Solid State Phenomena *Submitted: 2025-12-27*
ISSN: 1662-9779, Vol. 387, pp 43-51 *Revised: 2026-02-10*
doi:10.4028/p-mkOd5g *Accepted: 2026-02-20*

Online: 2026-04-14

Wrinkling Behaviour of Engineering Fabrics in Diaphragm-Assisted Deep Drawing

Ali Tabatabaeian[1,a*], Conor Blair[1,b], Kaspar Ambuehl[1,c], Philip Harrison[1,d]

[1]James Watt School of Engineering, University of Glasgow, Glasgow, UK

[a]ali.tabatabaeian@glasgow.ac.uk, [b]2662267B@student.gla.ac.uk, [c]2520880A@student.gla.ac.uk, [d]philip.harrison@glasgow.ac.uk

(*corresponding author)

Keywords: Deep draw, engineering fabrics, wrinkling, lubrication, diaphragm forming.

Abstract. Wrinkling during diaphragm forming of engineering fabrics compromises structural integrity and surface quality. This study investigates two strategies—diaphragm pre-tensioning and fabric inter-ply lubrication—to mitigate wrinkle formation. A pre-tensioning (PT) blank holder was designed and evaluated through deep-draw experiments supported by finite element analysis (FEA). Results show that pre-tensioning (50% strain) significantly reduces wrinkle severity compared to a conventional blank holder. The PT blank-holder creates initial equi-biaxial strain consistent with analytical and FEA predictions. Resin inter-ply lubrication also decreased wrinkling and reduced forming force by approximately 70%, primarily by lowering inter-ply friction. However, pre-tensioning proved more effective overall. These findings demonstrate the potential of diaphragm pre-tensioning for improving forming quality and provide a foundation for advanced multi-step thermoforming processes.

Introduction

Forming multi-axial composite preforms and consolidated blanks into complex geometries remains a significant challenge for automotive and aerospace applications, primarily due to wrinkling, which compromises structural integrity and surface quality of the final parts. Conventional matched-die forming and blank-holder systems can manage certain lay-ups, such as unidirectional or simple cross-ply configurations, but often fail to suppress wrinkles in complex lay-ups and geometries [1,2]. Various approaches have been investigated to improve the forming process and reduce forming-induced defects, particularly wrinkling [3–9]. Previous studies have shown that reducing the forming rate [3,10,11], increasing the forming temperature [11,12], decreasing the preform size and increasing diaphragm stiffness [3] can mitigate wrinkle formation. Codolini et al. [8] conducted a combined experimental and numerical study to investigate the influence of key process parameters on wrinkling during double-diaphragm forming. Their results demonstrated that variability in diaphragm pre-tensioning has the greatest influence on wrinkle amplitude, followed by variations in the friction coefficient between fabric plies. This finding highlights the critical role of these two parameters in wrinkle initiation and growth.

Previous studies have shown the feasibility of a diaphragm assisted multi-step thermo-forming process using lubricated blanks [9]. Diaphragm-assisted press forming, although more complex and costly, offers unique advantages for multi-step thermo-forming processes involving lubricated blanks, including lubricant containment, void removal, and protection of the multi-step tooling from matrix ingress [9]. The present study explores the potential of *pre-tensioned diaphragms* to further mitigate wrinkle formation during double diaphragm press forming operations. To investigate this, a pre-tensioning device was designed and manufactured and its performance was evaluated using a deep-draw test configuration through both numerical and experimental investigations. Experiments were conducted on dry woven glass fabrics at room temperature, with and without lubrication. The study examines the influence of diaphragm pre-tensioning and inter-ply lubrication — two key process parameters that can improve forming behaviour by reducing wrinkling [8]. By establishing the benefits and challenges of *diaphragm pre-tensioning*, this work provides a foundation for its application in more advanced configurations, such as diaphragm-assisted multi-step thermo-forming processes for lubricated multi-axial preforms with complex geometries.

Experimental and FEA Methods

Materials, Design, and Manufacturing. Diaphragm materials consisted of general-purpose translucent silicone rubber sheets (40° Shore hardness, 1 mm thick) supplied by Silex [13]. The fabric material used was woven glass fabric with an average thickness of 0.26 ± 0.02 mm and diameter of 240 mm [14].

Two blank-holder systems were developed, including a conventional *no-tension (NT)* holder and an innovative *pre-tension (PT)* holder (see Fig. 1). The design of the PT blank holder was based on (a) kinematic calculations of the engineering strain created by the deformation during full diaphragm draw-in into the blank-holder cavity under vacuum pressure (assuming symmetric draw-in of the upper and lower diaphragms and also zero-friction) and (b) a finite element analysis (FEA) performed using Abaqus software. Both blank holders were manufactured from aluminium. O-rings along with bolts and nuts were used for sealing and fastening. For a better understanding of the working principle of the PT blank holder, see Fig. 5.

