TIME DEPENDENCE OF MULTI-PLY FORMING OVER DOUBLY CURVED SHAPES

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Keywords: Double curvature, wrinkle, complex, Automated Tape Laying (ATL), defect

Abstract
The potential for reducing wrinkling during the forming of a preconsolidated composite laminate, by slowing the forming rate, was investigated. This research came about due to observations of a proposed new industrial manufacturing method for constructing a large aerospace component, which upon initial forming trials suffered from severe wrinkling. A lack of interply slip was seen as a key factor behind the wrinkle formation in the process. A range of regulations and constrains in the industrial setting meant that the only available method by which the process could be modified was to dramatically reduce the forming rate, with the hope of utilising the viscoelastic properties of the epoxy resin - to reduce the generated stresses in the resin and allow the prepreg to form wrinkle free. Conforming to those constraints, bias extension and lap shear tests were used to study materials behavior at a range of strain rates, showing a significant reduction in the forming forces. The effect of rate change was further investigated by forming circular laminates over a hemispherical shape in a novel test set-up. Simple 0.90 or 45.135 cross-plied blanks showed significant improvements in forming at slower forming rates, while [0.90, 45.135] preforms continued to wrinkle even with vastly reduced forming rates.

1. Introduction

Advanced composite materials offer a range of benefits over traditional metallics, predominantly their excellent specific strength and corrosion resistance. Accordingly, their use is commonplace in high performance applications such as Formula One and military aircraft [1]. Larger volume industries such as civilian aerospace, and (potentially in the near future) the automotive sector, have rapidly begun to use composites in an effort to reduce weight and increase performance/efficiency. Some excellent examples of composites use in components are available, however they are still not ubiquitous to these industries, and other materials can increasingly compete with them on an as-cost basis. Unfortunately the take-up of composite materials is hampered by the high-cost and low-rate of the traditional construction methods. Manufacturing with composite materials to form components is particularly complicated because in order to make the most of the advantageous specific strength, fibres should ideally be aligned in the primary loading direction and remain free from defects [2]. Presently there are a wide range of manufacturing techniques available - ranging from manual techniques through to complex robotic based systems - as well as a wide variety of materials and application methods.

The aerospace sector is subject to a wide range of certifications & regulations which can dramatically restrict composite material choice, limiting supply chain manufacturers to a narrow range of thermoset prepreg materials that may also include tight controls on temperatures, time out of freezer, and other factors [3]; which cascade to making step changes in innovation difficult to achieve. Presently the dominant methods for producing primary and secondary structures appear to be hand layup and

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Automated Fibre Placement (AFP), both of which are focused more on quality rather than outright production rate. Both involve building up the laminate directly onto the mould layer by layer, ensuring fibres are laid down in a highly aligned state and free from defects. While these approaches can create extremely good quality laminates, they can be very slow and in the case of AFP potentially carry (for most) a prohibitively large initial capital outlay.

An alternative to these two dominant techniques is Automated Tape Laying (ATL), which lays down wide (up to 300mm) tapes of unidirectional (UD) material, and can achieve very impressive layup rates, but is only really suited to flat components or those of simple single curvatures [1]. There are a wide range of new processes being developed based around Pick and Place systems, that automatically transfer single plies from a ply cutting table to a mould, but focusing more in terms of high volume rather than quality [4-6]. A hybrid of these two processes, as a new industrial manufacturing method for constructing a large aerospace component, was proposed; whereby an ATL machine was used to layup the full laminate blank (also known as a charge), and then Pick and Place the whole laminate onto a doubly curved mould tool for forming. This proposed process was quite distinct to that seen in the hot drape forming of spars [7], as forming was to be rapidly achieved by vacuum into a female tool (due to outer mould surface finish requiremnts) at room temperature, and the charge size & complexity offered plies of an extremely large surface area. Observing an initial forming test it was noted that significant fibre wrinkling was encountered, but through regulations and constrains in the industrial setting little process development for elevating temperatures etc was possible. Thus a study was developed that could explore rate effects on the layup quality as this was a potential controllable feature of the process.

