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Fabric Patching: A Simple Approach to Mitigate Defects

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Abstract. Forming of dry textile preforms for liquid moulding processes becomes increasingly challenging for geometries exhibiting strong double curvature and aggressive tapering. While sequential draping can mitigate defects, it is often impractical for high-rate manufacturing and lacks robustness for dry fabrics with limited inter-ply tack. This paper investigates an alternative approach in which locally printed and cured or semi-cured resin patches are used to steer deformation during forming and suppress shear localisation. A numerical framework is developed to model patched preforms using a superposition-based material representation and is applied to an extreme "bow-tie" benchmark geometry. Initial simulations reveal severe shear-strain localisation leading to fibre-path instability. Various patching strategies are explored to identify the dominant drivers governing defect mitigation. The results demonstrate that appropriately placed and sufficiently stiff patches can significantly delocalise shear and eliminate multi-stripe deformation patterns. Based on these findings, key optimisation parameters and practical guidelines for patch placement and stiffness selection are formulated, providing a foundation for future automated optimisation of patch-assisted preform forming.

Introduction

Forming of textile preforms in the context of liquid moulding processes becomes particularly challenging when complex geometries are involved. Even when fabrics are sufficiently drapable under carefully controlled sequential lay-up operations, they may not be formable in a single-step process using rigid moulds, diaphragm forming set-ups, or thermoforming stations. This is particularly apparent when comparing results of kinematic drape models and mechanical simulations [1,2]. Sequential draping of dry preforms is, however, not always feasible in industrial settings due to the absence of inter-ply tack. Powder binders partially address this limitation, but their thermal activation typically requires large thermoforming stations in which forming must again be performed in a single step, effectively reintroducing the original challenge.

Controlling the draping deformation of delicate dry preforms is therefore a technologically demanding task. Low resistance to compressive stresses, combined with shear limits governed by lateral yarn interactions, makes the process prone to fibre-path defects. Various strategies have been proposed to alter the effective formability of preforms and suppress uncontrolled fibre motion. These include external constraints, such as blank holders [3,4], tensioning systems [5,6], and risers [7], as well as internal modifications of the preform, including tufting [8] and stitching [9]. The common objective of these approaches is to minimise excessive shear and compressive stresses by locally modifying the mechanical response of the preform or constraining critical regions.

Turk et all [10] have was shown that incorporating internal constraints directly into the preform, i.e. specifically by printing resin patches and curing them locally, can effectively protect critical regions from excessive shear and promote delocalisation of forming deformations. This fabric treatment enables more controlled preform deformation while avoiding the complexity associated with manual draping operations or external constraint systems. Importantly, patching does not alter fibre orientation and does not introduce structural disruptions that could degrade material properties. In addition, local patch properties can be tailored, for example by controlling the degree of cure. The viscosity of the printed resin directly governs patch deformability, offering an additional lever for process control. Thermal conditioning of partially cured printed patches has also been shown to be feasible and well controlled [11].

As with any forming-defect mitigation strategy, determining the optimal placement of patches is non-trivial and requires numerical optimisation. Over-constraining the preform may lead to adverse effects by restricting the degrees of freedom required for the fabric to conform to the tool geometry. The objective of patching is therefore to protect critical areas from excessive deformation, diffuse shear localisation where possible, and steer deformation toward regions with lower defect risk. Employing patches that are not fully rigid (which is achievable by limiting the degree of resin cure) may provide a gentler and more effective constraint strategy. Previous studies have demonstrated that patch material properties can be identified through bespoke characterisation procedures and incorporated into numerical models for process optimisation [12]. One of the promising material for patches is vitrimeric resins that are fully compatible with subsequent infusion resins and can be tuned to create seamless interface with the patch [13].

A range of optimisation techniques has been proposed for forming simulations, such as Bayesian surrogate modelling, which has shown significant efficiency gains in the optimisation of diaphragm-forming processes [14]. In this framework, successive simulations are strategically selected to reduce uncertainty in the response space. In the present work, patch optimisation is considered through the lens of such techniques. However, the associated design space is large, as patches may vary in shape, size, position, number, and stiffness. Prior to formal optimisation, it is therefore essential to identify the dominant parameters governing process performance. This paper discusses the key drivers of the patch optimisation problem, presents simulations highlighting the associated constraints, and identifies optimisation metrics relevant to defect mitigation. Finally, initial guidelines are proposed for selecting patch configurations for arbitrary geometries.

