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## **Double diaphragm forming simulation for complex composite structures**

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### **Abstract**

A finite element (FE) material 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 (bridging stress). The FE simulation is in good agreement with experiments performed on a generic automotive 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 bridging stress parameter has been used 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.

## **Keywords**

A. Fabrics/textiles; B. Defect; C. Finite element analysis (FEA); E. Forming; E. Preform

## **1 Introduction**

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), due to lower capital investment compared to matched-tool forming. The forming process applies a hydrostatic pressure to the fabric stack via a diaphragm, which is commonly used as a preforming step for autoclave cure cycles in the aerospace industry [1]. It is typically 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 the pressure between the diaphragms to avoid fibre wrinkling and buckling and control in-plane shear. DDF is used to form the full ply stack in one operation, as the presence of the lower diaphragm prevents subsequent operations. 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, rather than inducing 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 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 large flat region surrounding the perimeter, creating a frictional force, affecting 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 MPa - 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 constitutive 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  $\pm 45^\circ$  plies to  $0^\circ$  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 [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 developed at the University of Nottingham to preform binder-stabilised dry fabrics, and is shown in Figure 1. The diaphragms were 1.8 m × 1.5 m. The lower diaphragm was clamped between a support frame and 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 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 (Figure 2a). A vacuum was drawn between the two diaphragms to clamp the material. The diaphragm/picture frame arrangement was raised to within 150 mm of the infrared heaters in order to melt the powdered binder at 90°C. Once the set-point was achieved, the diaphragm arrangement was quickly lowered and draped over the tool (Figure 2b). A second vacuum (independent of the first) was then drawn between the lower diaphragm and the tool to complete the forming process (Figure 2c). The preform was left to cool to below the melting point of the binder before removing (Figure 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 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.

A generic geometry was developed to represent a section from a complex automotive structure, as shown in Figure 3. The surface shape includes regions of single and double curvature and surface features which could lead to fabric bridging.

## 2.2 *Non-crimp fabric*

All preforms were produced using two plies of FCIM359 biaxial non-crimp fabric (NCF), supplied by Hexcel, Leicester, UK. Each ply consisted of 440 gsm of carbon fibre with a 24K tow size, in a  $\pm 45^\circ$  architecture [26, 27] with a pillar stitch at  $0^\circ$ . A small amount (6 wt%) of Momenive Epikote 05390 binder was applied between layers to stabilise the post-formed shape. The thickness of each ply was measured to be 0.4 mm, using a vernier caliper. The in-plane shear behaviour of the FCIM359 fabric has been previously characterised by the authors using the picture frame test [28]. Flat ply outlines were exported from the simulation in DXF format and plotted to scale to provide a template, which was used as a guide to cut the fabric plies by hand.

## 2.3 *Diaphragm characterisation*

The diaphragms were made from Supervac silicone sheet with 50 Shore A hardness, supplied by Silex Ltd, UK. A series of mechanical tests were performed on coupons to characterise the in-plane behaviour of the diaphragm. Uniaxial tensile tests were performed on a universal testing machine at a strain rate of  $0.03 \text{ s}^{-1}$ . The tensile force was recorded by a 5 kN load cell and balanced travelling extensometer was used to measure the axial strain (see Figure 4a). The cross-section of the sample was  $5 \text{ mm} \times 1.56 \text{ mm}$ , and rubber-faced jaws were used to reduce stress concentrations due to clamping.

A Flexible Biaxial Film Tester [29] was used to perform equibiaxial tensile tests and planar shear tests on the silicone diaphragms (see Figure 4b). The machine consisted of a horizontal biaxial frame driven by two independent leadscrews and controlled by a LabView interface. The biaxial specimen was 75 mm × 75 mm, clamped by 7 miniature pneumatic grips along each edge. Load cells are integrated into the two central grips to record the forces, and strain was measured using a non-contact video tracking system which relied on a series of markers applied to the top surface of the specimen. The equibiaxial tensile tests were performed by applying the same displacement rate, corresponding to a strain rate of  $0.03 \text{ s}^{-1}$  to each grip. The pure shear test was performed by constraining one lead screw so that the specimen width remained constant, whilst applying a displacement corresponding to a strain rate of  $0.03 \text{ s}^{-1}$  to the other lead screw.

### **3 Double diaphragm forming process simulation**

#### *3.1 Modelling approach*

A schematic of the simulation geometry is presented in Figure 5. Each fabric ply was modelled in Abaqus/Explicit using quadrilateral membrane elements (M3D4R), with a maximum edge length of 5 mm, according to the mesh sensitivity study presented previously [28]. The diaphragms were modelled using 5 mm × 5 mm S4 shell elements, which were constrained in the x-y plane around the perimeter to replicate the constraints of the picture frame on the diaphragm forming rig. All parts of the tooling (tool and machine bed) were modelled as rigid bodies. A penalty contact algorithm was used to define the behaviour at the interfaces. An isotropic Coulomb friction model was adopted for tooling-diaphragm, diaphragm-material and material-material contacts, with measured constant



coefficients of 0.67, 0.52 and 0.36 respectively, according to experiments performed to ASTM D1894, ISO8295.

Pressures were applied to the upper surface of the top diaphragm and the lower surface of the bottom diaphragm, as shown in Figure 6. Initially both pressures were equal in magnitude but opposite in direction (A to B) to simulate the clamping force on the fabric plies generated by the vacuum between the diaphragms. Displacement boundary conditions were then applied to the edge nodes of the diaphragms to simulate the picture frame being lowered to make contact with the bed of the machine. Subsequently, a pressure differential was created between the two diaphragm surfaces to simulate the vacuum being applied between the lower diaphragm and the tool. The pressure applied to the bottom diaphragm was reduced (B to C), drawing the diaphragm arrangement into contact with the surface of the tool.

### 3.2 NCF material model

The constitutive model for the NCF plies was previously developed by the authors [28]. A non-orthogonal constitutive relation was employed to define the asymmetric forming behaviour of NCF based on homogenisation. The force required to shear the fabric,  $F_{norm}$ , is derived from two components; rotation of the principal fibre yarns and tension in the intra-ply stitches:

$$F_{norm} = F_{norm}^{yarn\ rotation} + F_{norm}^{stitch} \quad (1)$$

where the contribution of the yarn rotation is approximated by

$$F_{norm}^{yarn\ rotation} = (29.56\gamma_{12}^5 - 65.56\gamma_{12}^4 + 137.06\gamma_{12}^3 + 94.73\gamma_{12}^2 + 112.19\gamma_{12})\text{N/m} \quad (2)$$

and the contribution of the stitch tension, considering progressive stitch failure, is described by

$$F_{norm}^{stitch} = \begin{cases} (2000\gamma_{12} - 120)N/m & , \quad 0.06 \leq \gamma_{12} < 0.50; \\ (-3520\gamma_{12} + 2640)N/m & , \quad 0.50 \leq \gamma_{12} \leq 0.75; \\ 0 \text{ N/m} & , \quad \text{else.} \end{cases} \quad (3)$$

where  $\gamma_{12}$  is the shear angle in radians. The shear compliance of the NCF is described by superimposing these two contributions according to Equation (1). This material model is implemented using a user-defined subroutine in Abaqus/Explicit. For validation, force-displacement data from the simulation of a picture frame test was shown to be within the bounds of the experimental data (the root mean square error was approximately 5%). Further validation was conducted for a hemisphere forming [28], for which the constitutive relation for the NCF fabric plies was shown to suitably capture the onset of the main defect mechanisms, and local shear angles were predicted within  $\pm 5^\circ$  of the experimental values.

### 3.3 Diaphragm material model

An Ogden model [30] was used to describe the hyperelastic, non-linear stress-strain behaviour of the silicone diaphragms. The model assumes that the material behaviour can be described by a strain energy density function expressed in terms of the principal stretches and the constitutive relationships are obtained from the derivative of the strain energy with respect to stretch and by applying appropriate boundary and symmetry conditions. The nominal stress-strain relationships for the three load cases, uniaxial tension (subscript  $u$ ), biaxial tension (subscript  $b$ ) and pure shear (subscript  $s$ ) are presented in Table 1, where  $T$  is the nominal stress,  $\epsilon$  is the nominal strain,  $N = 2$  is the order of the Ogden model, and  $\alpha_i$  and  $\mu_i$  are material constants.

A non-linear least-squares fit was performed simultaneously on the uniaxial and equibiaxial test data to establish  $\alpha_i$  and  $\mu_i$ , using the built-in Marquard-Levenberg algorithm within Abaqus [31]. A second order model was found to produce a satisfactory quality of fit, with virtually no improvement at higher orders. The constants from the least-squares fit are presented in Table 2 and a comparison of the model to the experimental data can be seen in Figure 7. The root mean squared error (RMSE) between the experimental data and the analytical Ogden model is 2.2% for the uniaxial case and 5.5% for the equibiaxial case. The pure shear data was excluded from the least-squares fit, and was used instead to further validate the model with a different mode of deformation. Figure 7 shows that the Ogden model adequately captures the response of the silicone diaphragm when subjected to pure shear, with an RMSE of 5.5% compared to the experimental data. The Ogden parameters were implemented into an Abaqus/Explicit simulation using the in-built hyperelastic Ogden model to verify the numerical stability of the fitting parameters, considering the non-linear behaviour of the material. The model passed all of the internal stability checks within Abaqus/Explicit and the mechanical response in a 1-element simulation was identical to the analytical solution for each test case.