1.1. Blank forming

The concept of laying up full thickness blanks and them forming them over doubly curved shapes is used frequently with thermoplastic composites. A key difference between thermoplastic and thermoset matrix materials is that thermoplastics can be heated above their melting point and held for an extended period without effecting the final laminate properties. The liquid matrix material can lubricate the plies, enabling them to easily slip past each other during forming, which as discussed in Section 1.2 is very important forming feature. Other advantages of using thermoplastics include reprocessing, recycling potential, toughness, and welding. As such they may see much greater use in aerospace in the long term [8]. The disadvantages in these materials are the difficulty and expense of achieving the required high process temperatures (especially on large parts), poor chemical resistance for some resins, and a limited range of materials certified for aerospace - although this particular issue is diminishing.

At present high performance thermoplastic prepregs are also significantly more expensive than thermosets. An in depth comparison of the two resin types is given by Cunningham [9] who concludes that thermosets will still be used for a long time, primarily due to cost issues, and the difficulty in forming due to the need for heating. Thermoset prepregs can also have their resin viscosity reduced temporarily for forming via heating - a technique regularly used during traditional hand lamination [2]. However uncontrolled heating and exposure times risk initiating the curing process, which could negatively affect the strength of the final laminate; thus during hand lamination or AFP single plies are surface heated for only a few seconds. For a blank over 40 plies thick it would take a considerable time to heat it all the way though the thickness, exposing some plies to an extended heated period, and so risking premature curing. Industrial standards generally prohibit against this lack of control [10], and so manufacturing typically uses a resin that is preserved in a state that is very viscous and difficult to form.

Previous research efforts into forming quasi-isotropic thermoset laminates have been dogged by wrinkling defects, and have apparently only managed to overcome it by making radical changes to the component such as changling layups or removing plies [11], adding inter-ply lubrication [12] or by slitting some of the plies [13]. These approaches could all be argued to risk a reduction in laminate properties, sit outside of current certification guidelines, or would require major redesigns. Due to the initial forming test already being conducted, it was argued that the layup orientations and order were pre-defined, leaving forming rate as the only feasible variable that could be experiemnted with. Epoxy

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resin is strongly viscoelastic, such that its apparent viscosity can be reduced by reducing the strain rate [14], and as the observed test was rapidly formed it was proposed that dramatically reducing the forming rate could lower the resin resistence enough to allow inter-ply slippage.

1.2. Why is interply slip important?

Heating a prepreg or slowing the forming rate are primarily focused on enabling interply slip, and this is especially important to successfully manufacture doubly curved geometries. Firstly, consider the case of single curvature as shown in Figure 1. The interply slip is caused by the slight difference in path length between adjacent plies as they bend round a corner. The ply slip distance around a single curvature corner is calculated via Equation 1, and shows the slippage is only a function of the corner angle and ply thickness, not the corner radius. Assuming the material is the same, so that the ply thickness remains constant, the only variable is the angle of the corner and the required slippage is no different regardless of the size of the part. Thus for example, bending around a 90° corner with a ply thickness of 0.25mm, the slippage is relatively small at about 0.4mm. However, wrinkling defects in single curvature forming is still an ongoing issue [15].

$$Slip = \beta t \tag{1}$$

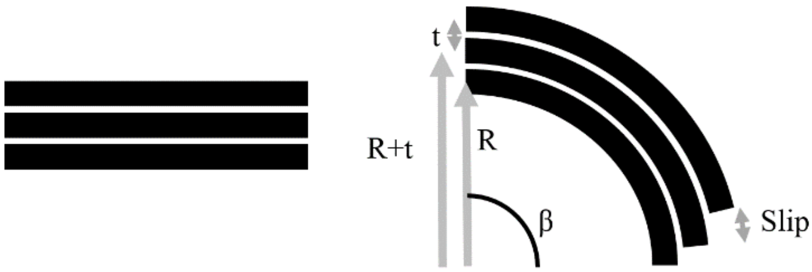

Figure 1. Schematic of ply slippage while bending a laminate over single curvature bending.