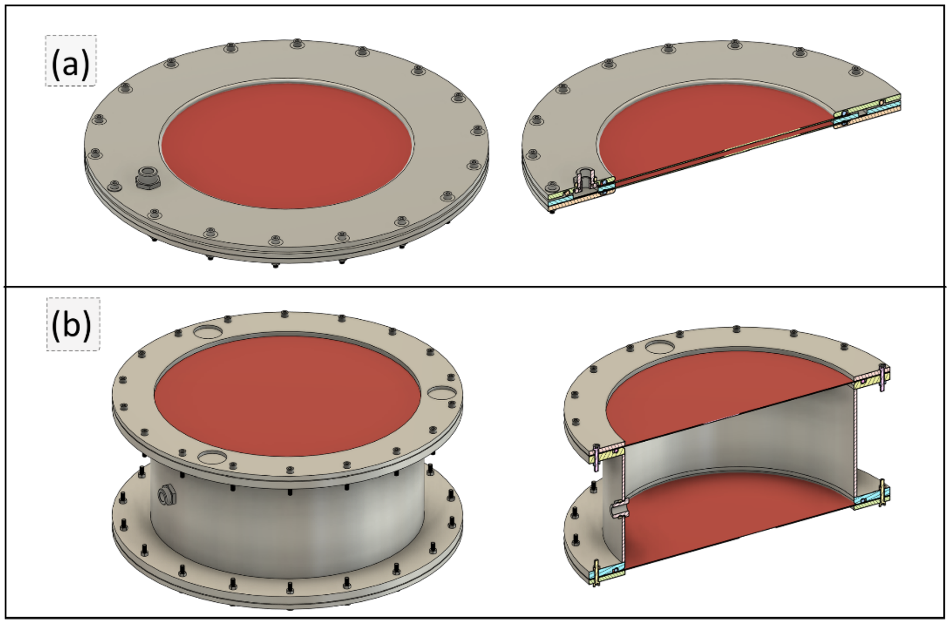

Fig. 1. CAD representation of the blank holders manufactured in this study: a) no-tension (NT), b) pre-tension (PT) (diaphragms indicated in red).

Changing the dimensions of two design parameters of the PT blank holder — cavity depth (*2A*) and radius (a + b) — outlined in the following analytical formulation, enabled the achievement of desirable strain (pre-stretch) values (see Fig. 2 and Eq. 1). A pre-stretch of 50% was intended for the design and manufacturing of the PT blank holder.

$$\varepsilon = \frac{u}{b} \qquad u = \frac{b(2T+t+A)-aD}{(a+b)} \tag{1}$$

where, b is radius of interest, T is flange overhang, t is flange thickness, A is cavity half depth, a is “diaphragm radius – b”, and D is a hole depth that diaphragms are deep drawn into after vacuum draw-in has been completed.

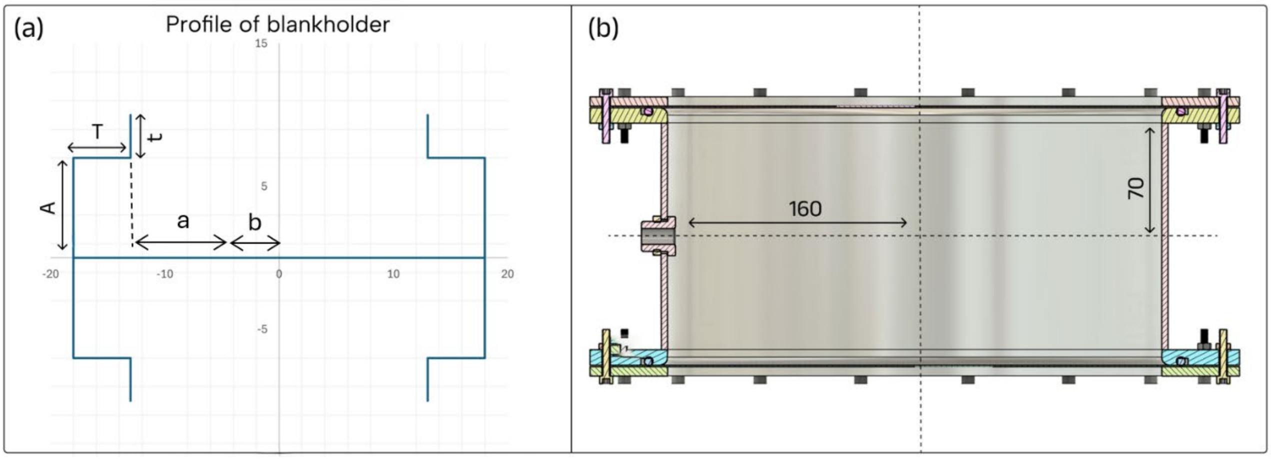

Fig. 2. Schematic of the PT blank holder and its design parameters (with values shown in Fig. 2(b) to achieve 50% theoretical pre-stretch).