## 4 Results and discussion

### 4.1 Net shape forming

The initial ply outline of the 2D blank was determined for the geometry presented in Figure 3, in order to achieve a net-shaped component. The ply orientation was assumed to be  $\pm 45^\circ$  (where the  $+45^\circ$  fibre orientation was aligned with the x-axis and the  $-45^\circ$  fibres were aligned with the y-axis in Figure 3), as this was the most challenging fibre architecture for the chosen geometry. The initial ply was rectangular (900 mm  $\times$  550 mm, see Figure 8(a))

and the perimeter shape was revised iteratively according to the forming result obtained from the previous step. Elements positioned outside the final trim line on the formed ply were deleted and the simulation was run again. Multiple iterations were required, since the initial ply shape was too large and fabric bridging occurred around the base of the tool (Figure 8(a)). The fabric therefore did not make contact with the tool in all areas, which made it difficult to determine the trim line. Four iterations were required in total to achieve a near net-shaped preform, as shown in Figure 3.

The simulation results presented in Figure 8 demonstrates some of the forming defects that occur, such as out-of-plane wrinkling and excessive local shear, but the most dominant defect is fabric bridging due to the deformable diaphragms.

#### *4.2 DDF defect formation*

Fabric bridging is typically quantified in forming simulations as a measured distance between the formed surface and the tool, and is a characteristic of the conformity of the fabric. However, bridging may be detected at the same position on the component for a  $0^\circ/90^\circ$  ply and a  $\pm 45^\circ$  ply, but different solutions may be required to improve the fabric conformity for the two cases. Hence, additional criteria are required to support the conventional distance measurement, in order to overcome fabric bridging.

As shown in Figure 9, the resultant force from the pressure differential discussed in Figure 6 generates the forming forces to drive the fabric onto the tool surface. However, it also simultaneously generates a friction force which constrains the material sliding. Whilst a high vacuum pressure increases the forming force, a corresponding increase in in-plane friction may make it difficult to overcome fabric bridging, particularly for deep concave features. If bridging occurs, the fibres carry the forming forces applied in the bridging area. Yarns are

locally pinned and material movement becomes constrained, preventing draw into the cavity. This results in the generation of considerable local tensile stresses in the primary yarns around concave sections of the tool, and has therefore been defined here as the “bridging stress”. The bridging stress enables the cause of bridging to be identified, i.e. the location and direction of bridging yarns.

The laboratory diaphragm forming machine in Figure 1 has been used to validate the model, forming the case study component presented in Figure 3. Two plies of biaxial FCIM359 NCF were cut to the net-shape shown in Figure 8(e), with the  $45^\circ$  fibres aligned in the x-direction and the pillar stitches running at  $45^\circ$ . Figure 10 indicates that there is very good agreement between the simulation and experiment in terms of the formed shape, including the ply outline. Both include similar defects and three different field variables have been evaluated from the simulation to investigate their cause. These are defined as the local shear angle, the wrinkling strain (negative strains along the principal yarns) and the bridging stress (positive stresses along the principal yarns).

The shear angle distribution (see Figure 10(b)) represents over-shear induced defects, which can cause out-of-plane wrinkling and intra-ply stitch rupture under positive shear. In the positive shear areas (shear angles greater than  $0^\circ$ ), there are some regions which experience shear angles of over  $50^\circ$  (see red area in Figure 10 (b)), indicating that stitch rupture has occurred. This is in agreement with the experiment, as shown by the inset images. In negative shear areas, over-sheared regions (see blue area in Figure 10 (b)) represent the occurrence of out-of-plane ply wrinkling induced by over-shearing. These wrinkling defects were also observed in the experiment. It is important to note that the exact (out-of-plane) wrinkle shape cannot be predicted using the current material model, since the bending

stiffness is not included. The shear angle is therefore only an indicator of macro-scale wrinkling defects.

Wrinkling strains (negative strains along the principal yarns) are plotted along the two primary yarn directions, in Figure 11. Wrinkling strains were relatively low (for example in comparison to previous reported work [28]), therefore mesoscale wrinkling due to yarn buckling (negative strains) was limited to some minor regions on the top surface of the formed part (green contours), as indicated by the photos.

The dominant defect for DDF was observed to be fabric bridging in this study, as shown in Figure 12. Bridging was more severe along the  $+45^\circ$  yarns in the x-direction (see Figure 12 (a)) than the  $-45^\circ$  yarns in the y-direction (Figure 12 (b)). Comparisons with the experimental results indicate that the “bridging stress”, where the tensile stress in the direction of the fibre exceeds 35 MPa, is an appropriate metric for predicting the likelihood of defects caused by bridging. The bridging stress output from an FE solution can be used to identify the location and orientation of yarns in tension that induce bridging defects, in order to improve the quality of the formed shape.

In addition, some wrinkling defects were observed as a side effect of fabric bridging, due to the Poisson’s ratio contraction effects of the diaphragms. As shown in Figure 12 (a), two significant areas of fabric bridging occurred around the large curvature area as the yarns in the x-direction were in tension. However, the yarns in the y-direction in same areas were unconstrained, and therefore the fabric was more compliant in this direction, inducing wrinkles.

#### 4.3 *Scenarios for bridging reduction*

In order to reduce the fibre bridging defect, the forming mechanism should involve rigid body movement (yarn rotation and slippage) rather than fibre elongation. Shear deformation occurs by rotation of the yarns, which is limited by the phenomenon of shear locking [28]. In DDF, the most effective solution for avoiding bridging is to delay contact between the diaphragm assembly (two diaphragms plus fabric plies) and the tool surfaces. Rigid body movement of the yarns should be generated progressively, as the contact area increases.

In order to increase material draw-in in the present work, darts (local cuts) were added to the optimised ply shape shown in Figure 13(a). Darts were positioned to reduce the high tensile stresses in the longitudinal yarns (x-direction), which were the main cause of the severe bridging regions. Darts were cut perpendicular to these yarns in order to minimise the damage to the transverse yarns, as shown Figure 13(b). Darts were only permitted on the near vertical sides of the component and not on the top surface, as these fibres coincide with the primary load path. It is important to note that additional plies at different angles would be added to this single ply to manufacture the final component. Therefore the openings created by the darts would be covered by neighbouring plies, or small patches of material, to satisfy secondary load cases.

Both FE simulations and experiments were conducted using the modified ply shape and results were compared against the case without darts as shown in Figure 14. Bridging was effectively reduced by adding darts, compared to the case without darts. The results from the simulation are in agreement with the experimental data, showing that the model can suitably capture the effect of fabric darts. Furthermore, this study demonstrates that the

“bridging stress” is a feasible way of determining potential bridging sites and identifying the yarns responsible. In the present work, placing darts perpendicular to the bridging yarns appears to have had no adverse effect on the surrounding fibre architecture, as seen from the experimental data.

As shown in Figure 14, the wrinkling and over-shear induced defects decrease simultaneously as the number of bridging fibres decreases. This indicates that bridging is the dominating defect in DDF, and a reduction of bridging may result in reduction of other forming defects. Applying suitable darts helps to overcome bridging-induced yarn wrinkling and release fabric shear locking, providing better fabric conformity.

## **5 Conclusions**

A forming simulation was developed to model the behaviour of a biaxial non-crimp fabric during double diaphragm forming. The model is used to identify the likelihood of defects occurring during forming of a generic automotive structure, using three different field variables: local shear angle, wrinkling strain and bridging stress. The model indicated that in-plane wrinkling is generally reduced for DDF compared to matched-tool forming, but fabric bridging can occur in large-curvature regions. Bridging is the dominant defect for diaphragm forming, as the forming pressures are relatively low (up to 1 bar) compared to matched tool forming. The fabric gets pinned between two points on the tool by the applied pressure, preventing further rigid body movement such as yarn rotation or inter-ply slippage. The finite element simulation was successfully used to identify feasible locations for darts, in order to alleviate fabric bridging and improve surface conformity, whilst minimising any detrimental effects on the mechanical performance of the component.



