DEFECT REDUCTION IN THE DOUBLE DIAPHRAGM FORMING PROCESS

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ABSTRACT

Diaphragm forming is one potential method for implementing automation in the production of low cost preforms for high volume composite applications. Components with double curvature have been produced using three different processes; press forming, double diaphragm forming and single diaphragm forming to compare preform quality. Press forming was found to produce the best quality preforms, whilst single diaphragm forming produced the worst, as the single diaphragm did not constrain the material sufficiently. Using risers in the diaphragm forming process was investigated to reduce defects in preforms without affecting the mechanical properties of the finished part. It was found that out of plane wrinkling defects could be successfully alleviated, but areas of fabric bridging remained.

1 INTRODUCTION

One of the major challenges in any composites manufacturing process is forming doubly-curved 3D shapes from flat 2D fibre broad goods. In order to reduce cycle times and manufacturing costs, touch labour needs to be minimised, and process automation implemented. Diaphragm forming (or hot drape forming) is one potential method for automating the production of low cost preforms for high volume applications (30,000 ppa+), since it requires lower capital investment compared to matched tool forming [1]. However, a major challenge is establishing the limitations of the diaphragm forming process to produce defect-free preforms.

There are two diaphragm forming options; using either one 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. 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 subsequent 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 variability, particularly for complex geometries.

Preform defects caused by diaphragm forming are different to those commonly experienced in matched tool forming processes [2]. The aim of this work is to: (1) compare the quality of components manufactured by DDF, SDF and press forming processes, (2) improve the formability of composite reinforcement during diaphragm forming and (3) develop processing strategies to mitigate forming defects in diaphragm forming.

2 EXPERIMENTAL APPROACH

2.1 Double diaphragm forming

A laboratory-scale diaphragm forming machine was designed to preform binder-stabilised dry fabrics. The dimensions of the diaphragms were 1.8 m × 1.5 m. The lower diaphragm was clamped to a rectangular picture frame, 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 Figure 1. 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 (Figure 1a). A vacuum was drawn between the two diaphragms to clamp the material. The diaphragm/picture frame 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 (Figure 1b). A second vacuum (independent of the first) was then applied between the lower diaphragm and the tool to complete the forming process (Figure 1c). The preform was left to cool to below the melting point of the binder before removing (Figure 1d). 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 minutes 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.

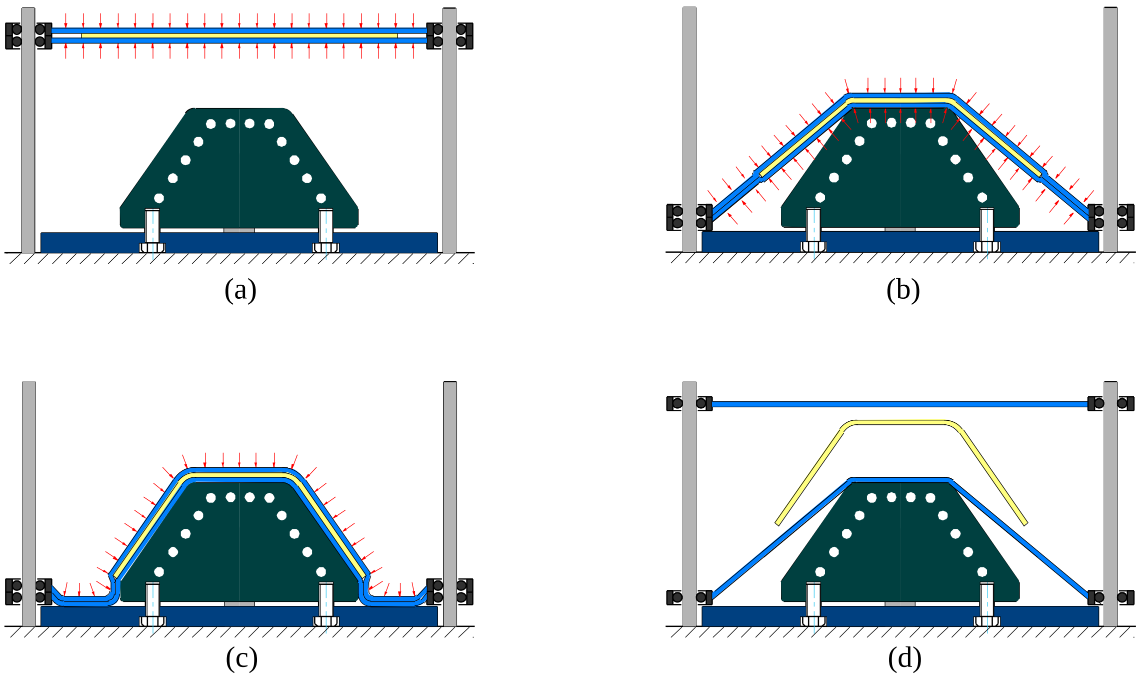


Figure 1: Schematic of the double diaphragm forming process.