Following [14], for the deep-draw tests, a cylindrical punch and a matching female die were designed and manufactured from aluminium (see Fig. 3). The punch diameter was 50 mm, while the inner and outer diameters of the female die were 60 mm and 120 mm, respectively, providing a 5 mm clearance on each side between the punch and the inner wall of the die that is identical to a previously developed setup, which allows for direct comparison with that study [14].

Deep Draw Tests. A StepLab machine was set to a displacement rate of 25 mm/min, with a travel limit of 80 mm, starting from the moment the punch contacted the upper diaphragm. The vacuum was activated prior to the test and maintained throughout the experiment. A custom-designed 3D printed tool was used to ensure all components of the setup were centrally aligned. A silicone lubricant spray (3-IN-ONE brand) was applied to all external surfaces, including the interfaces between the diaphragms and the tools, to reduce friction. All tests were performed with three fabric plies, with lay-up arrangement of [(0/90)/±45/(0/90)], placed between the two diaphragms. Videos from the top view were recorded throughout the entire test duration, and photographs were taken at the end of each test. Circles with known radii were marked on unstretched diaphragms to experimentally measure the subsequent strains. To examine the effect of diaphragm pre-tensioning, tests were conducted using both NT and PT blank holders. To assess the influence of inter-ply lubrication, tests were performed with and without resin lubrication in the NT blank holder. Here, resin lubrication refers to applying 20 mL of a mixture of EL2 epoxy laminating resin and AT30 epoxy hardener (supplied by Easy Composites and prepared with mixing ratio of 100 (resin) – to – 30 (hardener)) between fabric plies. Note that the resin was applied only between the fabric layers, not between the fabric and diaphragm surfaces (referred to here as partial lubrication).

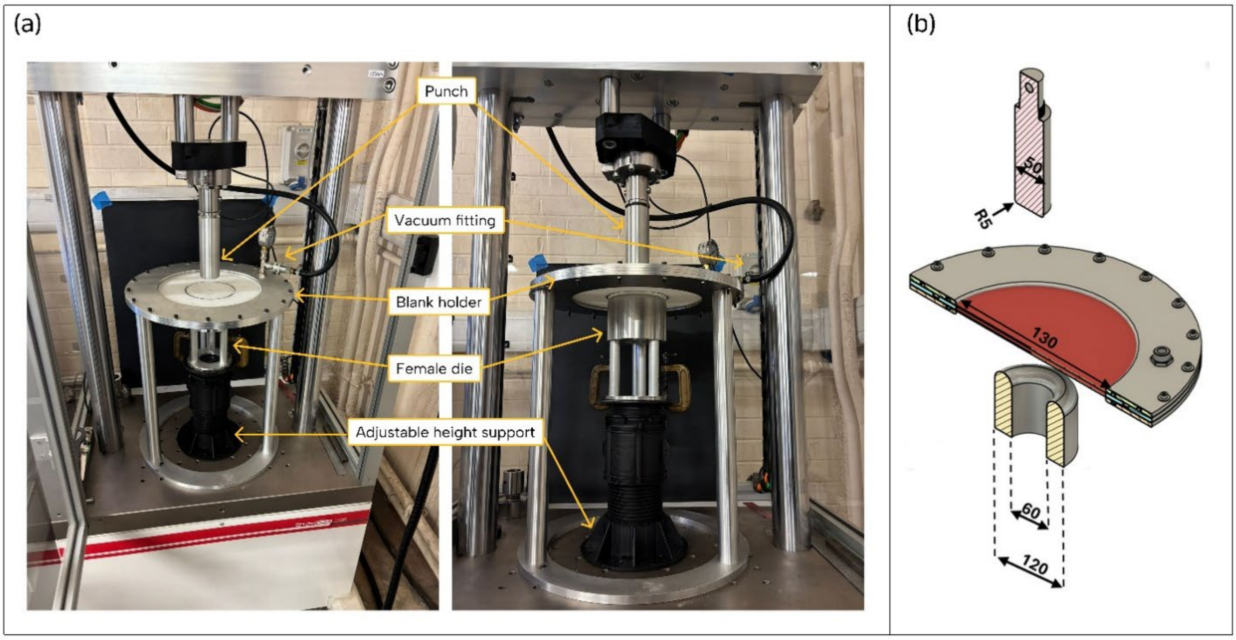

Fig. 3. Deep draw test setup with NT blank holder: a) experimental, b) CAD.

Finite Element Analysis. The blank holder and forming tools were modelled as discrete rigid shell revolutions, while the diaphragms were defined as deformable planar shells (S4R) with thickness assigned via a homogeneous shell section. The hyperelastic material properties of the diaphragms and the friction properties were characterised previously and reported in [13]; therefore, all these data were taken from this reference. Each rigid body was linked to a unique reference point using a rigid-tie constraint. Gravity and a uniformly distributed pressure load of 100,000 Pa were applied using linearly increasing amplitudes. Time steps of 0.25s and 1s were used for the application of gravity and pressure respectively, using an explicit analysis. Note that FEA gives logarithmic or true strains (LE11 and LE22), from which the numerical engineering strain (pre-stretch) can be calculated ($\varepsilon_{eng} = e^{\varepsilon_{true}} - 1$).