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## 8 Tables

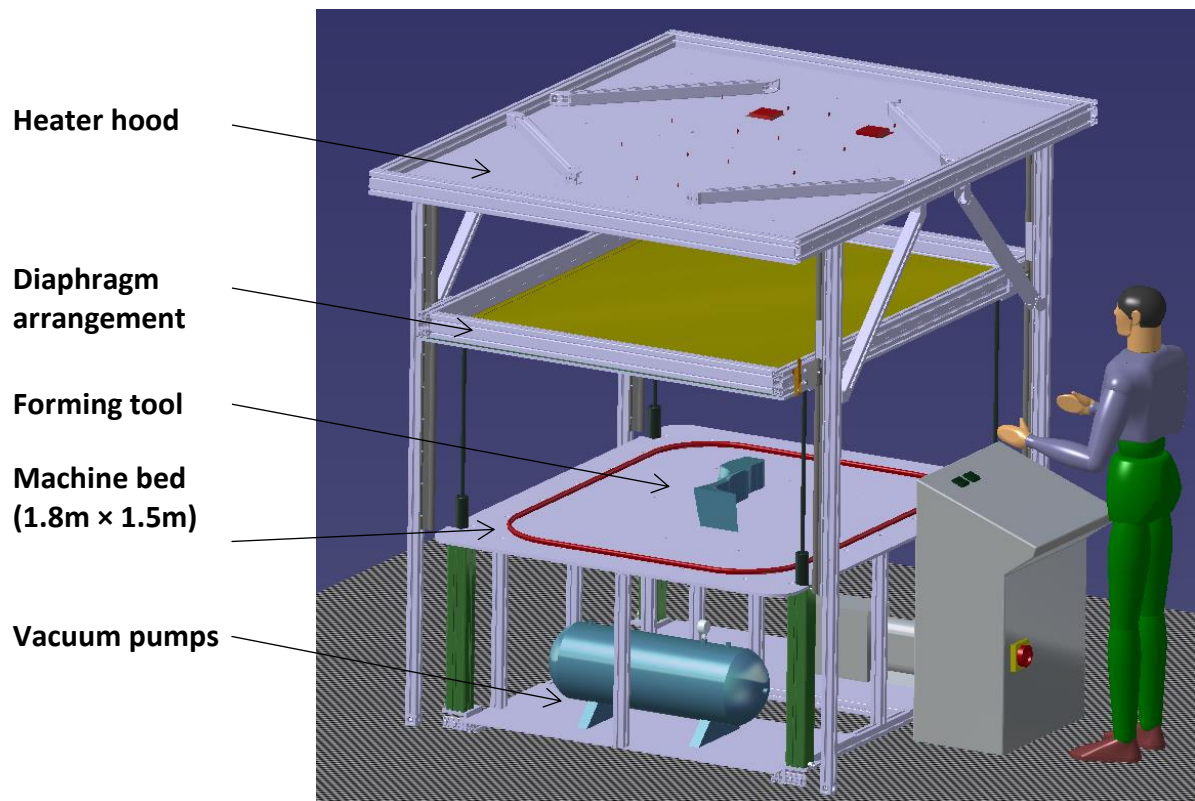
**Table 1:** Stress-strain relations for three load cases using the Ogden hyperelastic material model.

Mode	$\lambda_1$	$\lambda_2$	$\lambda_3$	$T$
Uniaxial	$1 + \epsilon_u$	$(1 + \epsilon_u)^{-\frac{1}{2}}$	$(1 + \epsilon_u)^{-\frac{1}{2}}$	$\sum_{i=1}^N \frac{2\mu_i}{\alpha_i} \left( (1 + \epsilon_u)^{\alpha_i-1} - (1 + \epsilon_u)^{\frac{1}{2}\alpha_i-1} \right)$
Equibiaxial	$1 + \epsilon_b$	$1 + \epsilon_b$	$(1 + \epsilon_b)^{-2}$	$\sum_{i=1}^N \frac{2\mu_i}{\alpha_i} \left( (1 + \epsilon_b)^{\alpha_i-1} - (1 + \epsilon_b)^{2\alpha_i-1} \right)$
Planar (pure) shear	$1 + \epsilon_s$	1	$(1 + \epsilon_s)^{-1}$	$\sum_{i=1}^N \frac{2\mu_i}{\alpha_i} \left( (1 + \epsilon_s)^{\alpha_i-1} - (1 + \epsilon_s)^{\alpha_i-1} \right)$

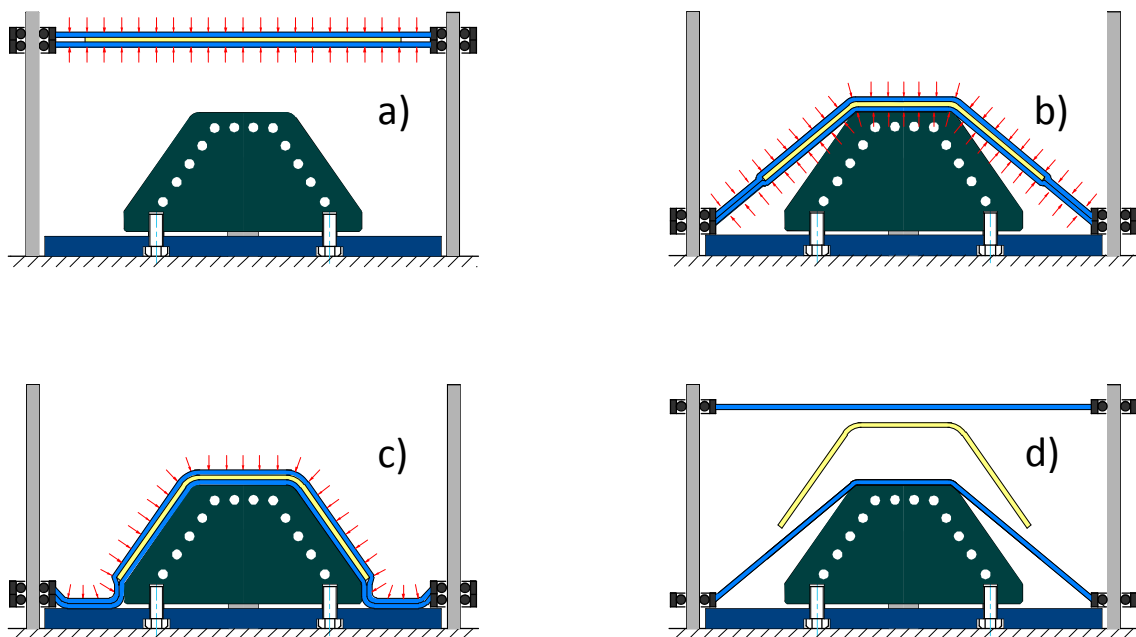
**Table 2:** Material constants for Ogden hyperelastic model used to describe the deformation of the silicone diaphragm material.

Diaphragm material	$\mu_1$ (Pa)	$\alpha_1$	$\mu_2$ (Pa)	$\alpha_2$
1.56mm silicone	150904	3.0918	813392	0.18451