2.3 Single Diaphragm Forming

The SDF process is similar to the DDF process, but without the lower diaphragm. Fabric was preheated in an oven at 90 °C and then transferred quickly onto the male forming tool. The single diaphragm was then lowered and a vacuum was applied between the diaphragm and the tool. The preform was left to cool and then the diaphragm was carefully raised to enable the preform to be removed.

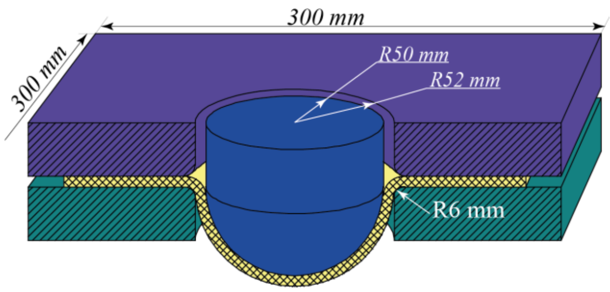
2.4 Press forming

A laboratory-scale hemisphere press forming tool, integrated into a universal testing machine, was used for preforming, as shown in Figure 2. Two 300 mm × 300 mm square heated platens with central holes with 104 mm diameter were used to clamp the fabric plies. A clamping force of 1200 N was applied to the blank holder. A hemispherical punch with a diameter of 100 mm was attached to the crosshead of the machine via a 25 kN load cell, which allowed the forming force to be monitored. A punch speed of 100 mm/min was used to form the plies. Blanks were first heated to 90 °C to activate the binder, before the forming experiment was started. Experiments were conducted using a punch displacement of 50 mm (hemisphere fully formed).

2.5 Materials

All preforms were produced using two plies of FCIM359 biaxial non-crimp fabric (NCF), at $[0°/90°]_2$, supplied by Hexcel, Leicester, UK. Each ply consisted of 440 gsm of carbon fibre with a 24K tow size [1] with a pillar stitch at 45°. A small amount (6 wt%) of Momentive Epikote 05390 binder was applied between layers to create a stiff preform that was suitable for measuring fiber angles after forming. The thickness of each ply was measured to be 0.4 mm, using a Vernier caliper.

(a) Tool setup



(b) Dimensions

Figure 2: Hemisphere forming tool.

2.6 Shear Characterization

To quantitatively characterise the shear behavior of the fabric in the press forming and diaphragm forming process, the visible surfaces of the NCF layers were marked with a square grid with a line spacing of 10 mm prior to forming. The grid lines were aligned with the directions of the primary yarns. Grid strain analysis (GSA) was used to determine the level of shear deformation in the formed hemispheres. The 3D coordinates of grid intersection points were digitised using a coordinate measuring machine (CMM), and the angles between them were calculated using GSA. A Matlab script was written to process the Cartesian coordinate data generated by the CMM, which was presented as a 3D surface plot.

2.7 3D Scanning

To capture the geometry of the preform post forming, a Faro 3D Focus scanner was used. This tripod mounted scanner was moved around the part, taking a series of scans which were then stitched together using SCENE software. A point cloud was then exported to Matlab, where a mesh was fitted using the GRIDFIT [3] algorithm. Scans of the tool were also taken whilst it was in position, and these were used to calculate the distance between the preform and the tool after forming to highlight wrinkles and defects.

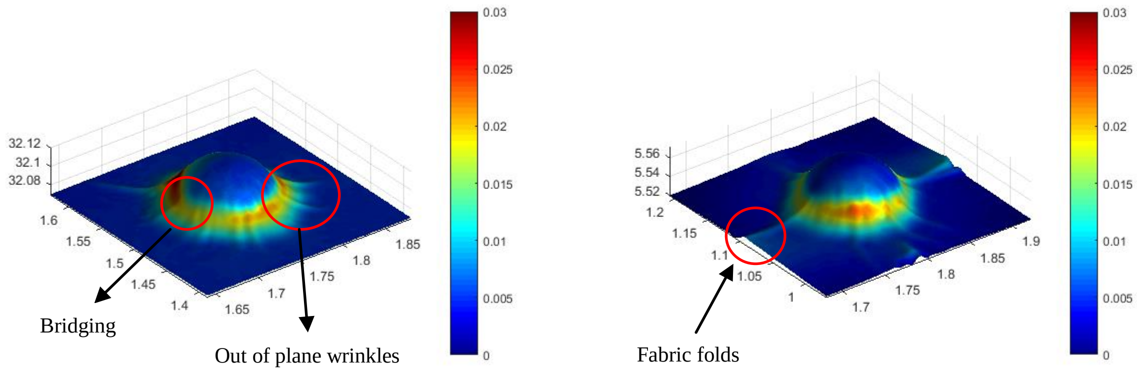
3 COMPARISON OF SDF, DDF AND PUNCH FORMING

A series of Ø 50 mm hemispheres were formed from two layers of 300 mm × 300 mm NCF in a 0°/90° orientation using three different processes; press forming, SDF and DDF (Figure 3). The press forming process is able to produce preforms with lower levels of out-of-plane wrinkling than the diaphragm forming processes. This is due to the clamping force provided by the blank holder, which prevents the preform from wrinkling out-of-plane and also enables the material to conform to the shape of the hemisphere without significant bridging.