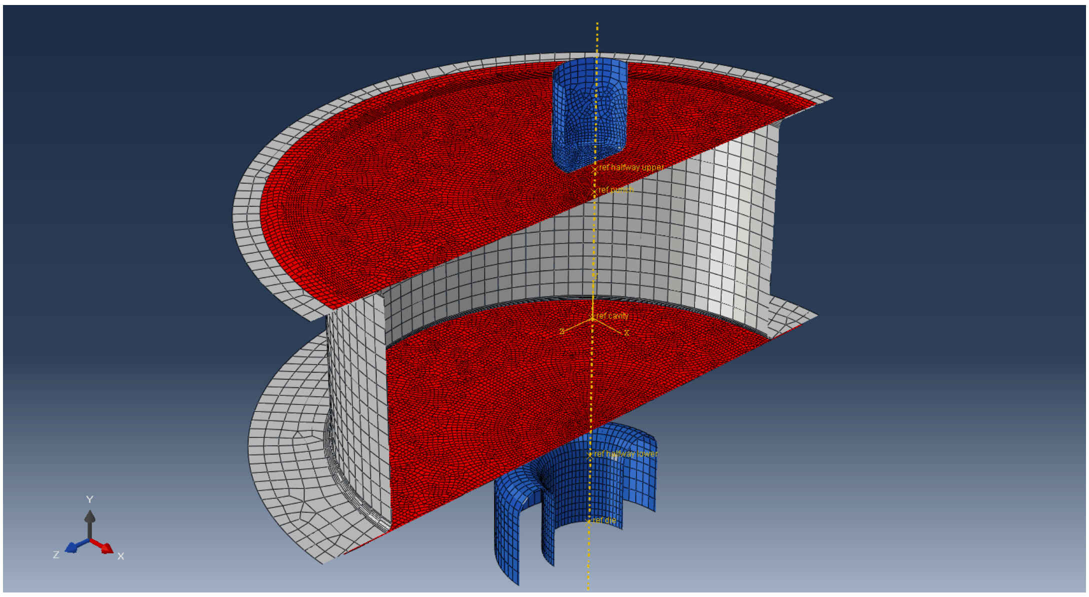

Fig. 4. Schematic of the FEA model (diaphragms indicated in red).

Results and Discussion

Evaluating the Performance of Pre-Tension Blank Holder. The dimensions of the PT blank holder used for FEA modelling were selected based on a theoretical pre-stretch target of 50%. The FEA results confirmed the expected diaphragm deformation under vacuum—the diaphragms gradually approached each other and remained at half the cavity depth under full vacuum—achieving a pre-stretch of 59% near the centre of the upper diaphragm (Fig. 5). Similarly, vacuum draw-in experiments demonstrated stable diaphragm behaviour, with the diaphragm rest-position close to the mid-depth of the cavity wall (see the vacuum fitting in Fig. 6(a)), and strains near the central area measuring 55%. The slightly higher strains observed in both FEA and experimental measurements compared to the analytical solution can be attributed to the assumption of a frictionless scenario in the analytical model, whereas in FEA and experiments, friction between the diaphragms and between the tools and diaphragms was not zero, creating slightly non-homogeneous deformation with localised regions of higher/lower deformation. The experimental results confirm that the PT blank-holder induces an equi-biaxial strain state, as visually evident in Fig. 6 and quantitatively verified through measurements obtained during the draw-in tests. The deformation can be considered stable because the diaphragms met at approximately half the cavity depth and remained flat throughout the process, indicating the absence of instability. The equi-biaxial nature of the deformation is further confirmed by diameter change measurements of the marked circles before and after vacuum draw-in, which show equal strains along the two in-plane principal directions. In addition, visual inspection shows that both *the fabric ply between the diaphragms* and *the marked circles on the diaphragms* retained a perfectly circular shape after deformation, providing further evidence of a uniform equi-biaxial strain state.