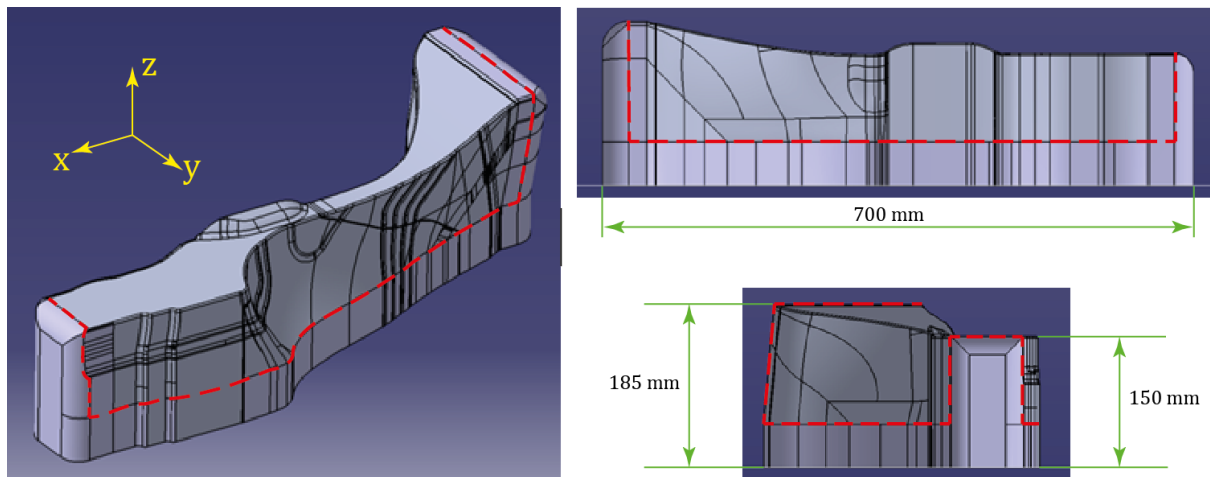
## 9 Figures



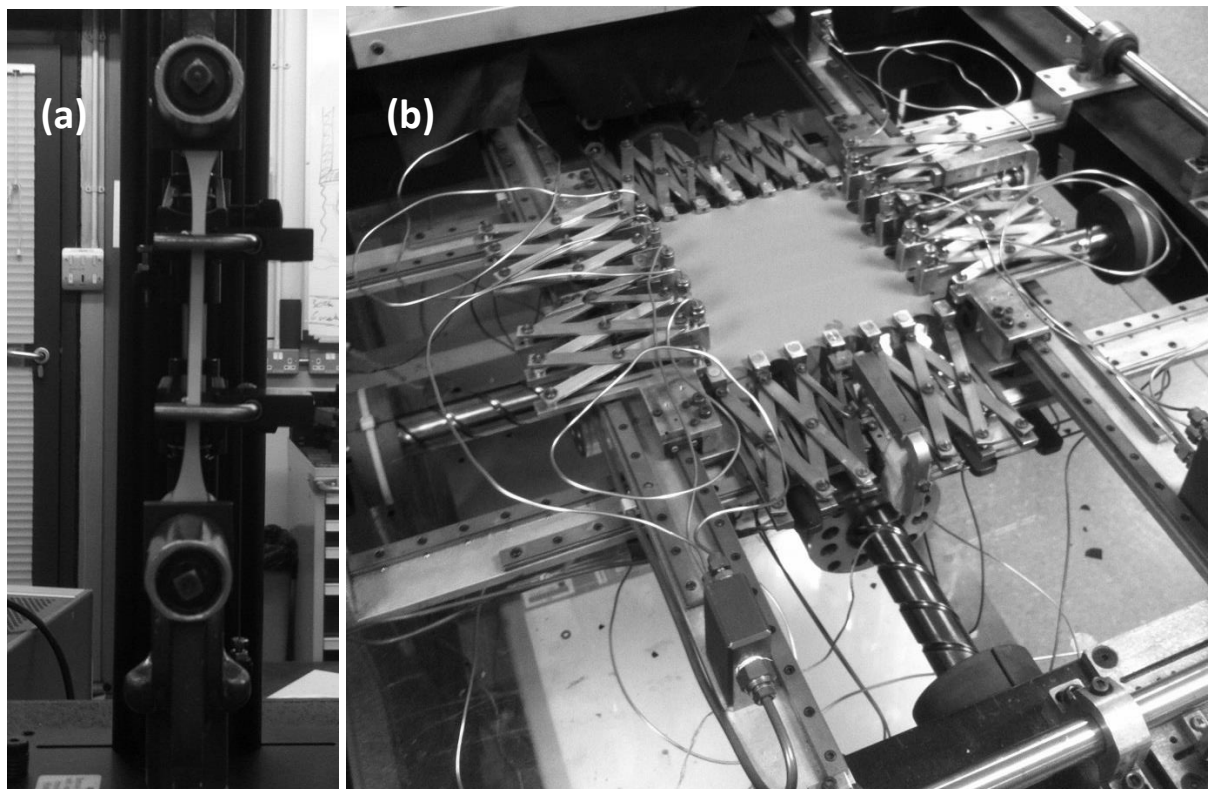
**Figure 1:** Details of the diaphragm forming machine.



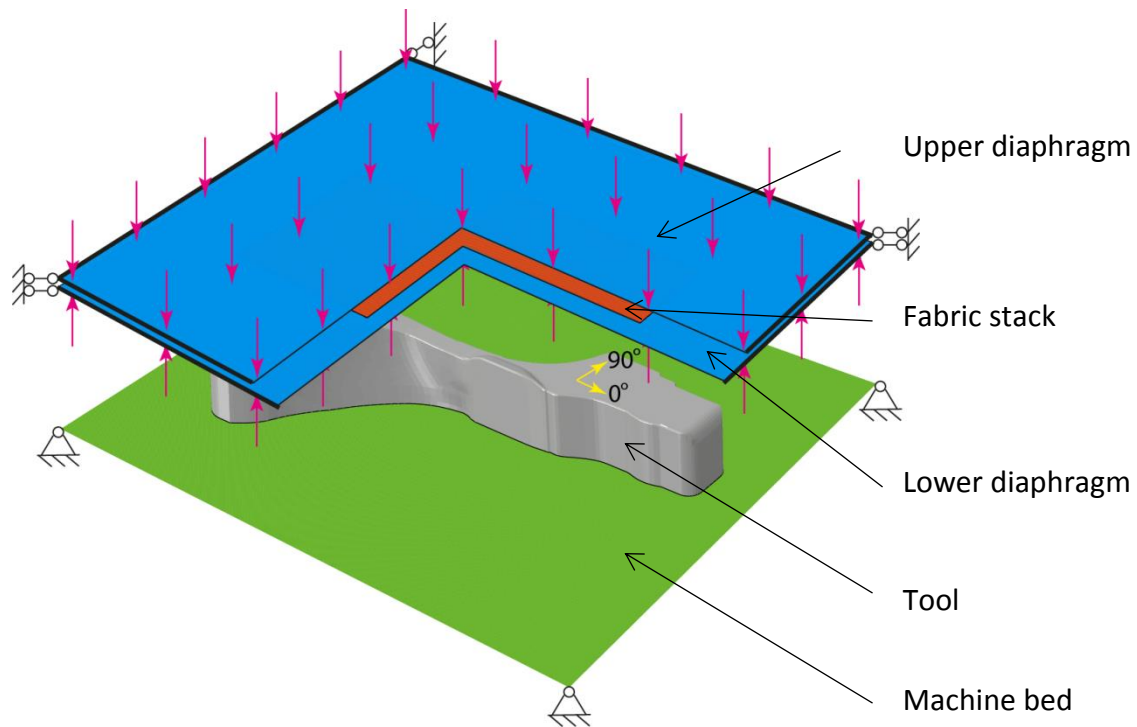
**Figure 2:** Schematic of the double diaphragm forming process



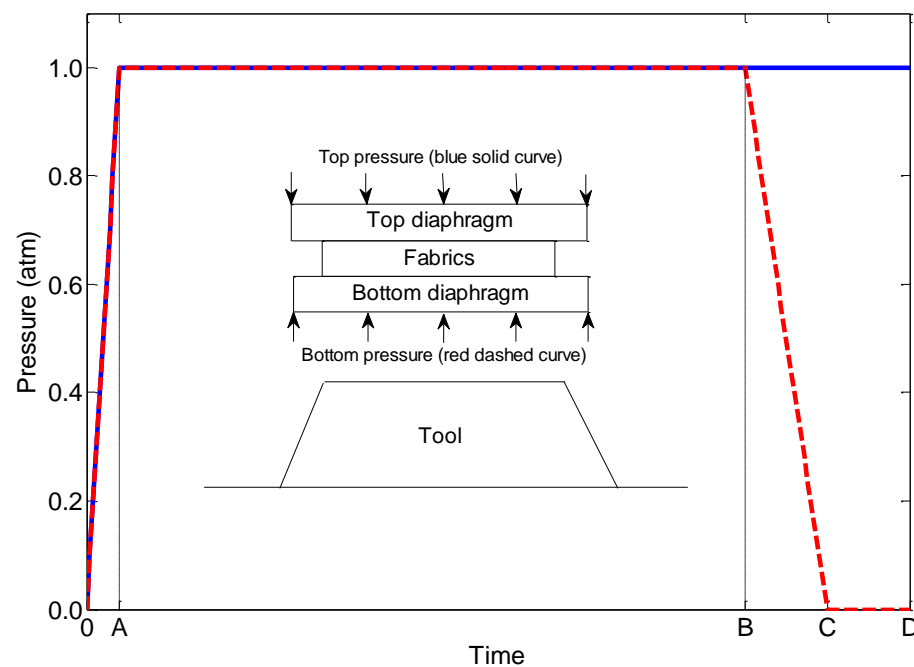
**Figure 3:** Tool geometry for the case study component. Red lines indicate the trimmed edge of the final component.



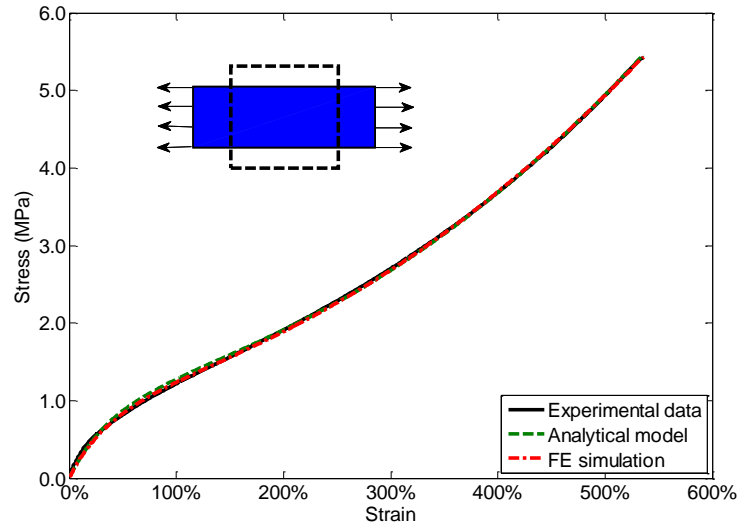
**Figure 4:** Photographs showing test rigs for (a) uniaxial tensile testing and (b) biaxial tensile testing of silicone diaphragms.



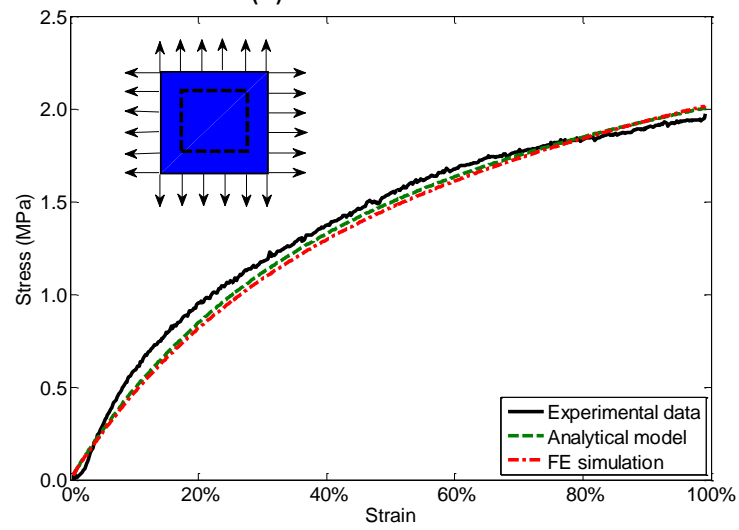
**Figure 5:** FE model of double diaphragm forming. A quadrant from the two diaphragms and the fabric stack has been removed for clarity. Arrows indicate the direction of the applied pressure.