(a) Press Forming (b) DDF (c) SDF

Figure 3: Formed hemispheres.

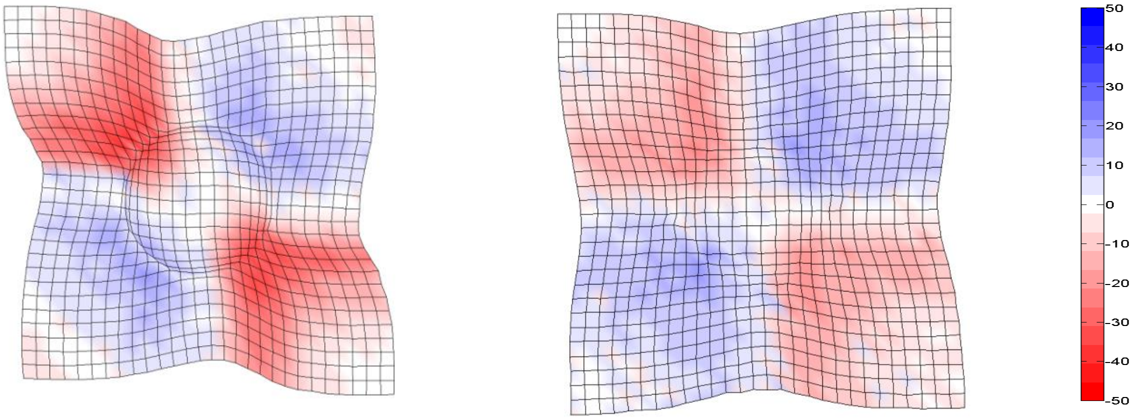
The majority of defects in diaphragm forming are out-of-plane wrinkles and bridging around the concave regions (i.e. the base of the hemisphere) (Figure 4 (a)). In these regions, the vacuum-only pressure may not be sufficient to provide enough force for the blank to conform to the tool surface. DDF produces better quality preforms than SDF, as more severe defects (particularly wrinkles) are observed in SDF. The single diaphragm configuration is unable to sufficiently constrain the fabric plies during draping, leading to folds in the fabric (Figure 4(a)), whereas DDF provides a smoother surface finish but with greater levels of bridging.



(a) DDF (b) SDF

Figure 4: 3D scans of SDF and DDF hemispheres.

The GSA results for the press formed and double diaphragm formed hemispheres are shown in Figure 5. The orientation of the stitches relative to the primary yarns leads to asymmetric behaviour. In the positively shared region, the stitches are in compression, while in the negatively shared region, stitches are in tension. The asymmetric behaviour is most pronounced in the press formed hemisphere with angles ranging between -44.5 ° and 19.8 °, leading to an asymmetric perimeter. Shear angles in the DDF hemisphere are lower than those of the press formed hemisphere, particularly in the negatively shared region, which has a maximum shear angle of -32.1 °. Out-of-plane wrinkles form due to the lack of constraint from the membranes in the diaphragm forming process, which induces less shear compared to the press formed case.



(a) Press formed (b) DDF

Figure 5: 3D surface plots of shear angles in the preforms.

4 DEFECT MITIGATION

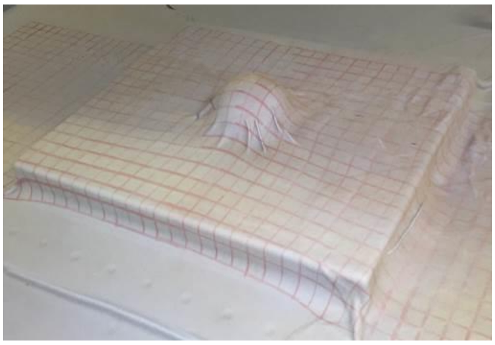
Whilst forming-induced wrinkles can be reduced by optimising ply shapes, introducing darts or even redesigning the tool, these solutions may result in lower mechanical performance [1] of the finished component. In the current work, the introduction of risers is investigated as a possible solution for reducing forming defects in DDF. Risers are rigid blocks positioned around the tool to increase the local tension in the diaphragm and to control the seed point (the first point of contact) with the tool. Hemispheres have been formed using risers with incrementally increasing height ranging from 25 mm to 75 mm. Risers were arranged in a square pattern, 175 mm from the centre of the hemisphere tool as shown in Figure 6.