Test Case

The selected test case represents a "bow-tie" geometry, which may be regarded as an extreme variant of a spar featuring a recessed central region. This configuration was chosen because, despite its relatively simple composition of flat segments, it exhibits aggressive tapering that leads to high shear angles (above 50°) and highlights the primary challenges associated with double-curvature forming. The preform is formed within a double-sided rigid mould representative of an RTM process (Figure 1).

A single-ply orthogonal fabric preform is considered, with warp and weft yarns initially aligned with the part edges. The fabric dimensions are 231.4 × 250 mm, the width of the web 150 mm, the length of the recess area of 70 mm, and the radii of curvature in the web-flange corners are 10 mm. In the simulations, the concave mould is held stationary while the convex mould advances until full tool contact is achieved.

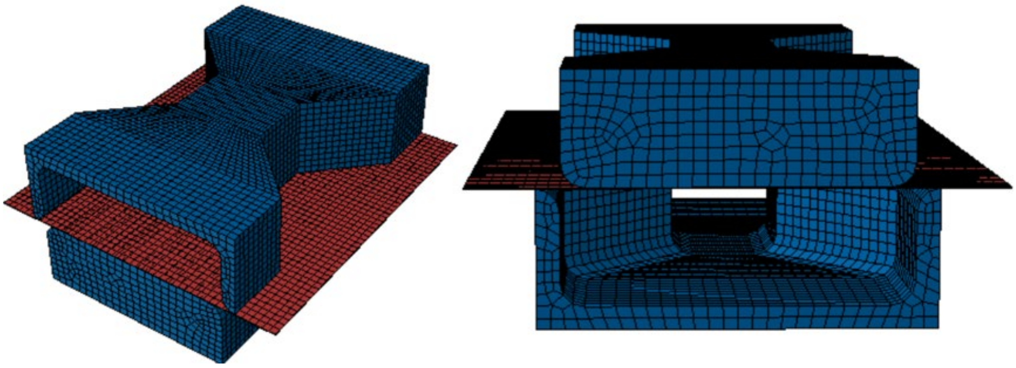

Fig. 1. Geometry of the moulds and initial model setting (blue – steel moulds, red – preform prior to compaction).

Physical Model and Numerical Implementation

To represent fabric behaviour, a computational approach differing from conventional forming models is adopted. Instead of defining explicit constitutive relations, the material response is represented through a superposition of several components:
(1) warp yarns with elastic stiffness along the fibre direction and negligible transverse and shear stiffness, (2) weft yarns with analogous properties but initially orthogonal to the warp direction, (3) a connecting "quasi-matrix" medium calibrated to reproduce the fabric shear response in bias extension tests, (4) locally applied rigid patches with stiffness representative of cured composite material. This framework allows accurate calibration of bending and shear behaviour while seamlessly incorporating rigid or semi-rigid patches into an otherwise compliant preform. The bending response of the fabric is controlled by the Young's modulus of fibrous plies in the longitudinal direction, whereas the quasi-matrix media regulates the shear response of the system. Such assembly allows to tune the properties critical for predicting main wrinkling modes. However, in contrast to shell/membrane formulations [16] such approach does not account for decoupling of membrane and bending responses and can only be applicable in the absence of preform stretching and considerable loads in the plane of the fabric. The embedded element approach has previously been shown to be effective for modelling viscoelastic behaviour associated with uncured resin systems [15].
In the present model, shear properties representative of a carbon plain woven fabric are adopted [16]. The connecting medium is implemented using a hyperelastic isotropic formulation, with material input provided in the form of uniaxial test data. The bending stiffness of the material is controlled by the Young's modulus of fibrous plies in the longitudinal direction. Patch properties were calculated using Chamis micromechanical formulas for unidirectional properties in warp and weft direction and then averaged across the two directions. The moulds are modelled as rigid steel surfaces. All simulations are performed using Abaqus/Explicit. The effective material density is adjusted to balance computational efficiency with dynamic stability – a scaling factor of 100 was applied to the densities of all materials in the model.
During the sequence of numerical trials, it was observed that a low flexural stiffness of the fabric occasionally led to convergence difficulties caused by excessive local rotations associated with wrinkle initiation, which in turn resulted in element distortion. This premature wrinkling terminated the simulations prior to full mould closure and altered the redistribution of shear deformation, thereby preventing a consistent comparison between different configurations. To ensure stable mould closure in all trials and to isolate the influence of patching from numerical instabilities associated with early-stage buckling, the bending stiffness of the fabric was temporarily increased by assigning a longitudinal Young's modulus of 3.1 GPa to the fibrous ply. This modification was introduced solely as a numerical stabilisation measure and was not intended to represent the physical behaviour of the material. The increased bending stiffness suppressed premature wrinkling, enabled complete mould closure, and allowed a controlled and consistent comparison between patched and non-patched configurations under otherwise identical conditions. After identifying the optimal patch configuration, the bending stiffness was restored to its physically realistic value (the flexural modulus was reset to 33 MPa [16]) for subsequent simulations and interpretation of the results.