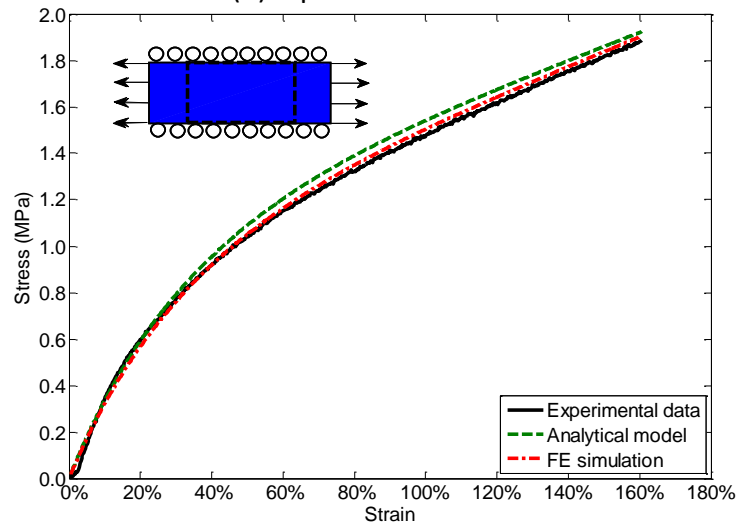
**Figure 6:** Definition of pressure applied to the diaphragms in the FE model.



(a) Uniaxial tension



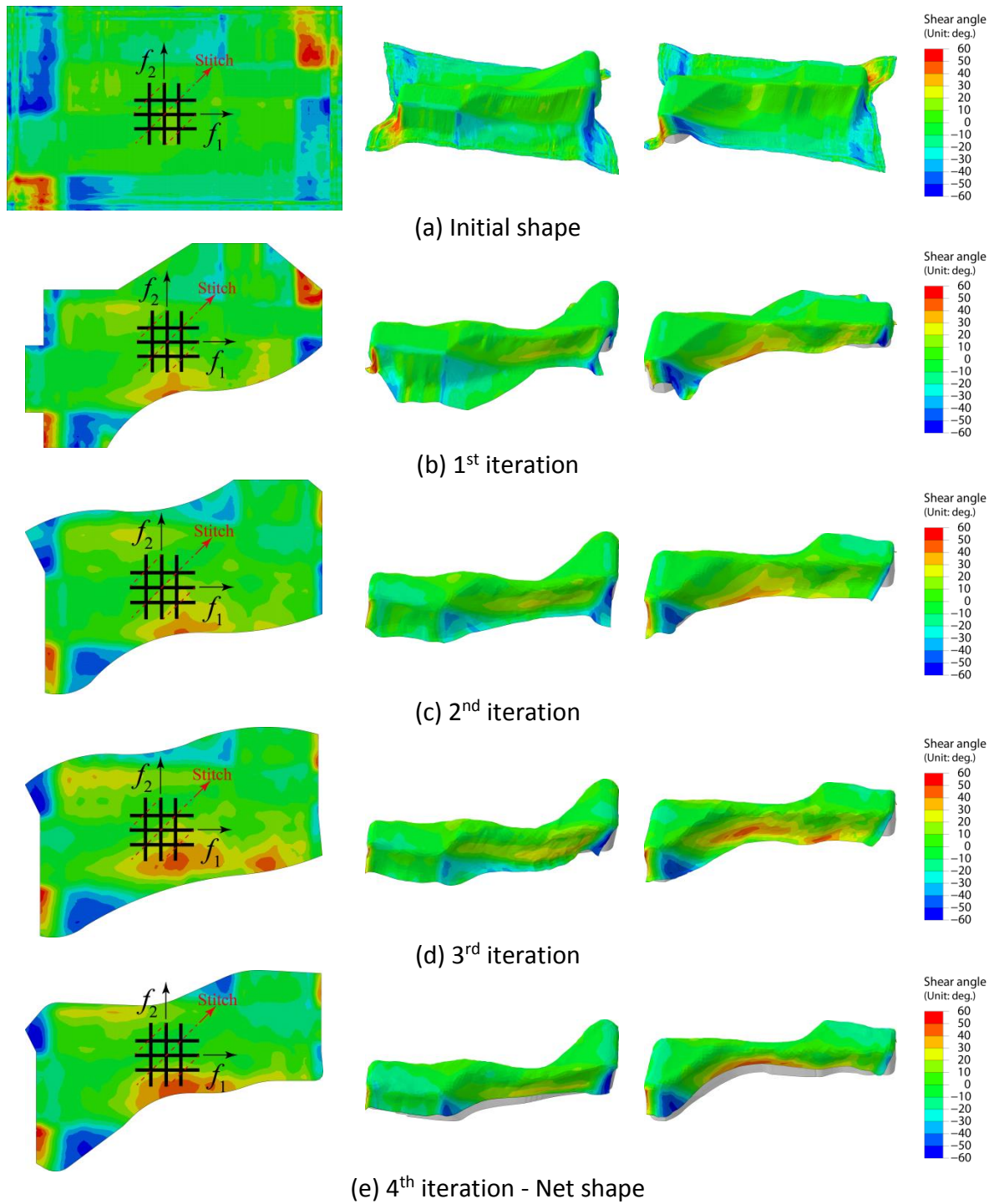
(b) Equibiaxial tension



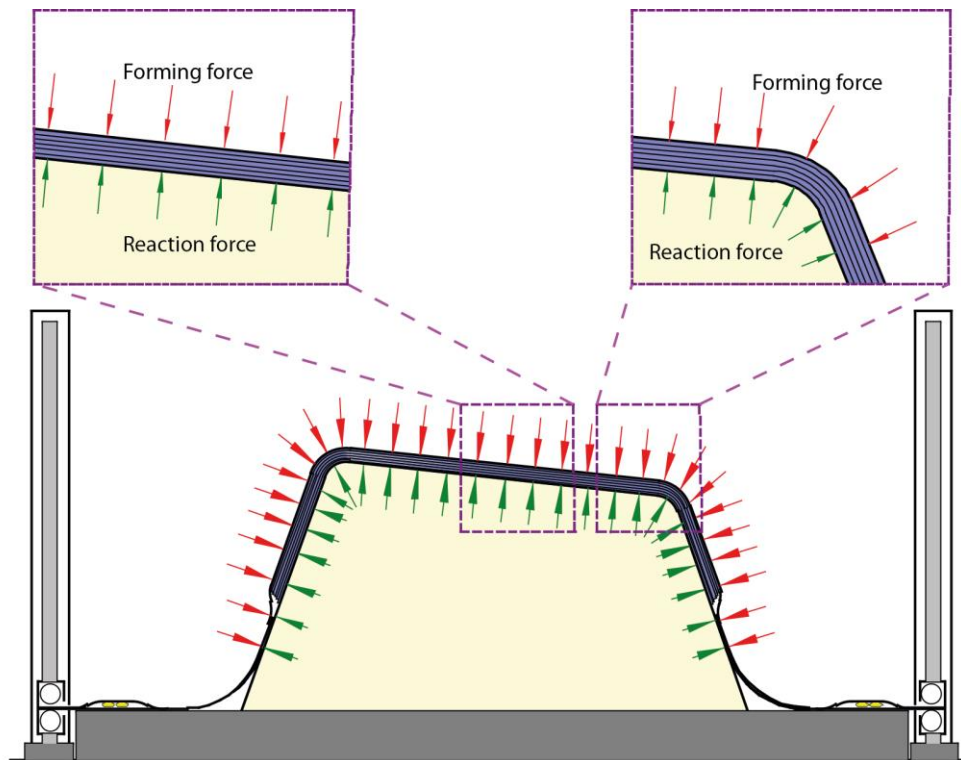
(c) Planar (pure) shear

**Figure 7:** Data used to characterise the deformation behaviour of the silicone diaphragms. Experimental data is presented for three load cases and compared to analytical solutions and Abaqus simulations using the Ogden model.