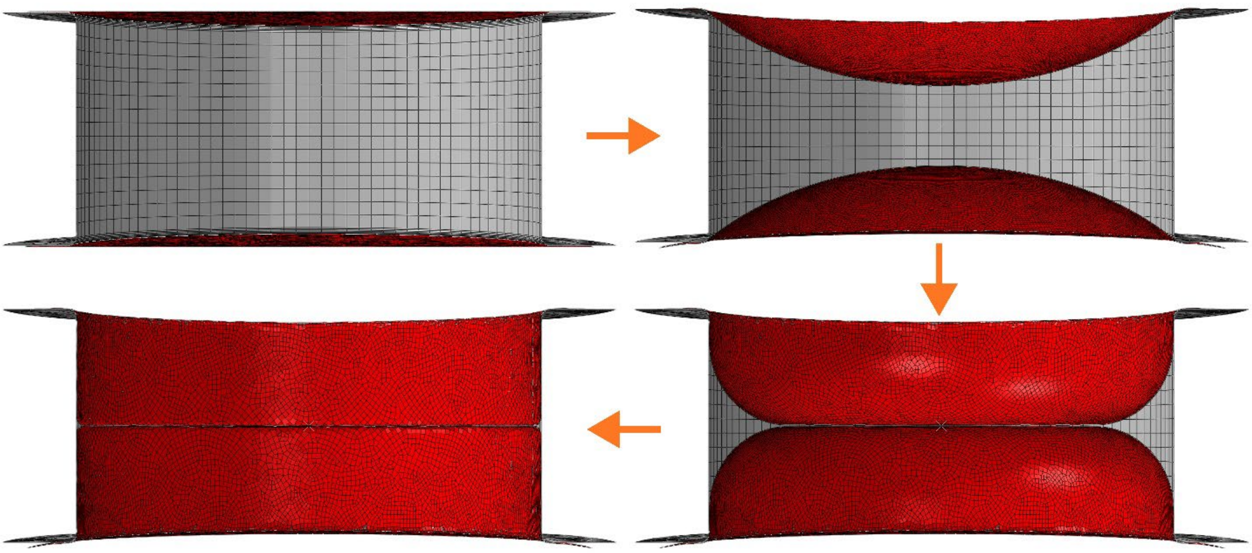

Fig. 5. FEA results showing vacuum draw-in process.

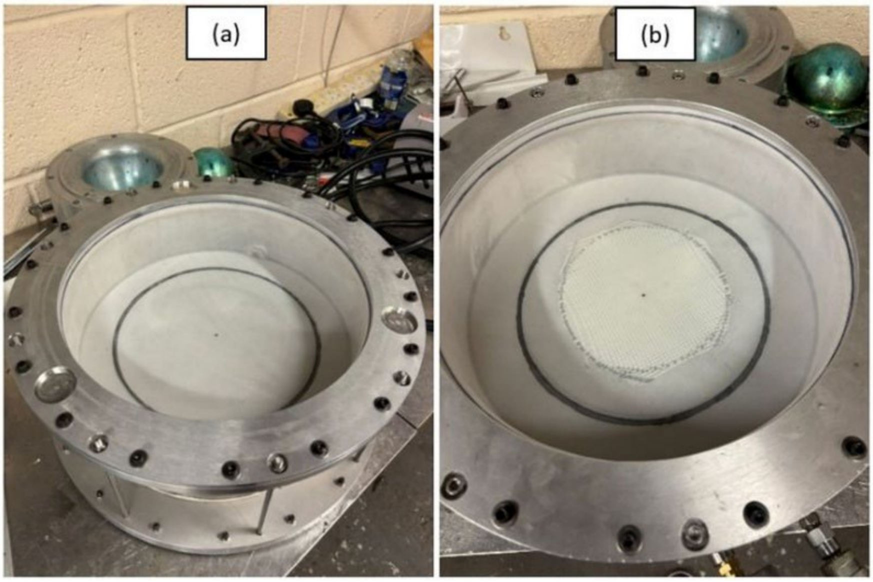

Fig. 6. Experimental vacuum draw-in results showing stable and equi-biaxial diaphragm deformation: a) without fabric layers between diaphragms, b) with fabric layers between diaphragms.

Influence of Diaphragm Pre-Tensioning. The influence of diaphragm pre-tensioning (by 50%) can be evaluated by analysing visual inspection images (Fig. 7) and force–displacement graphs (Fig. 8). As shown in Fig. 7(a) and Fig. 7(b), pre-tensioning significantly reduced wrinkling, both in number and severity. In the test with the PT blank holder (Fig. 7(b)), only a few minor wrinkles appeared along the inner edge of the die, whereas numerous pronounced wrinkles were observed at the same displacement in the NT blank holder test (Fig. 7(a)). Regarding the force–displacement curves, both tests exhibited non-linear behaviour. Up to a displacement of 30 mm, the curves were nearly identical; beyond this point, they diverged. The maximum force recorded at the end of the test was approximately 2450 N for the NT blank holder and 1850 N for the PT blank holder.