To compare different riser configurations, a CMM was used to digitise the perimeter of a spherical cap 40 mm below the top of the hemisphere as shown in Figure 7. At this height, all of the out-of-plane wrinkles were captured at their highest amplitude. The severity of wrinkling is quantified by the root-mean-square (r.m.s.) amplitude of the spherical cap profile (Figure 8). When riser heights of 25 mm and 50 mm are used, wrinkles are still present in the preform but they are reduced in size, indicating that there is still insufficient tension in the membranes at these riser heights. At a riser height of 75 mm, which is higher than the apex of the tool, wrinkling defects have been alleviated, but some stretching of the fabric has occurred (Figure 7(d)), due to increased tension in the membrane. This indicates that a riser height between 50 mm and 75 mm is expected to produce the best quality preforms as sufficient tension will be present in the membrane to prevent out of plane wrinkling while not exceeding the tension where fabric stretching can occur.

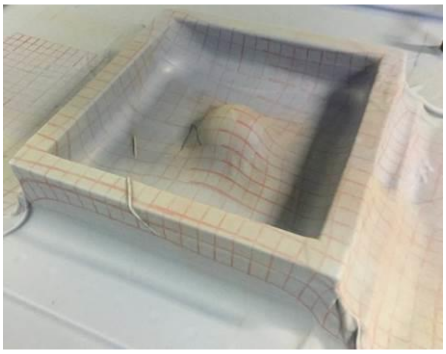
Figure 9 shows vertical cross-sections of hemispheres formed by press forming and DDF. Hemispheres formed using press forming follow the shape of an ideal hemisphere closely. However, the conformity of preforms formed using DDF is poor around the equator of the hemisphere. This is because the diaphragm pressure cannot overcome the large frictional forces in the flat area of the blank. Risers have not affected bridging, as hemispheres formed with 75 mm risers have an almost identical cross section to hemispheres without risers.

One of the advantages of the diaphragm forming process is that, unlike press forming, parts can be produced using a net shape blank. The original 300 mm × 300 mm blank causes bridging because the material becomes pinned in the flat area of the blank. This area of fabric is required for press forming because it is clamped in the black holder, but it is no longer required for the diaphragm forming process. Using the model described in [1], the ply shape was optimised to suit the diaphragm forming process, where the preform only covered the hemispherical part of the tool. Figure 10 shows that the preform has been successfully formed without bridging.

In Figure 11, the probability density function of local shear angles measured using GSA are shown. The curves for no risers and 75 mm risers are very similar. This shows that using risers has not significantly affected the way the material has sheared during forming. Instead, the increase in membrane stiffness has prevented the material from buckling out of plane.



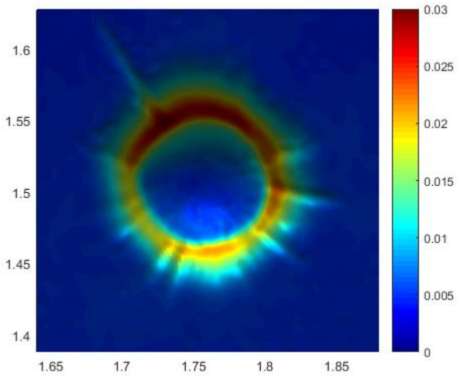
(a) DDF without risers



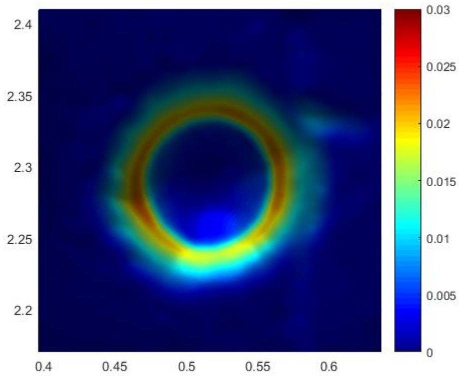
(b) DDF with 75 mm risers

(c) DDF Preform without risers

(d) DDF Preform with 75 mm risers



(e) 3D scan of preform without risers



(f) 3D scan of preform with 75 mm risers

Figure 6: Double diaphragm forming of hemisphere tool.