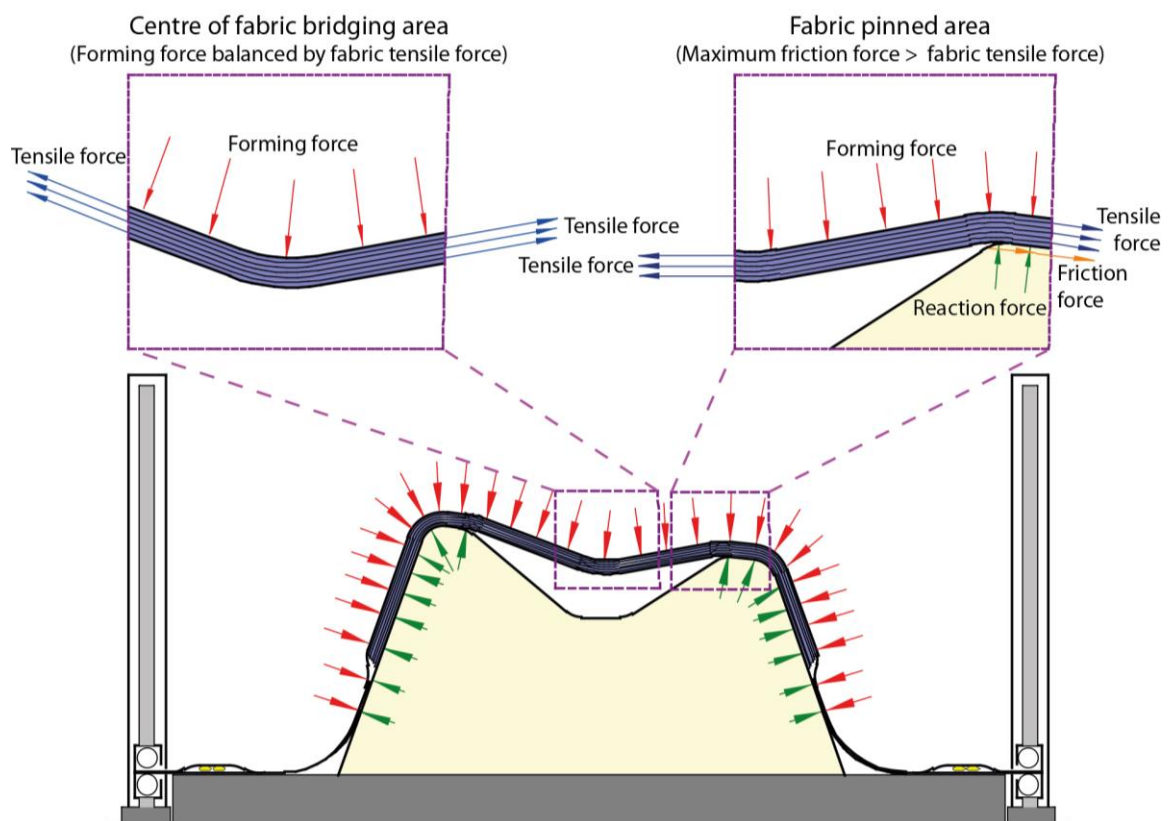




**Figure 8:** Iterations of net ply shape for biaxial  $\pm 45^\circ$  ply with  $0^\circ$  stitches formed by DDF. Undeformed ply shape (left column), different views of deformed ply shapes (middle and right column).

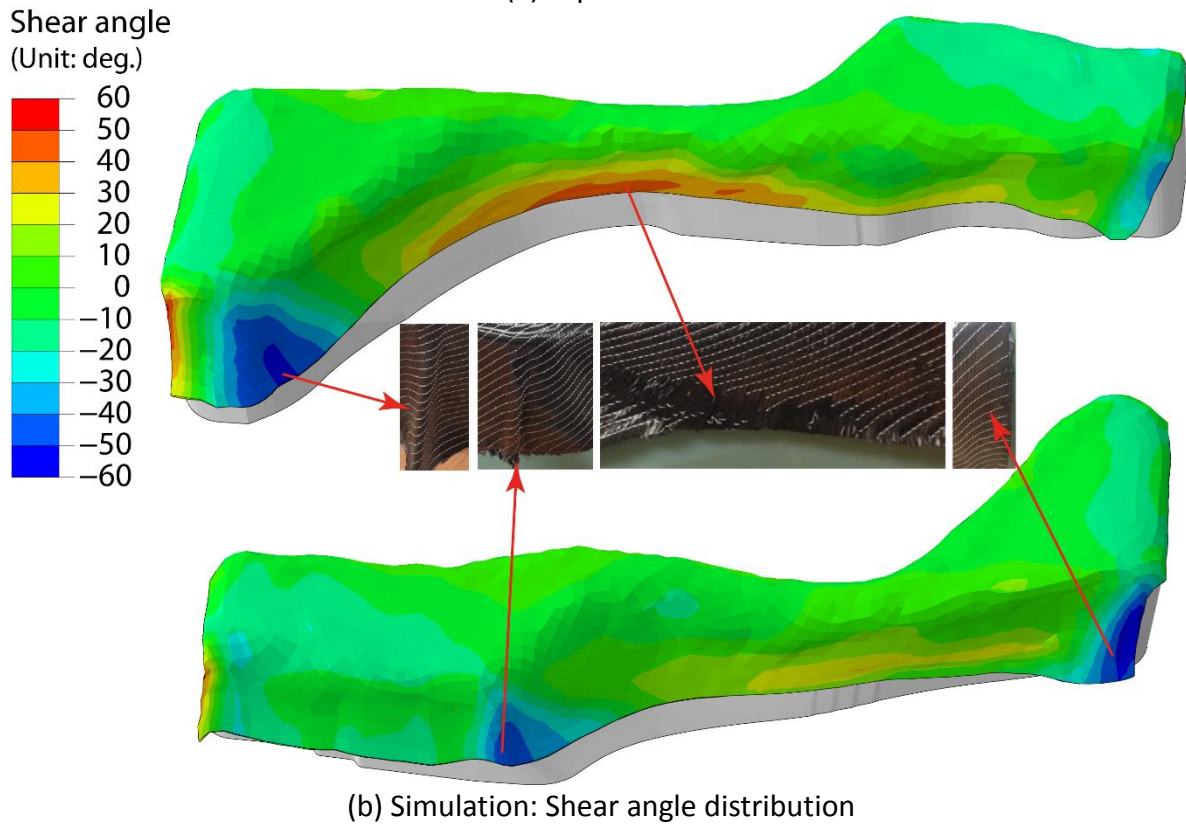
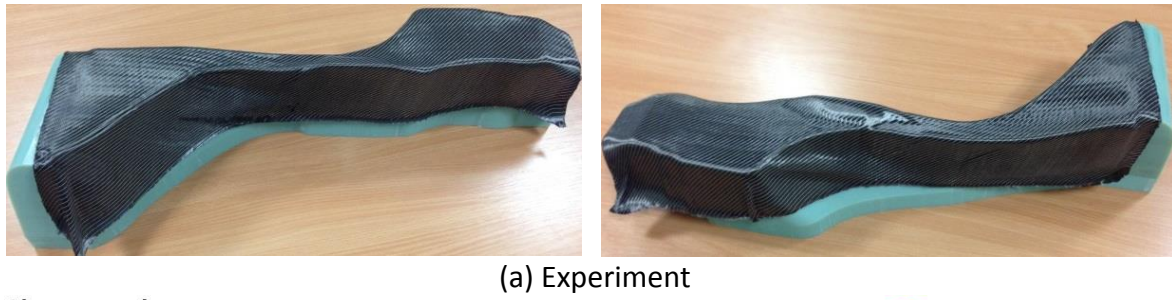


(a) Formed component without bridging defect



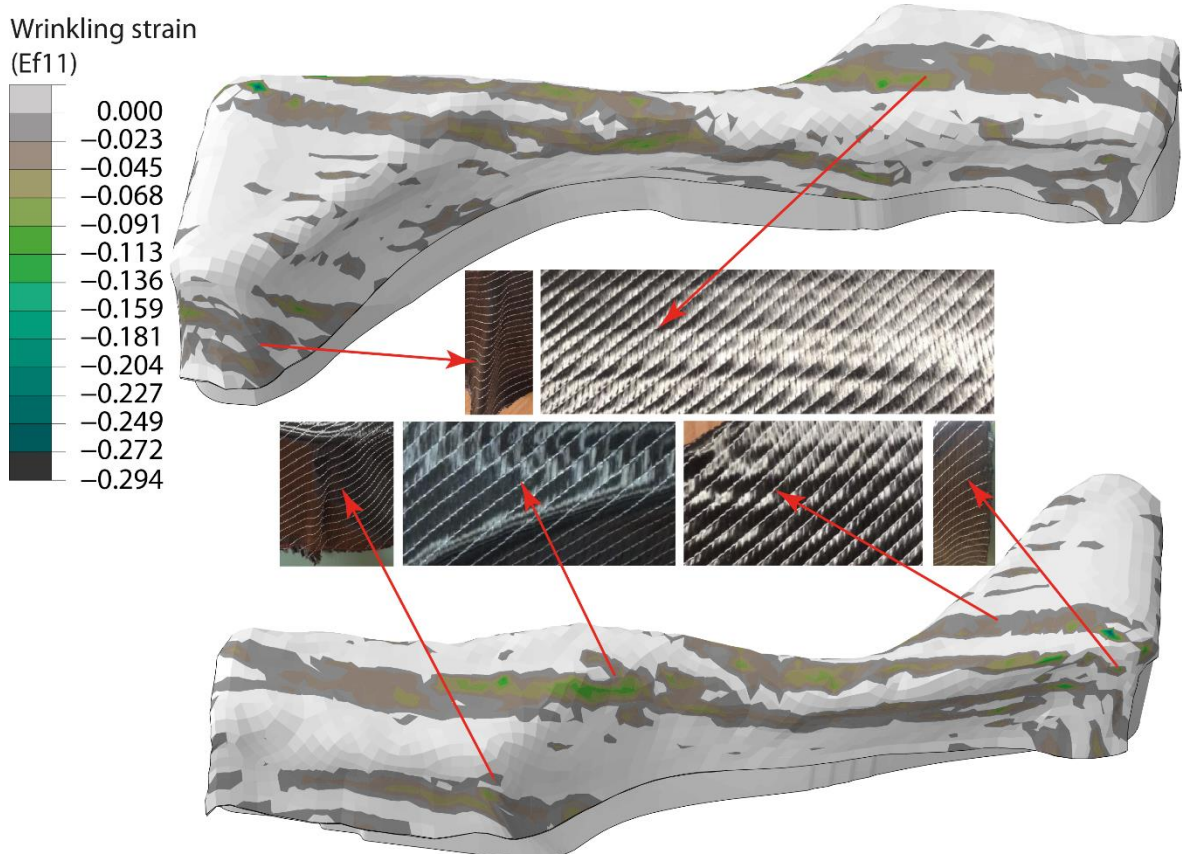
(b) Formed component with bridging defect