Double curvature is a very different prospect. In order for a flat ply to form onto a double curvature shape, it needs to deform in-plane to avoid wrinkling [14]. The diagram on the left of Figure 2 shows that when a woven ply or cross-plied UD plies have a shear stress applied, they has to ability to 'shear' [15]. Accordingly Figure 3 shows how an 0.90 or 45.135 cross-plied layers could deform via in-plane scissor shear over a hemisphere shape. Crucially for the two different orientations this deformation occurs in different places and in different directions. Thus in order for these cross plied pairs to form in their own separate patterns when combined into a [0.90, 45.135] preform or a larger quasi-isotropic laminate, they would need to slip relative to each other. An alternative explanation of the shearing issue is given in the diagram on the right of Figure 2 which shows that if an in-plane shear stress is applied to [0.90, 45.135] preform or a larger quasi-isotropic laminate, instead of shearing, the additional 45.135 layers will react the force via tension and compression respectivly. During forming such behaviour is highly counter productive and creating compressive in-plane forces in a thin laminate will generally cause it to buckle, leading to wrinkles. The alternative is for the plies to slip between each other such that a [0.90.45.135] would slip at the 90.45 interface, and the layup would then become [10.80.45.135], if for example 10° of shear were required. However as discussed in Section 1.1 and shown later in Section 2.2, this interply slip can require large forces, and wrinkles may still occur.

Another difference between double and single curvature is how the required slip scales. The shear angle *only* increases with the amount of double curvature, not with the scale of the part. However the slippage distance between adjacent 0.90 and 45.135 cross-plied pairs increases with both the amount of double curvature, *and* the scale of the part. For example an interface between a 45.135 and 0.90 plies requiring just 1° shear over a 1 x 1m could need slippage of +15mm - much greater than is generally seen during single curvature forming, hence it is much more difficult to facilitate.

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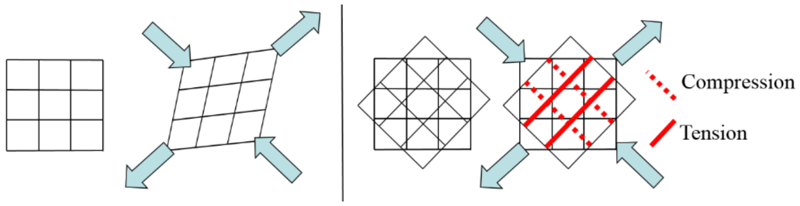

Figure 2. Schematics of shearing in woven or cross-plied UD material (left) and a 0.90, 45.135 preform of UD material (right).

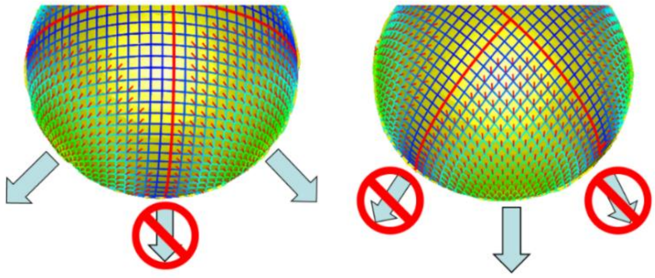

Figure 3. Schematic of fibre deformations over a hemisphere shape for 0.90 (left) and 45.135 (right) layups using Virtual Fabric Placement [16], 75° representing max. in-plane scissor shear.

2. Methodology and Results

To establish if forming rate alone is an effective tool to facilitate interply slip and combat wrinkling, a series of tests were proposed. Firstly the rate dependence of the material was tested in isolation - the shearing in a cross-plied sample was investigated via bias extension testing, and the inter-ply slippage rate dependence was tested via a double lap shear test. Following these trials the forming of charges consisting of both cross-plied and [0.90, 45.135] preforms over double curved shapes, at a variety of rates was conducted. The trials were conducted using IM7 UD carbon fibres preimpregnated with Hexcel 8552 resin [17], and despite male moulds with thin ply preforms being used, the forming results are still transerrable to the female mould version.

2.1. Shear deformation

A shear bias extension test was used to establish the dependence of rate on the shear stiffness, following a method used in [18-19]. A 200 x 40mm rectangular laminate consisting of 2 plies orientated at 45.135 relative to the sides was elongated along its length, as shown in Figure 4. As the rectangle elongates the central region shears, and the required force is used to assess the shear stiffness. The extension was carried out at rates of 5, 25, and 200mm/min; equating to 3, 16, and 125%/min respectively in terms of strain in the shearing region. The result shows rate has a clear effect of the shear stiffness, with the fastest samples being almost three times as stiff as the slowest. The effect of this difference in forming is further demonstrated in Section 2.3.

