are unable to overcome the large frictional forces, therefore preventing the fabric from drawing into the tool. A DDF process study by Krebs et al. [13] showed that for a hemisphere geometry, reduced wrinkling was seen when deep drawing into a female mould compared with draping over a male tool. Vacuum-only pressure is commonly used for thermosets, but a positive hydrostatic pressure (0.1–1.7 MPa) is typically used for forming thermoplastics, as the diaphragms tend to be thicker and stiffer in order to prevent wrinkling [14]. Bersee and Beukers [15] conclude that there is no real benefit to hydrostatic pressures above 1 bar, which significantly reduces capital costs and makes the process scalable for larger structures.

The deformation mode and the onset of defects are also dependent on the diaphragm material type. Disposable vacuum bag materials like modified urethane films or polyimide elastomers are often used to preform pre-impregnated materials ready for the autoclave cure cycle. The low thickness of these materials can cause problems with wrinkling [1], and thicker, stiffer diaphragms are therefore commonly used in commercial processes to alleviate shear-induced out-of-plane buckling [16]. The response of the upper diaphragm during forming can also differ from that of the lower diaphragm, depending on the heating arrangement.

Material wastage is difficult to avoid when using a matched tool forming process, as excess material must remain in the blank holder region in order to maintain tension to the end of the forming step [17]. There is an opportunity for producing net-shape preforms using diaphragm forming, as in-plane tension is provided by the frictional forces at the diaphragm/preform interface. Krebs et al. [13] showed the importance of optimising the ply shapes to reduce waste, but also to avoid redundant areas of fabric which can lead to instabilities, such as wrinkling, buckling and fabric bridging. Hallander et al. [18] showed the influence of the ply stacking sequence on the formability, with different fibre types influencing the local friction and inter-ply shear. The final formed shape is sensitive to the initial fibre architecture, and minimising the number of transitions from ±45° plies to 0° plies can help to reduce the overall level of wrinkling [19].

Numerical simulations play an important role in optimising preform lay-ups and processes for the manufacture of composite components. Matched-tool forming is well-understood, with a range of macroscale [20] and mesoscale [21,22] constitutive relationships available for describing the deformation behaviour of woven and non-crimp fabrics. Material models have been developed for diaphragm forming [9,10,23,24], but capturing the behaviour of the diaphragms is complex. Leutz et al. [9] simulated the SDF process, and Margossian et al. [10] simulated the DDF process, but neither reported details of the material models used for the diaphragms. The diaphragm was modelled using a plastic material model by Sorrentino and Bellini [23], based on an isotropic nonlinear viscoelastic shell element of the Maxwell type. A rubber diaphragm was modelled using a hyperelastic Mooney-Rivlin material model by Sjölander et al. [24], whose material constants were obtained from uniaxial tensile tests and assuming incompressibility. The influence of forming temperature has been reported [5,25] and forming at higher temperatures generally yields better tool conformity by reducing the diaphragm stiffness.

This paper investigates the use of DDF for producing geometrically complex fabric preforms suitable for liquid moulding processes. An FE model has been developed to simulate diaphragm forming of non-crimp fabrics, in order to investigate the geometrical limitations of the process and the cause of defects. A generic geometry is studied and results are presented to show how the ply shapes are optimised to provide a net-shape preform without defects.

2. Experimental approach

2.1. Double diaphragm forming

A laboratory-scale diaphragm forming machine was designed at the University of Nottingham to preform binder-stabilised dry fabrics, and is shown in Fig. 1. The dimensions of the diaphragms were 1.8 m × 1.5 m. The lower diaphragm was clamped between two frames, and the upper diaphragm was fixed to the lower diaphragm using a vacuum-tight zipper seal. This arrangement was fixed to four pneumatic cylinders which were used to raise and lower the diaphragms relative to the forming tool.

A schematic of the process steps is shown in Fig. 2. The fabric plies were placed on top of the lower diaphragm. The upper diaphragm was then added and the zipper seal was closed manually to encapsulate the fabric plies (Fig. 2a). A vacuum was drawn between the two diaphragms to clamp the material. The diaphragm arrangement was raised to within 150 mm of infrared heaters and heated to 90 °C in order to melt the powdered binder. Once the set-point was achieved, the diaphragm arrangement was quickly lowered and draped over the tool (Fig. 2b). A second vacuum (independent of the first) was then drawn between the lower diaphragm and the tool to complete the forming process (Fig. 2c). The preform was left to cool to below the melting point of the binder before removing (Fig. 2d). The vacuum was then released between the diaphragms and the top diaphragm was removed first, to prevent the preform from distorting or springing back. The vacuum between the lower diaphragm and the tool was released once the preform had been removed, enabling the lower diaphragm to recover before the next preforming cycle. The total cycle time was approximately 4 min for this laboratory setup. This time largely depends on the thickness of the ply stack and the chemistry of the binder, in order to ensure all binder has been activated. This could potentially be reduced further by implementing forced cooling and increasing the power of the heaters.

A demonstrator tool was designed, representing a section from a complex automotive structure, as shown in Fig. 3. The surface shape includes regions of single and double curvature and surface features which could lead to fabric bridging.

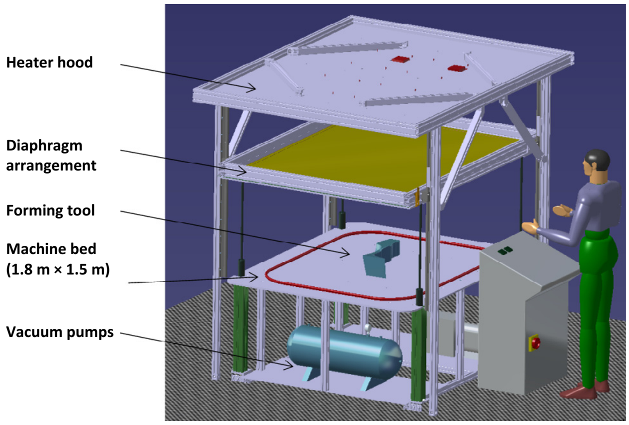

Fig. 1. Details of the diaphragm forming machine. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)