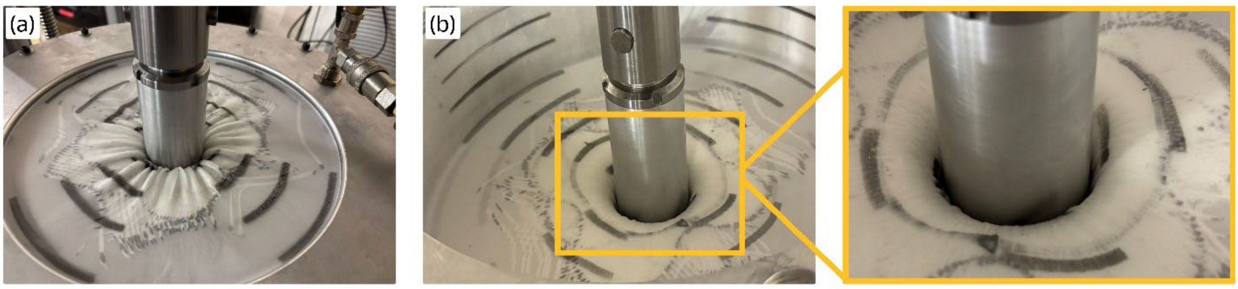

Fig. 7. Wrinkling behaviour at 80mm displacement: a) NT blank holder, b) PT blank holder.

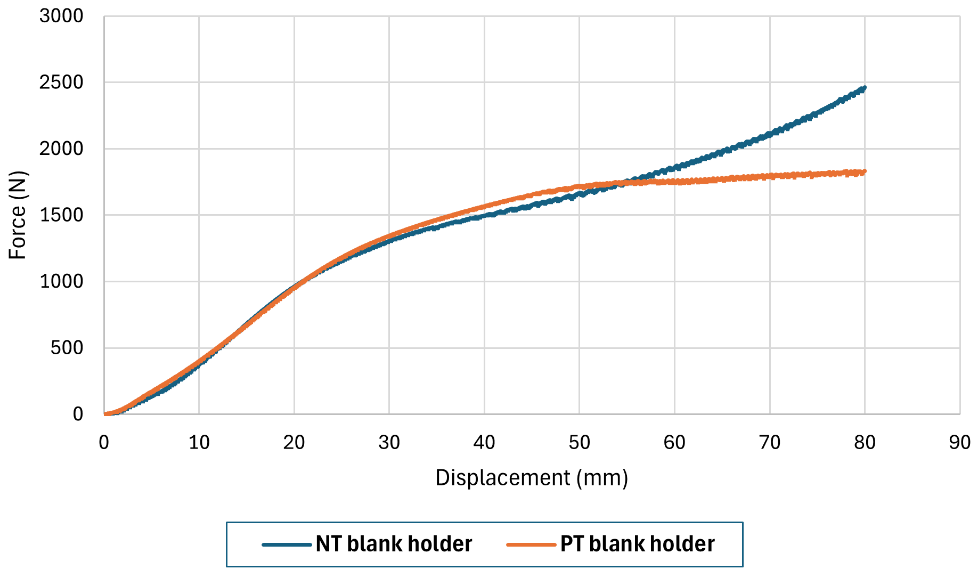

Fig. 8. Comparison of load-displacement graphs for tests with NT and PT blank holders.

Influence of Lubrication. Similarly, the effect of resin inter-ply lubrication using the NT blank-holder can be assessed by analysing visual inspection images (Fig. 9) and force–displacement graphs (Fig. 10). Lubrication also significantly reduced wrinkling: in the test with lubricated fabric layers (Fig. 9(b)), only a few minor wrinkles appeared shortly before the end of the test, whereas in the test without lubrication (Fig. 9(a)), numerous larger wrinkles developed much earlier. The force–displacement curves for the two tests differed markedly. Without lubrication, the curve was non-linear, and the maximum force reached approximately 2450 N. In contrast, with lubrication, the curve was nearly linear, indicating that resin applied between fabric plies substantially reduced inter-ply friction, resulting in a maximum force of about 700 N. Another factor contributing to the higher force in the non-lubricated test was the presence of large wrinkles from the early stages, which were gradually drawn into the die cavity, filling the gap between the punch and die and increasing friction. In the lubricated test, the punch moved freely without contacting the die. This is evident in Fig. 11, which shows the lubricated sample after curing for 24 hours at room temperature; some wrinkles remain visible on both the inner and outer edges of the hole.

Although both pre-tensioning and lubrication reduced wrinkling, pre-tensioning had a more pronounced effect, producing fewer and smaller wrinkles than lubrication. Future work will investigate the combined effect of these approaches and further examine pre-tensioning through detailed FEA modelling.