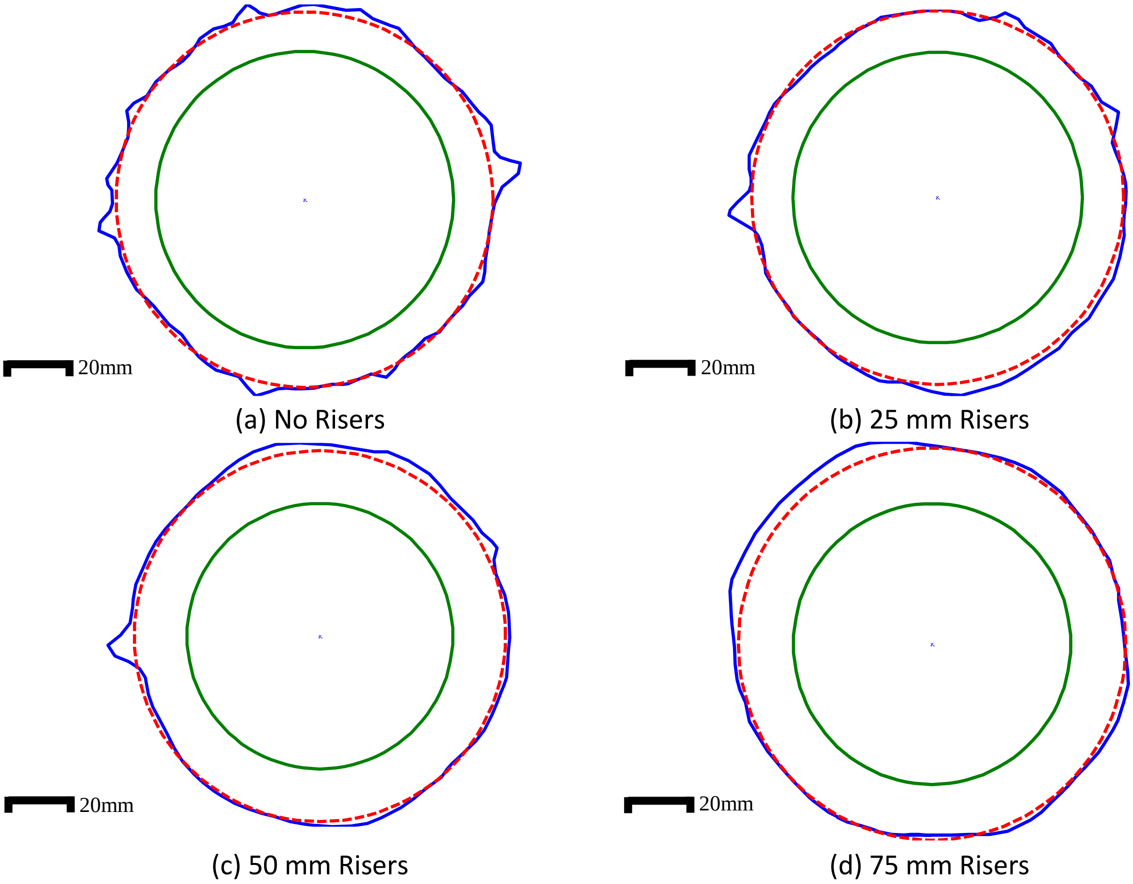


Figure 7: Cross section of hemispheres formed using DDF. Red dotted line indicates ideal case, blue line indicates actual measurement and green line represents tool surface.

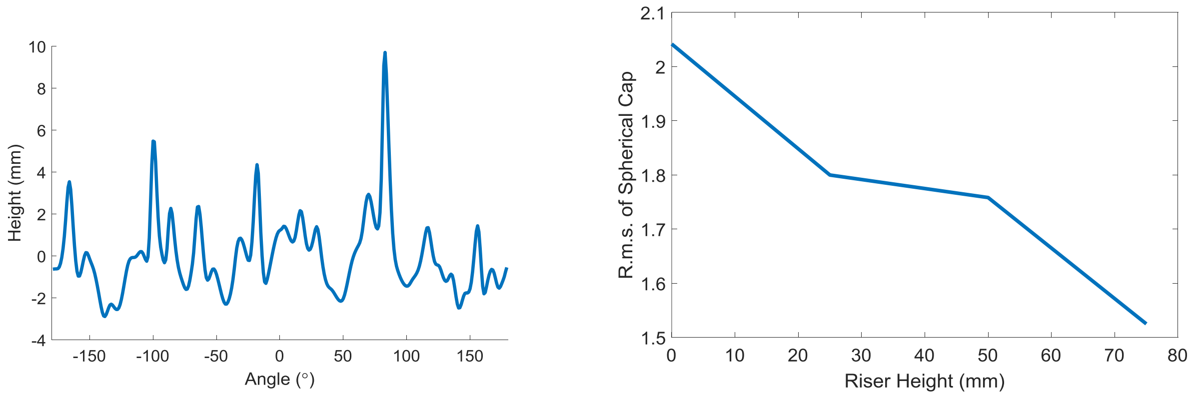


Figure 8: Spherical cap profile, 40 mm below the top of a hemisphere formed with no risers (a). R.m.s. value of spherical cap at four different riser heights.