**Figure 9:** Roles of forming pressure and mechanism of bridging defect.

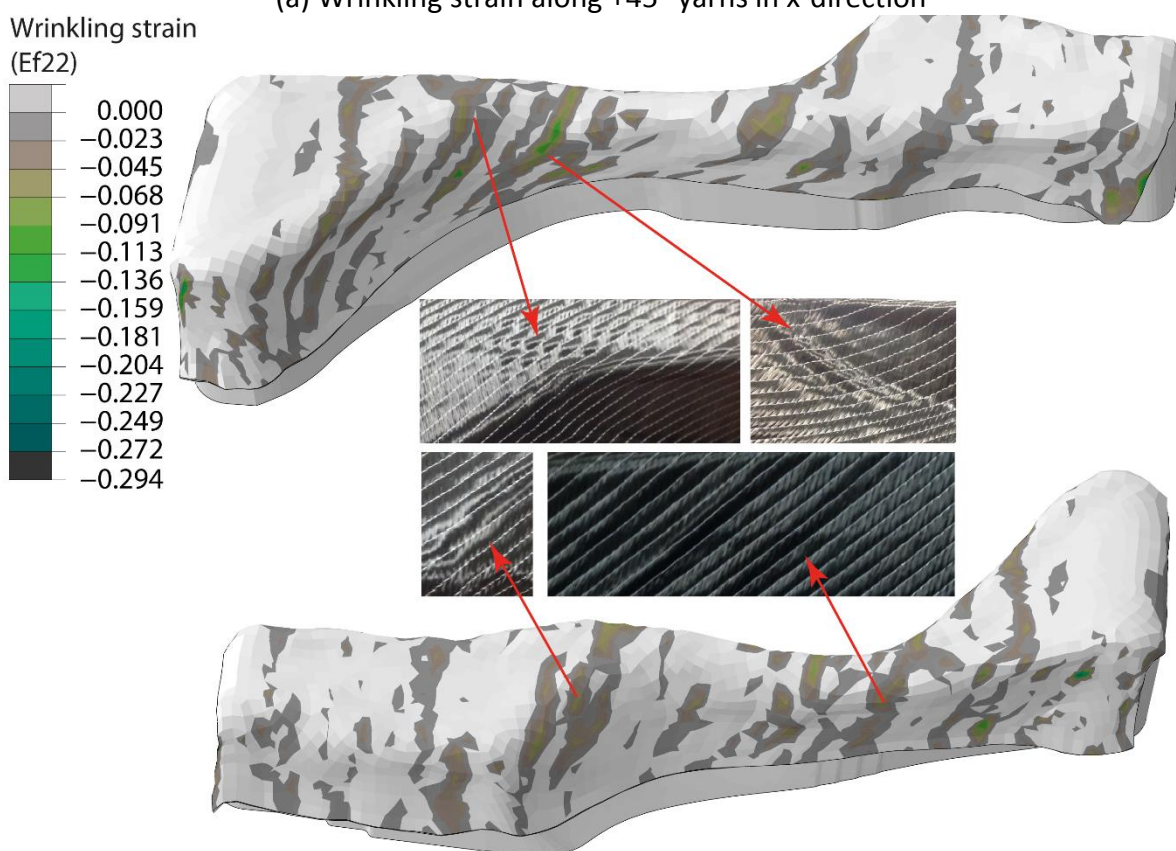


**Figure 10:** Comparison of shear angle distribution and experimental geometry for a biaxial  $\pm 45^\circ$  ply with  $0^\circ$  stitches, formed by double diaphragm forming.