All superimposed material components are modelled using 3D elements with a nominal thickness of 0.5 mm. The fabric was meshed with 8-node linear hexahedral (brick) solid elements with reduced integration specifically designed for non-linear and large deformation problems. The characteristic mesh size is 5 mm. Frictionless contact is assumed between the fabric and the mould surfaces. Material superposition is implemented using the embedded element technique.

Initial simulations and problem statement

Simulation of the unpatched preform during mould closure reveals severe localisation of shear strain. Narrow shear bands initiate near the flange–web corner, intersect with bands of opposite sign in the recessed web region, and terminate at the bottom of the part (Figure 2). This behaviour results in abrupt fibre-orientation changes over very short length scales. Although the model does not explicitly predict out-of-plane wrinkling, the deformation patterns clearly indicate severe fibre-path defects. In practice, such fluctuations would likely lead to yarn buckling, fabric splaying or unacceptable fibre waviness.

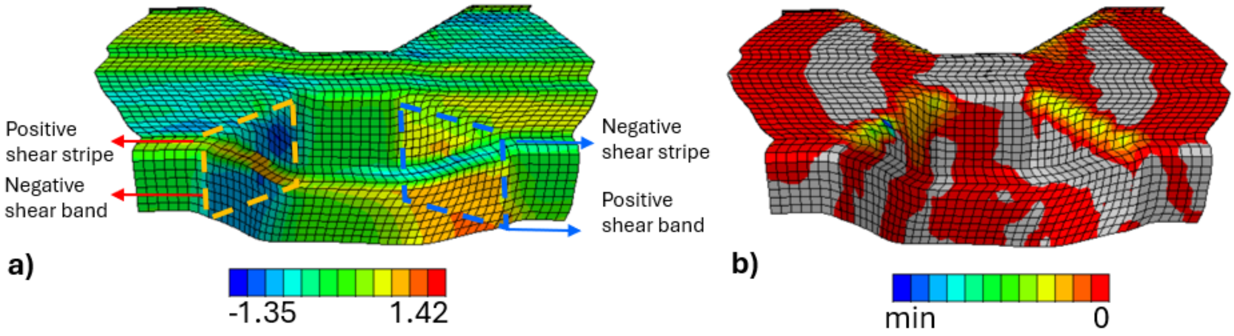

Fig. 2 (a) Shear strain of formed unpatched material, (b) Compressive stresses in the direction across the length of the spar.

It should be noted that the current model does not account for in-plane bending stiffness, which has been shown to play a critical role in predicting certain defect modes under rapidly varying constraints [17]. Nevertheless, whether these multi-stripe shear patterns correspond to in-plane waviness, out-of-plane wrinkling, preform splaying or intra-fabric buckling, they represent severe defects that must be avoided. These observations define the primary objective of patching: to prevent the formation of such shear-localisation bands.

For automated optimisation, suitable quality metrics must be defined. Maximum shear angle alone is insufficient, as a uniform shear band even at high intensity may still correspond to acceptable forming. Compressive stress is also of limited relevance in the present case, as it is largely concentrated near corners and does not correlate well with observed defect locations (Figure 2b). Out-of-plane displacement provides a direct measure of wrinkling but is not informative for the example considered here. The most relevant metric for the present study is therefore the shear-strain gradient, which can provide a quantitative measure of the observed defect severity. Shear strain gradient can be calculated using direct numerical differentiation of shear distribution or, to eliminate the numerical noise, using analytical differentiation of the locally approximated shear field. While no absolute threshold exists for acceptable gradients, minimisation of this measure offers a clear optimisation objective.

Patch optimisation

To enable numerical optimisation, the design space must be defined and patch parameters such as position, shape, size, and stiffness, must be parametrised. As noted previously, excessive constraint can worsen forming behaviour rather than improve it. Initial trials demonstrate that restricting deformation in regions where shear would naturally develop, such as along the symmetry axis or top flange, can lead to intensified cross-over patterns and alternating shear bands. In some cases, buckling within the patched region is observed, which in practice could result in fibre damage. These results confirm that overly large or overly stiff patch regions are counterproductive.