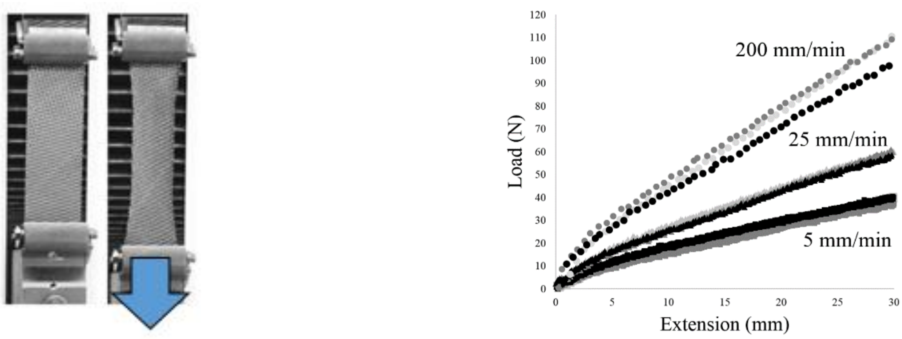

Figure 4. (Left) Bias extension test (showing different material to that used). (Right) Results showing the increased stiffness at higher deformation rates.

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2.2. Interply slippage

To test the rate dependence of pure interply slip a double lap shear test was conducted using 10mm strips of UD material aligned at 0° and arranged into a lap shear sample with a 5mm overlap, as illustrated in Figure 5. Samples were consolidated under vacuum for 10 minutes prior to test and then placed into a test machine for a pull out test. An example force/displacement graph of two samples is shown in the figure. It was noted that ‘fast’ samples (30 and 250mm/min) failed in a brittle manner with an audible ‘snap’, which can be seen as a sudden loss in force, while slower samples displayed a more gradual failure. The apparent displacements of up to approximately 1mm prior to failure is due to slack in the ply being taken up on loading rather than a large shear strain in the sample. Results show and almost ten fold difference between the slowest and fastest samples, suggesting slowing the forming down could be an effective anti-wrinkling stratergy. However, it is worth considering the value of the lowest speeds, which is still considerably high - 100N for an interface area of 100mm^2 equates to 1N/mm. Thus if an area of 20 x 20mm is required to slip, the required force would be approximately 400N per ply interface. Considering these forces can often be compressive, it is not supprising that laminates buckle under these loads, leading to wrinkles. Slowing the displacement again may further reduce the required force, but it would likely result in a prohibitively long forming time.

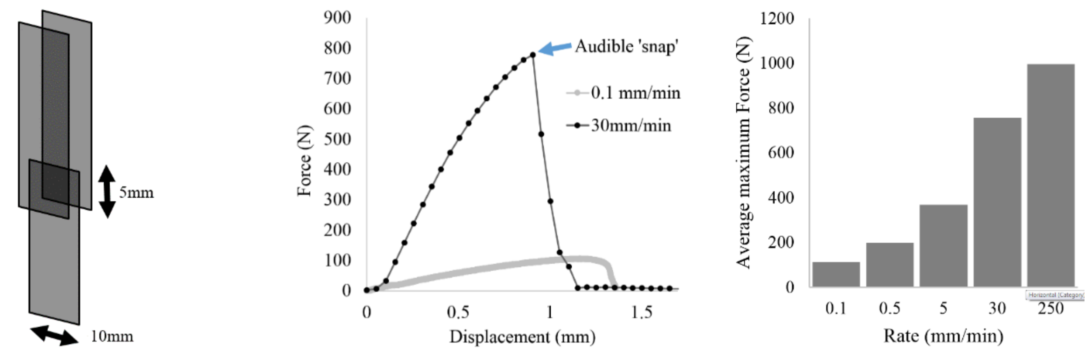

Figure 5. Schematic of the double lap shear samples (left), example results showing difference in failure at high and low speed (middle), and average max. force during double lap shear tests at different rates (right).

2.3. Forming trials

To achieve the forming trials with a small thin ply a method previously used by Newell and Buckingham [6] was adopted, and consisted of a large foam block being lowered onto the mould, as shown in the schematic in Figure 6. The foam block was attached to a compressive test machine, providing precise displacement control at very low speeds, allowing the forming rate to be dramatically reduced when needed. The exact crosshead speed was somewhat arbitrary and so the different trials were classified by the approximate forming time instead. The chosen mould for the tests was a hemisphere with an ~70mm radius, and the plies were circles of 100mm diameter. All tests were carried out at approximately 22-24°C and repreated three times. Ply slippage requirements was estimated to be 3-4mm, and was deemed proportional to the requirements in the originally observed forming test.