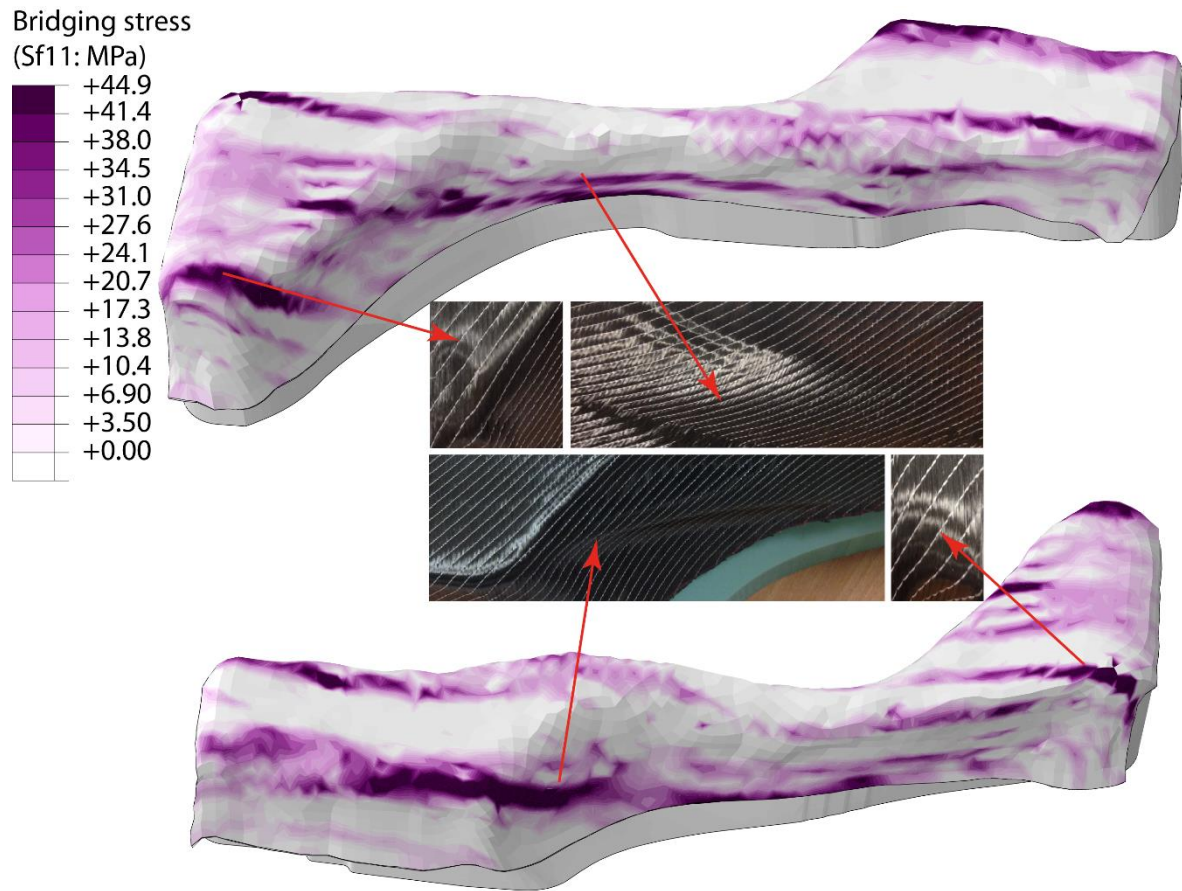


(a) Wrinkling strain along +45° yarns in x-direction

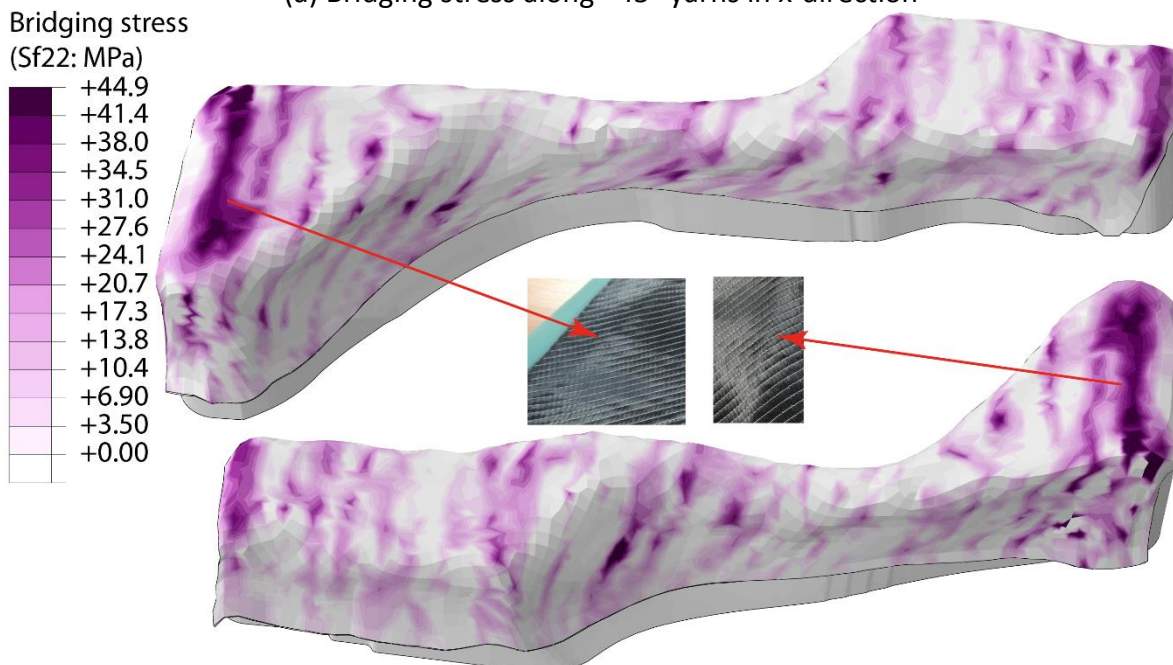


(b) Wrinkling strain along -45° yarns in y-direction

**Figure 11:** Wrinkling strains along two primary yarn directions.



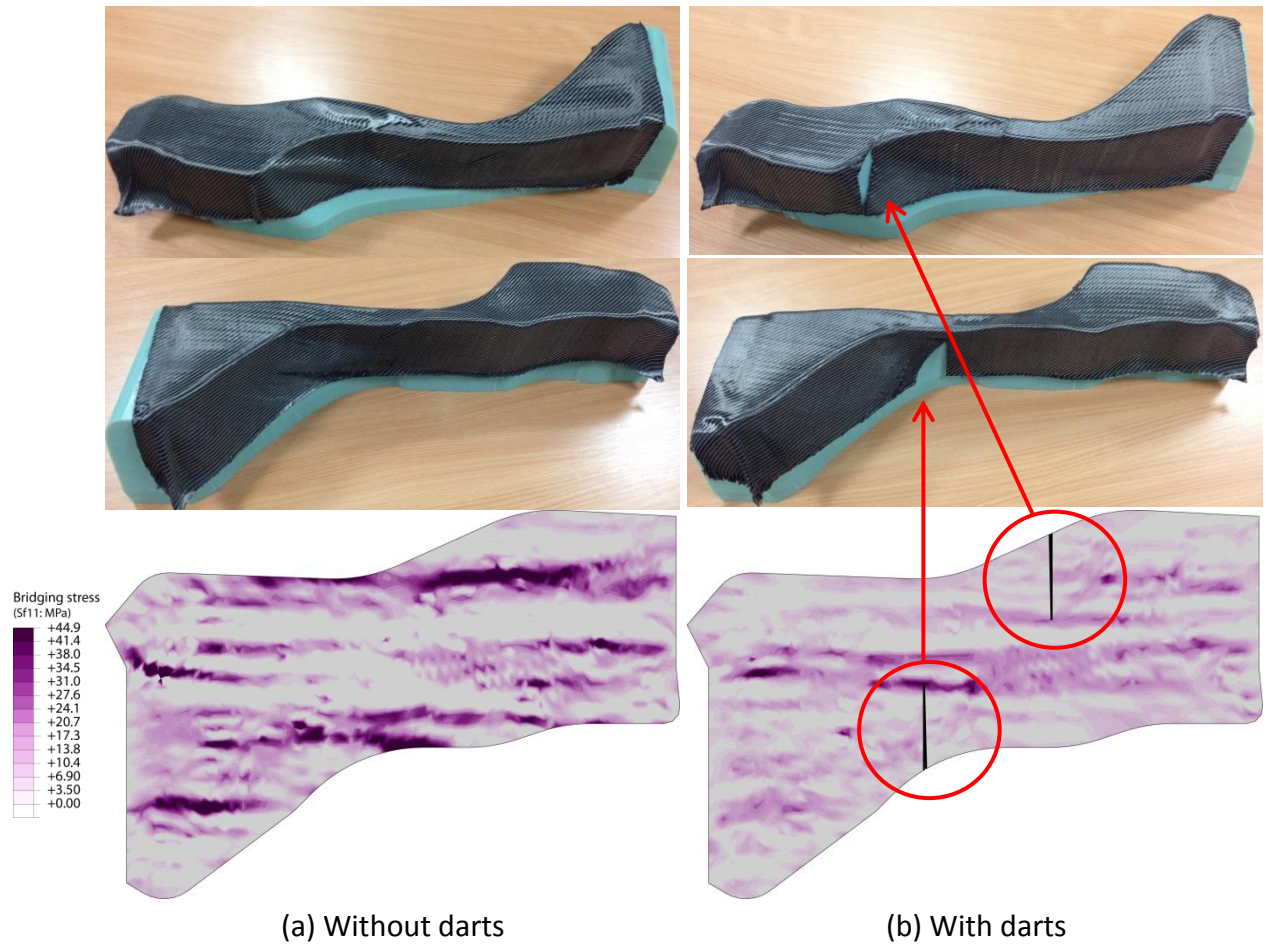
(a) Bridging stress along +45° yarns in x-direction



(b) Bridging stress along -45° yarns in y-direction

**Figure 12:** Bridging stress along the two primary yarn directions.

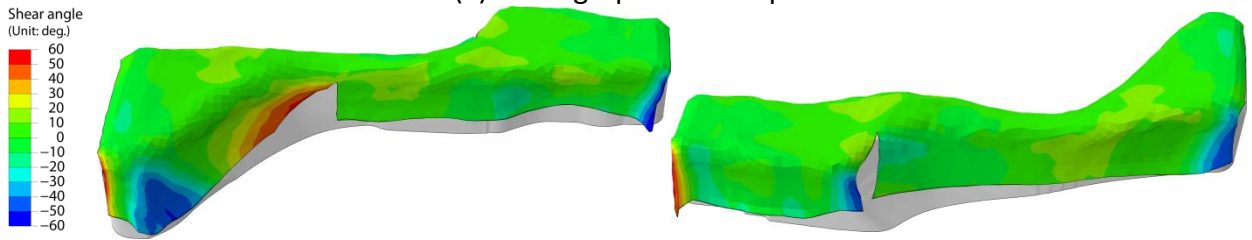




**Figure 13:** Influence of placing local darts on reducing bridging defects.



(a) Photographs from experiment



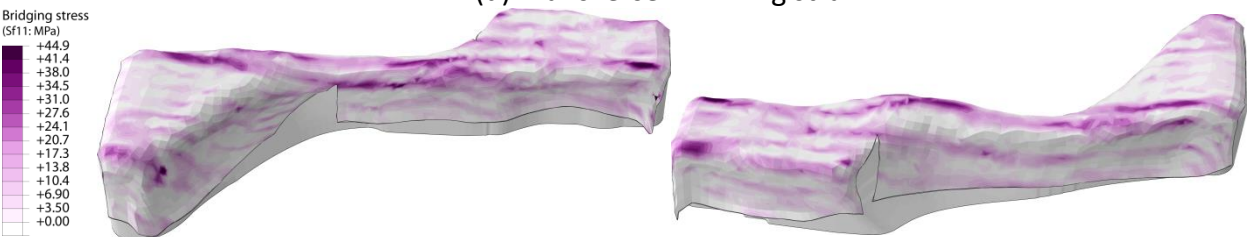
(b) Shear angle distribution



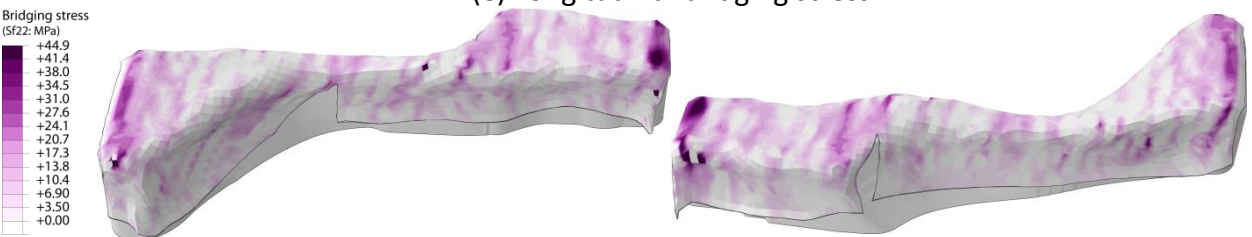
(c) Longitudinal wrinkling strain



(d) Transverse wrinkling strain



(e) Longitudinal bridging stress



(f) Transverse bridging stress

**Figure 14:** Defect formation for preforms with local darts.