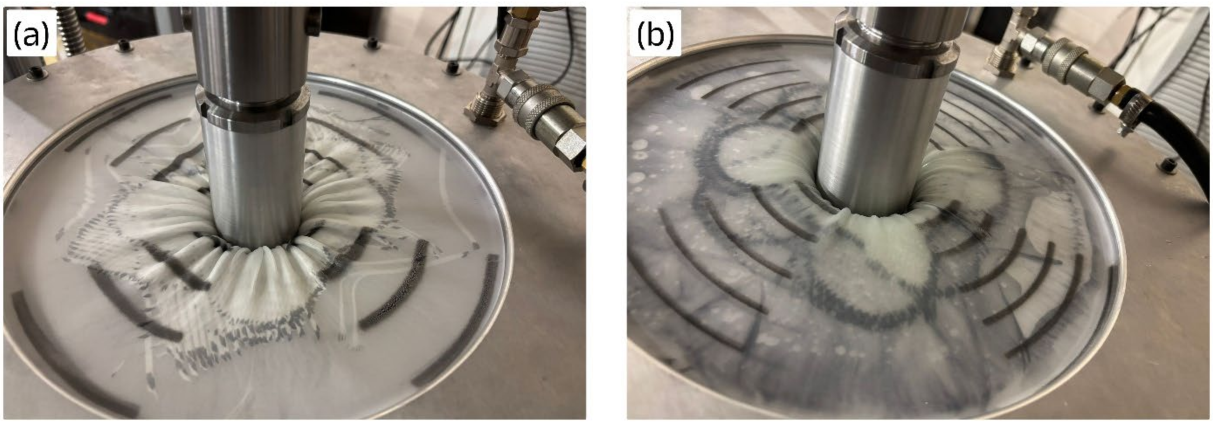

Fig. 9. Wrinkling behaviour at 80mm displacement: a) no lubrication, b) with lubrication.

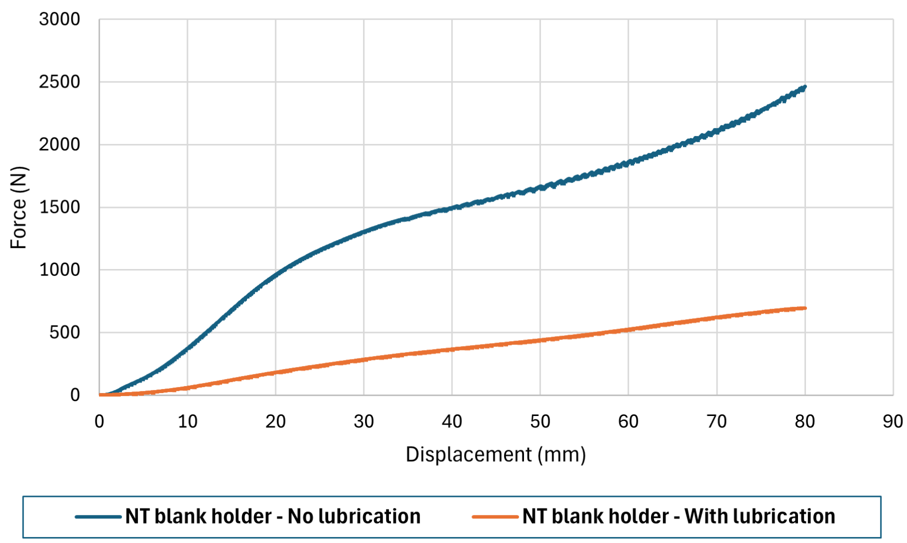

Fig. 10. Comparison of load-displacement graphs for tests with and without lubrication.

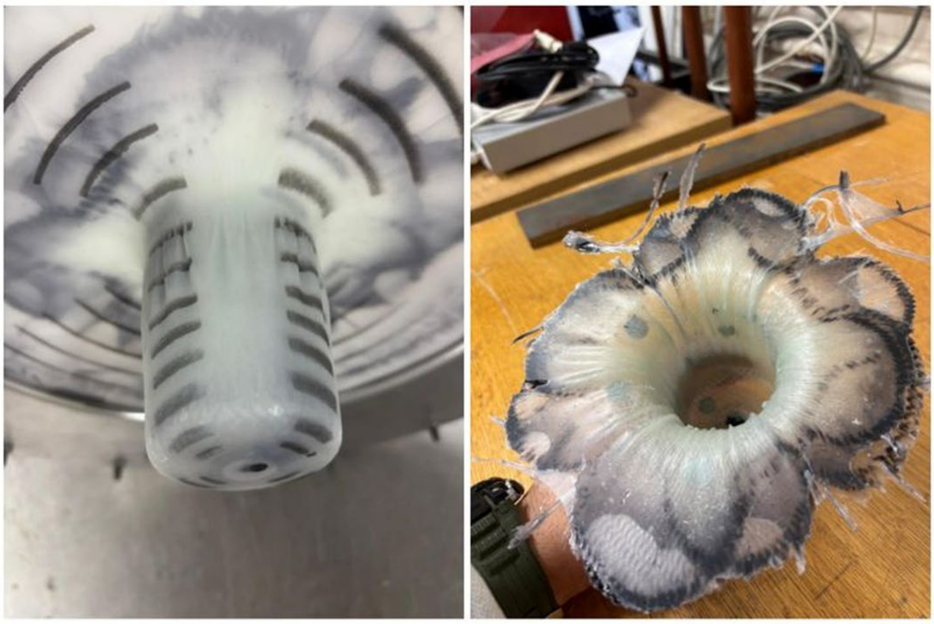

Fig. 11. Deep-drawn sample on NT blank holder (with lubrication) after curing for 24 hours at room temperature.