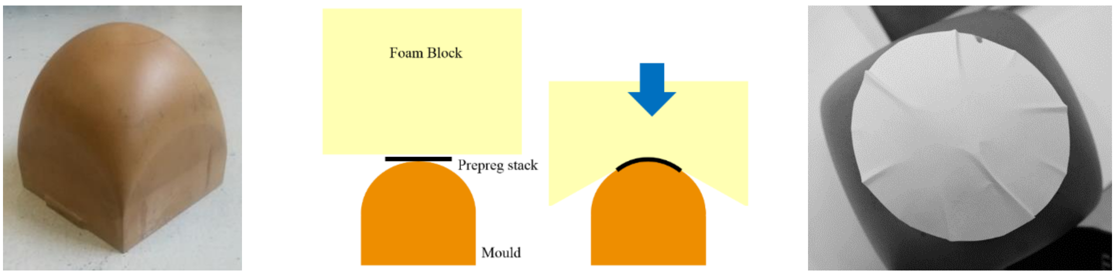

Figure 6. Tooling used for forming (left), schematic of foam block forming (middle), and results of forming the block with an inextensible sheet (right).

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Initially trials were conducted using circular plies of cross-plied 0.90 material, which, due to the ply and mould surface being circularly symmetric could equally be considered as 45.135. Forming trials were conducted at three rates - 1s, 10s, and 1 hour; Figure 7 showing examples of the forming process results. The trials formed in 1s and 10s all formed four distinct wrinkles at the outer edge while the trials formed over an extended period of 1 hour all formed wrinkle free. This suggested that forming rate is highly influencial on the forming of cross-plied laminates, and dramatically reducing the forming rate may eneable wrinkling defect issues to be overcome. It is likely that a successful results could be achived much faster than the 1hr trial shown here, which could be regarded as an extreme case.

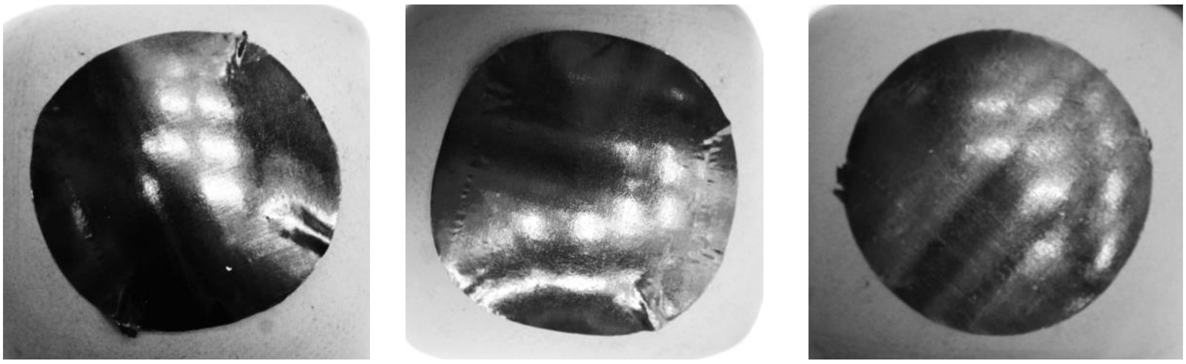

Figure 7. Example results from the forming of cross-plied UD laminates at rates of 1s (left), 10s (middle), and 1hr (right).

These tests were then repeated using the [0.90, 45.135] preform and over a wider range of forming rates. Figure 8 shows examples of the resulting formed laminates. The ‘fast’ forming trials both wrinkled, as did the 1hr samples which had worked previously for the cross-plied case. Unofortunately even when forming was extended to over 20hr, severe wrinkling was still present, though many of the smaller wrinkles had disappeared.

Figure 8. Results when forming [0.90, 45.135] preforms at different speeds, from left to right: fast (<0.5s), medium (10s), slow (1hr), very slow (2hr), and ultra-slow (20hr).

Finally further trials were conducted with different sized plies over a mould with a much reduced curvature of 230mm, Figure 9. Using a 1hr forming time, 100mm and 70mm plies still wrinkled severly, but a 50mm ply was able to form wrinkle free.