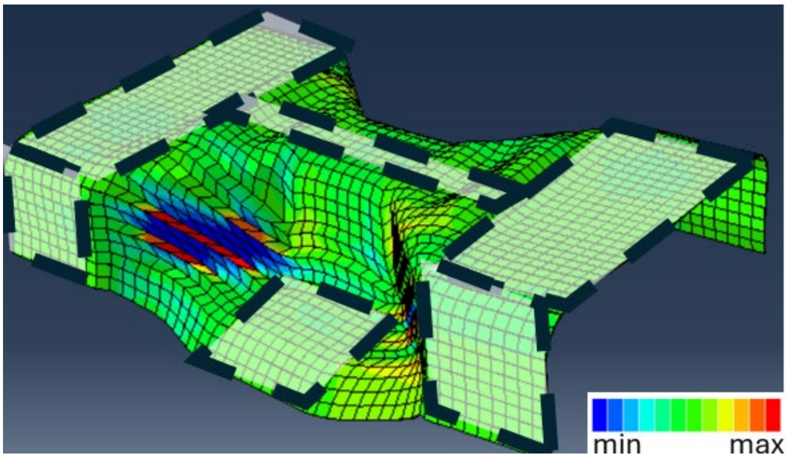

Fig. 3 (a) Shear map of formed bulk-patched material (contour lines show the borders of patches, inner patch area is highlighted, min: -1.68, max: 1.66).

A more effective strategy is therefore required. Based on the initial simulations, a working hypothesis was formulated: preventing multiple shear stripes from developing independently and instead forcing the formation of a single, continuous shear band could mitigate defect formation. This can be achieved by surrounding the high-risk region near the transition to recess area with a frame-like or rail-type patch configuration that suppresses localised shearing.

Several patch lengths and stiffness levels were investigated to assess the viability of this concept. The results (Figure 4) show that, beyond a critical patch length, fibre-orientation variations become significantly more gradual and the violent oscillations observed in the unpatched case are largely eliminated. These findings demonstrate that the proposed strategy is effective. The simulations further indicate that higher patch stiffness is beneficial for suppressing localisation. Figure 4 compares patches with varying stiffness: one assuming a fraction of cured resin stiffness and another is full stiffness (representative to engineering vitrimer or epoxy resins). It can be seen that the stiffer patch appears more effective in the hypothesised railing action and protecting the inner region from disjointed shear stripes.

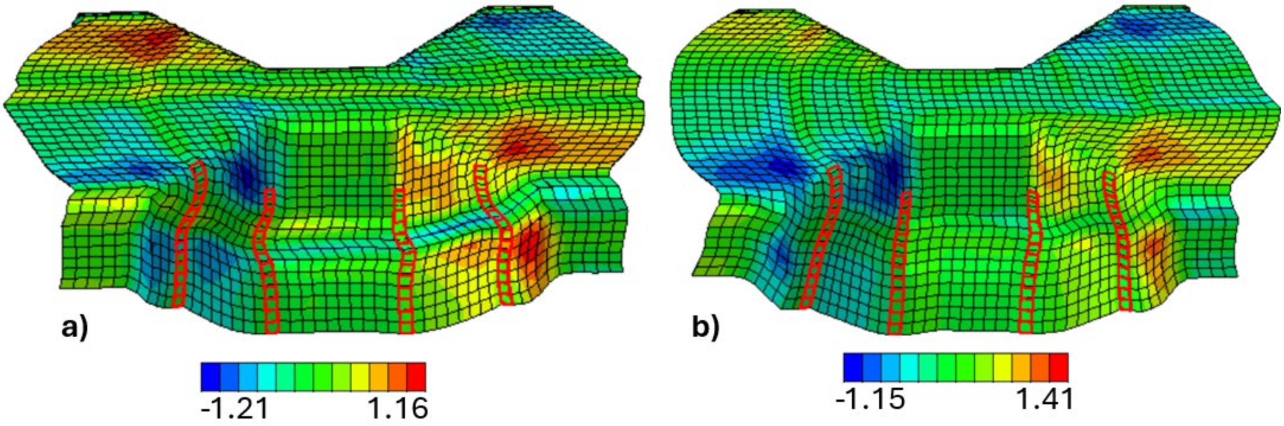

Fig. 4 Shear map of formed rail-patched material (red square show the position of the patch): (a) patch properties assuming 10% of epoxy stiffness, (b) patch properties assuming epoxy stiffness.