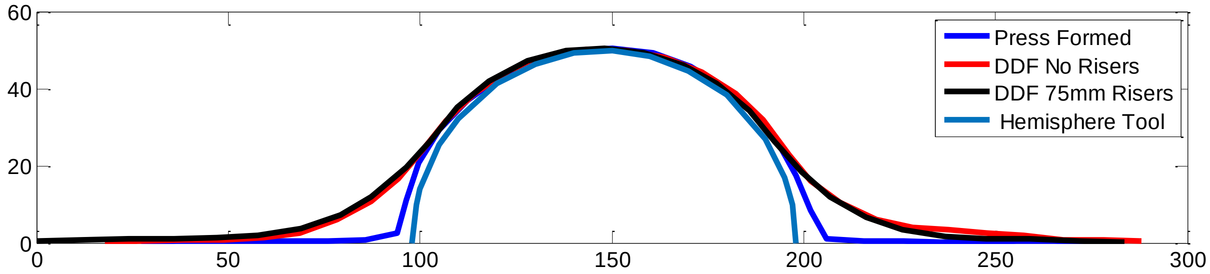
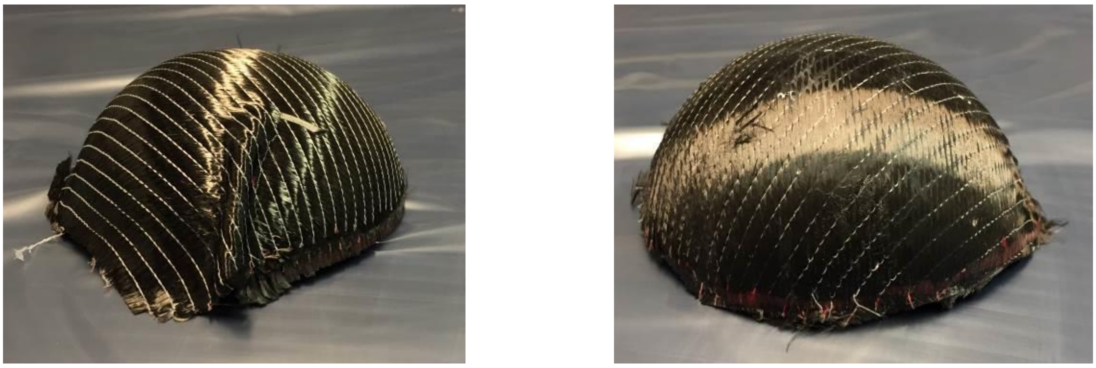


Figure 9: Vertical cross section of hemispheres.



(a) No Risers (b) With risers

Figure 10: Net shape hemispherical preforms.

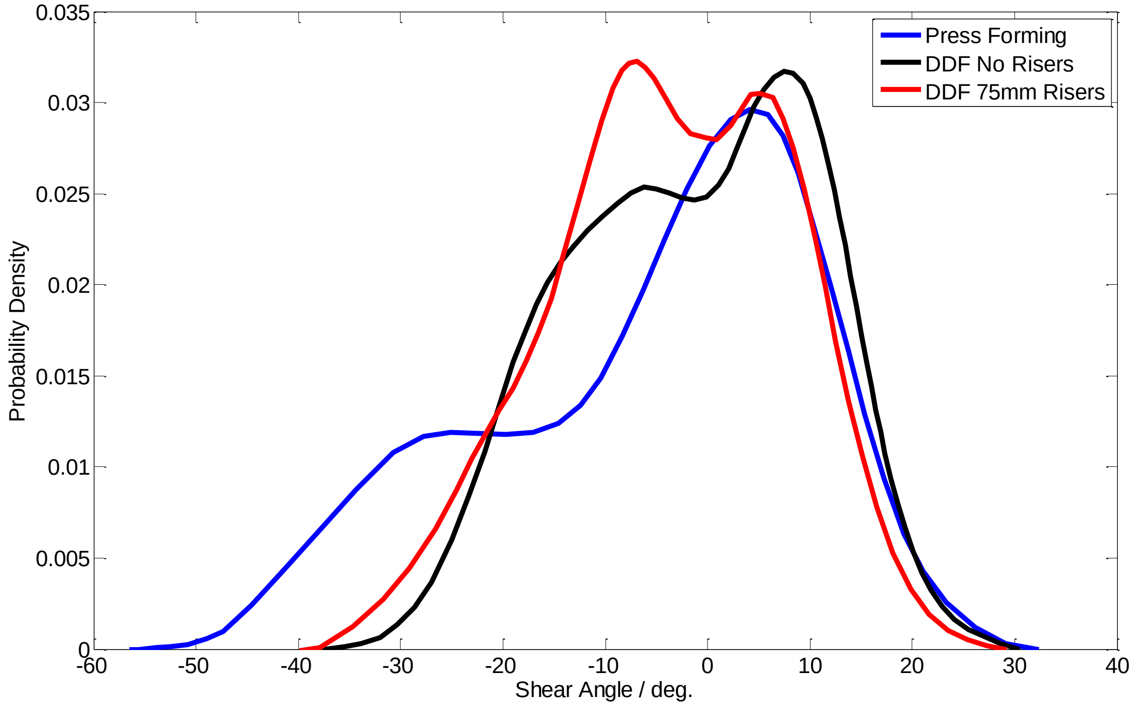
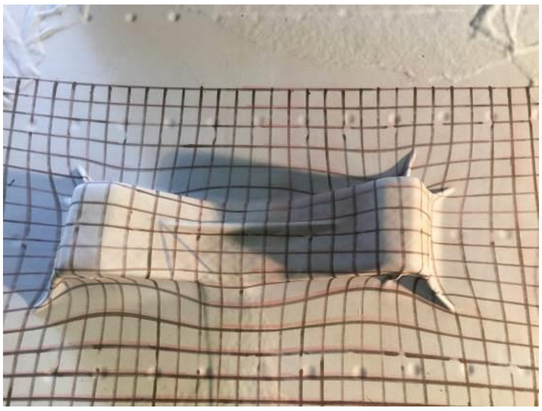