Summary

This study examined the effectiveness of diaphragm pre-tensioning and inter-ply lubrication in mitigating wrinkle formation during diaphragm-assisted deep drawing of woven glass fabrics. A bespoke pre-tensioning blank holder was designed and validated through deep-draw experiments supported by finite element analysis, confirming both feasibility and performance benefits. The PT blank holder delivered favourable results, achieving uniform biaxial strain consistent with analytical predictions and numerical simulations. Although both lubrication and pre-tensioning improved formability, the latter demonstrated a more pronounced impact on wrinkle suppression. Future work will investigate the synergistic effect of these strategies and employ advanced finite element modelling to optimise process parameters and accurately predict wrinkle behaviour of the fabrics.

References

[1] LT. Harper, S. Chen, Forming of non-crimp fabrics. Advanced Structural Textile Composites Forming: Characterization, Modeling, and Simulation, Woodhead Publishing; (2025), p. 109–43. https://doi.org/10.1016/B978-0-443-21578-0.00004-4.

[2] P. Harrison, Characterizing the forming mechanics of woven engineering fabrics. Advanced Structural Textile Composites Forming: Characterization, Modeling, and Simulation, Woodhead Publishing;(2025), p.57-85. https://doi.org/10.1016/B978-0-443-21578-0.00002-0.

[3] CM. O'Brádaigh, RB. Pipes, PJ. Mallon, Issues in diaphragm forming of continuous fiber reinforced thermoplastic composites. Polym Compos; (1991), p. 246–56. https://doi.org/10.1002/pc.750120406.

[4] GD. Lawrence, S. Chen, NA. Warrior, LT. Harper, The influence of inter-ply friction during double-diaphragm forming of biaxial NCFs. Compos Part A Appl Sci Manuf; (2023). https://doi.org/10.1016/J.COMPOSITESA.2023.107426.

[5] S. Chen, OPL. McGregor, LT. Harper, A. Endruweit, NA. Warrior, Optimisation of local in-plane constraining forces in double diaphragm forming. Compos Struct; (2018), P. 570–81. https://doi.org/10.1016/j.compstruct.2018.06.062.

[6] F. Yu, S. Chen, GD. Lawrence, NA. Warrior, LT. Harper, A global-to-local sub modelling approach to investigate the effect of lubrication during double diaphragm forming of multi-ply biaxial non-crimp fabric preforms. Compos B Eng; (2023). https://doi.org/10.1016/j.compositesb.2023.110590.

[7] G. Miris, M. Ravandi, A. Cardew-Hall, B. Eisenbart, A. Di Pietro, Efficient numerical analysis of in-plane compression-induced defects in thick multi-ply woven textile preforms during double diaphragm forming. Compos Part A Appl Sci Manuf; (2024). https://doi.org/10.1016/j.compositesa.2024.108431.

[8] A. Codolini, S. Chen, GD. Lawrence, LT. Harper, MPF. Sutcliffe, Characterisation of process-induced variability in wrinkle defects during double diaphragm forming of non-crimp fabric. Compos B Eng; (2024). https://doi.org/10.1016/J.COMPOSITESB.2024.111549.

[9] P. Harrison, I. Campbell, E. Guliyev, B. McLelland, R. Gomes, N. Curado-Correia, et al., Induction melt thermoforming of advanced multi-axial thermoplastic composite laminates. J Manuf Process; (2020), p. 673–83. https://doi.org/10.1016/J.JMAPRO.2020.10.026.

[10] SG. Pantelakis, EA. Baxevani, Optimization of the diaphragm forming process with regard to product quality and cost. Compos Part A Appl Sci Manuf; (2002), p. 459–70.

[11] XX. Bian, YZ. Gu, J. Sun, M. Li, WP. Liu, ZG. Zhang, Effects of processing parameters on the forming quality of C-shaped thermosetting composite laminates in hot diaphragm forming process. Applied Composite Materials; (2013), p.927–45. https://doi.org/10.1007/s10443-012-9310-7.

[12] J. Sun, Y. Gu, M. Li, X. Ma, Z. Zhang, Effect of forming temperature on the quality of hot diaphragm formed C-shaped thermosetting composite laminates. Journal of Reinforced Plastics and Composites; (2012), p. 1074–87. https://doi.org/10.1177/0731684412453778.

[13] G. Street. Thermomechanical Forming Simulation for Fibre Reinforced Thermoplastic Laminates. PhD Thesis at University of Nottingham; (2025).

[14] P. Harrison, LF. Gonzalez Camacho, Deep draw induced wrinkling of engineering fabrics. Int J Solids Struct; (2021), p. 220–36. https://doi.org/10.1016/J.IJSOLSTR.2020.12.003.