Once plausible results had been obtained using the artificially stiffened fabric configuration, the bending rigidity was reduced to more realistic values, consistent with those reported by Thompson et al. [16]. The reduction in flexural stiffness introduced an additional wrinkling mode, characterised by fold formation on the top surface. Once the mould is closed and the fold is squashed, it translates to the violent oscillations of shear deformations – Figure 5a. The shear distribution along the sides also became less regular, and several characteristic shear bands re-emerged even in the presence of rail patches. A pragmatic solution was achieved by introducing additional stabilising patches in the longitudinal direction of the part and by increasing the width of the side rail patches. The latter modification enhanced their in-plane bending stiffness and helped maintain the continuity of shear deformation within the shear bands (Figure 5b).

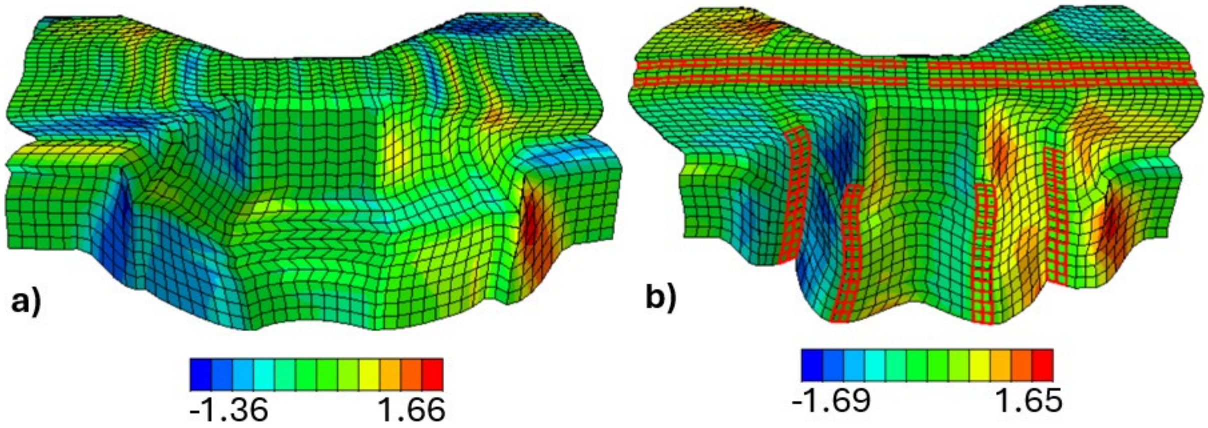

Fig. 5 Shear map of forming of preform with realistic flexural stiffness (a) without patches, (b) with patches (patches are highlighted in red).

Obviously there might be practical limitations to this approach. Fully cured composite patches are exposed to bending around part corners and may bear risk of fibre damage during tool closure. Potential alternatives include using high-viscosity but partially cured materials, terminating patches before sharp corners, or limiting patch length. Overall, the results establish a strong basis for defining a compact and practical design space in which patch length, termination location, and stiffness are the primary optimisation variables. Most importantly, the feasibility of patch-assisted forming is confirmed, offering a cost-effective and pragmatic alternative to complex external constraint systems for dry-fabric preforms.

Conclusions

This study demonstrates that locally applied resin patches can be an effective means of controlling deformation and suppressing defect formation during the forming of dry textile preforms for complex geometries. Numerical simulations of an extreme bow-tie test case reveal that unpatched preforms exhibit severe shear-strain localisation manifested as narrow, alternating shear bands, which are indicative of critical fibre-path defects. Conventional defect indicators such as peak shear angle, compressive stress, and out-of-plane displacement were found to be insufficient for capturing this behaviour, whereas the shear-strain gradient emerged as a robust and physically meaningful optimisation metric.

Systematic exploration of patching strategies shows that over-constraining the preform exacerbates localisation and can introduce additional instabilities, highlighting the necessity of careful patch placement. In contrast, targeted patch configurations that surround critical regions and inhibit independent shear-band formation promote the development of a single, smoothly varying deformation mode. Sufficient patch stiffness is required to achieve this effect; however, fully rigid patches may be impractical due to bending demands near tool corners, suggesting that partially cured or high-viscosity materials provide a more viable compromise. The approach is readily suitable for creating vitrimeric-epoxy multi-matrix hybrids, that can other forming and repair benefits [18], but could also be applicable in the context of liquid printing [19] or solid resin deposition [20].

The findings enable a significant reduction of the patch optimisation design space, identifying patch length, termination location, and stiffness as the dominant parameters governing forming quality. Overall, the results confirm the feasibility of patch-assisted forming as a practical and cost-effective alternative to external constraint systems, and establish a foundation for future automated optimisation frameworks for complex preform geometries.

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