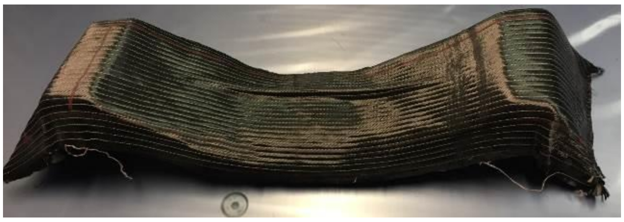
Figure 11: Probability density of shear angles measured from hemispherical preforms.

The saddle geometry (Figure 12) allows the effect of risers on a single out-of-plane wrinkle to be studied. The defect is caused when the diaphragm becomes pinned on the ends of the tool. As the diaphragm can no longer move, it must elongate to form the curve of the saddle. When the diaphragm elongates, the Poisson effect causes the diaphragm to contract inwards. The material constrained within the diaphragm cannot compress sufficiently and buckles, forming the out-of-plane wrinkle. To remove this wrinkle, risers have been placed perpendicular to the contraction force in the diaphragm. The risers increase the tension in the diaphragm, as can be seen from the grid spacing in Figure 12. The increase in tension overcomes the contraction force and prevents the out of plane wrinkle forming. Numerous riser sizes and positions were tested, and it was found that adding two risers of dimensions 100 mm × 100 mm × 400 mm, 40 mm from the longest edge of the saddle tool, was effective at removing this wrinkle, as shown in Figure 12b.

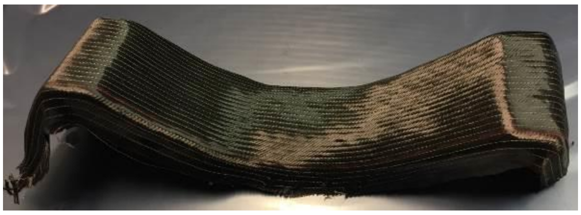


(a) No risers

(b) Risers 40 mm from part



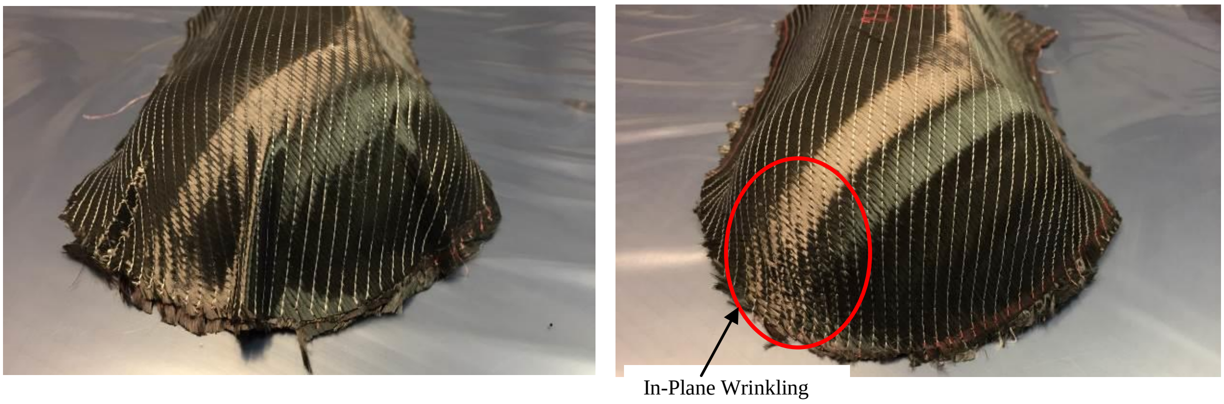
(c) DDF preform with no risers



(d) DDF preform with risers

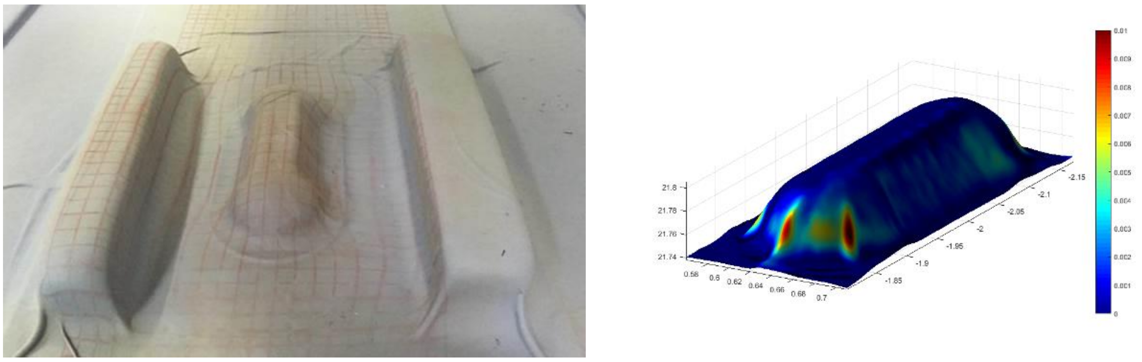
Figure 12: DDF forming of saddle tool preforms.