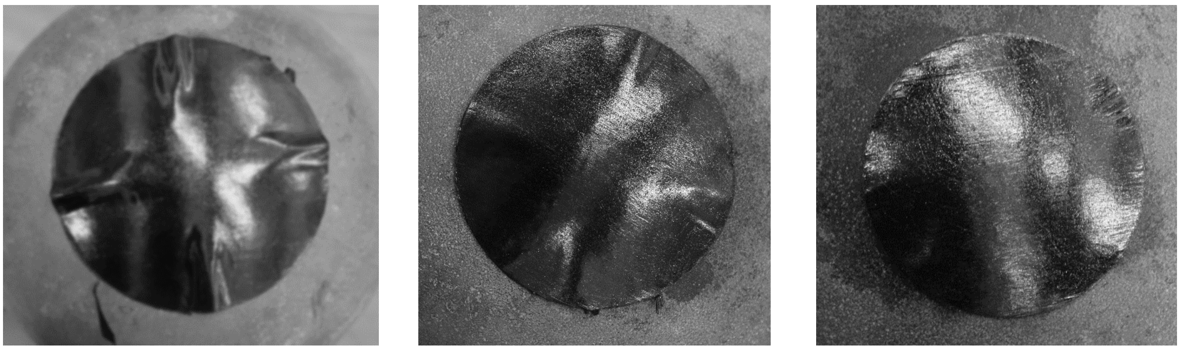

Figure 9. Results when forming [0.90, 45.135] preforms over a 230mm radii tool at a 1hr forming rate, but with ply diameter sizes of 100mm (left), 70mm (middle), and 50mm (right).

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3. Discussion

As is evident from the results in Section 2, forming trials for [0.90, 45.135] preforms were largely unsuccessful in producing wrinkle-free structures; suggesting that additional techniques are impossible to go without, to allow for the forming at room temperature of conventional large plies of prestacked laminates material. Increasing preform thickness to accommodate balanced and symmetric quasi-isotropic layups demonstrated the same behaviour. Clearly relaxation of the industrial regulations and constraints encountered in this work will help in this regard, despite the recertification challenges it would present, although historical and recent examples in spars, such as [20-22], also suggest that significant development works would still be required in taking this approach. Should relaxation of the manufacturing conditions be forthcoming then adopting some of the techniques listed in Section 1.1 may be able to provide an effective solution to the wrinkling problem, and examples such as [23] may also be able to serve as a route to downselect the appropriate technique.

That being said, the relative success of the forming of cross-plied preforms at room temperature opens up another potential avenue to that available in the present literature - i.e. the forming of the eventual laminate in preform sections. Rather than attempting to form the whole quasi-isotropic laminate at once, blocks of exclusively 0.90 or 45.135 plies could be formed individually and progressively. Naturally this will require a revaluation of conventional composites design principles, although this could be argued to be already taking place in some regard [24-25]. Beyond the conventional design principles such an approach would also have quite specific manufacturing challenges, such as the operation of multiple pick and place movements from the layup table to the mould, as well as productivity evaluations (perhaps similar to [26]). If this approach was to be adopted then immediate further work would be needed to asses how slow a rate they (the preforms) actually need to be formed at, and if this time is economically viable. Such viability assessments should include simulation (perhaps through tools such as [27]), estimates on learning curves and equipment efficiencies, as well as the more typical metrics.

4. Conclusions

The results of this work has shown that a sufficiently slow forming rate is crucial to achieving a wrinkle free layup when forming cross-plied laminates over double curvature shapes at room temperature. A trial component was formed wrinkle-free in one hour, but much faster forming is potentially possible, depending on the adoption of more novel forming inputs and/or modiication of the acceptance of allowable defects. Conversely, for [0.90, 45.135] preforms it has been shown that forming rate alone is simply not sufficient to allow for defect-free forming, apart from on very small plies with minimal curvature (thus requiring very minimal interply slippage). Even increasing the forming time to unrealistically long time spans could not prevent wrinkling during forming. While slowing the forming rate can help reduce the in-plane stiffness, the drop in apparent viscosity between plies will also likely reduce the out-of-plane stiffness of the laminate. This could in principle lower its resistance to bending and forming wrinkles, potentially counteracting any gains made from enhanced interply slippage.

Acknowledgments

The authors would like to acknowledge funding from the EPSRC Centre for Innovative Manufacturing in Composites (CIMComp) (Grant: EP/IO33513/1).

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