A double hemisphere represents a more complicated forming case than the saddle geometry, as defects form in a region of shear on the front of the hemisphere. During forming, the membrane initially contacts the flat top surface of the hemisphere and then the base. The diaphragm is pinned between these two points and must elongate to form the two curved ends of the double hemisphere. The Poisson effect causes the diaphragm to compress, buckling the fiber layers as they shear to form the curved edges of the double hemisphere, forming the three wrinkles shown in Figure 13(a). To alleviate this wrinkling, it was found that a 100 mm × 100 mm × 400 mm riser should be placed 80 mm from the horizontal edge of the part as shown in Figure 14(b). Adding risers has successfully alleviated the three out of plane wrinkles; however, in-plane wrinkling is now present in their place, as highlighted in Figure 13(b). The elongated diaphragm has provided sufficient out-of-plane constraint so that the material can no longer wrinkle out-of-plane, forcing the fabric to wrinkle in-plane to conform to the tool. This behavior is similar to that of a matched tool process, where the rigid tools also prevent out-of-plane wrinkling. In-plane wrinkling is generally more desirable than out-of-plane wrinkling, as mechanical properties are less affected, and it is still possible to fit the preform into a closed tool for moulding.



(a) No risers (b) Rises 80 mm from part

Figure 13: Double hemispherical preforms.



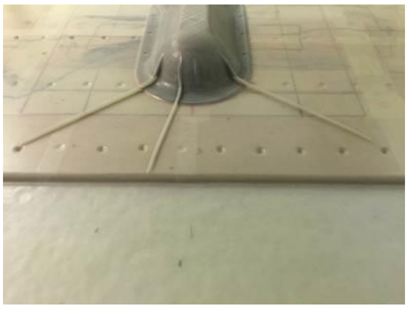
(a) Double hemisphere tool and risers (b) 3D scan of hemisphere preform

Figure 14: DDF forming of double hemisphere preforms.

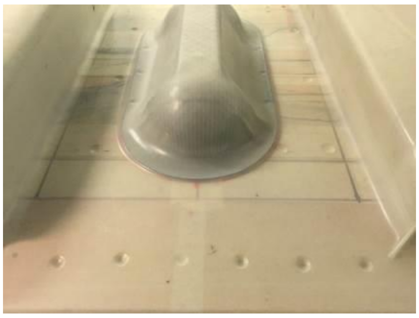
The double hemisphere geometry was formed using SDF to evaluate the effectiveness of using risers with this process. Without risers, the defects are in the same position as in DDF. However, they are reduced in magnitude (**Figure 15**(c)). When 100 mm × 100 mm × 400 mm risers (**Figure 15**(b)) are added 80 mm from the part, the wrinkles are steered around the preform to a different position (**Figure 15**(d)). The risers have altered the way the membrane contacts the tool, so that the faces of the double hemisphere are contacted before the sides. This forms the material against the tool on the faces and steers excess material to the sides of the part, where out-of-plane wrinkles form (**Figure 15**). This shows that adjusting the contact point could be used in both DDF and SDF to steer wrinkles away from critical locations in the preform and into run-off areas or locations where they will have less influence on final part properties.

5 CONCLUSIONS

The forming behaviour of biaxial NCF has been studied using press forming, DDF and SDF. Hemispheres were formed using each of the three processes and it was found that due to the clamping force provided by the blank holder, the press forming process is able to produce better quality double curvature preforms. The majority of defects in diaphragm formed hemispheres are out-of-plane wrinkles and bridging. DDF produces better quality preforms than SDF as the single diaphragm is unable to sufficiently constrain the blank. Risers have been successfully used to alleviate out-of-plane wrinkles for convex hemisphere and double hemisphere geometries and a concave saddle geometry. It is important to use risers of the correct size and place them in the appropriate position in relation to the tool. It is envisaged that this could be optimised using the FE model discussed in [1].

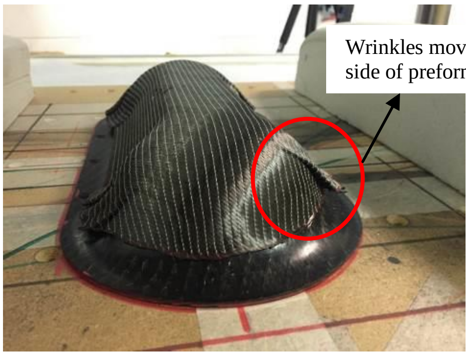


(a) SDF no risers



(b) SDF with risers

(c) SDF preform with no risers



(d) SDF preform with risers

Figure 15: SDF forming of double hemisphere geometry.

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