INVESTIGATING THE SHEAR BEHAVIOUR OF MULTI-PLY WOVEN CARBON FIBRE REINFORCED PA6 COMPOSITE LAMINATES

George. E. Street[1] and Michael. S. Johnson[1]

[1] Department of Mechanical, Materials and Manufacturing Engineering, University of Nottingham, Nottingham, UK

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ABSTRACT

The intra-ply shear behaviour of fibre reinforced thermoplastic laminates heavily dictates thermoforming behaviour. Accurate intra-ply characterisation is therefore required, especially as an input for thermomechanical simulation, in the push to reduce costly trial-and-error methods and improve process control. In this work, in order to understand how shear behaviour of multi-ply laminates can differ to conventional single-ply studies, bias extension tests were conducted to evaluate the intra-ply shear behaviour of carbon fibre reinforced polyamide-6 laminates of different ply-thicknesses. Initial results showed that single-ply laminates exhibit a higher shear stress response when compared to multi-ply laminates. It was hypothesised that this behaviour was attributed to thermal deconsolidation, leading to a reduction in the laminate volume fraction and therefore, the shear resistance. This is due to an increased level of thermal deconsolidation, the growth of voids mostly between adjacent plies, that occurs with the increasing number of laminate plies. To test this theory, pressurised bias extension tests were conducted to reconsolidate each laminate. The reconsolidated tests yielded shear curves approximately 72% higher than those for a conventional single-ply laminate. These results yielded a large error, and therefore further work is required to establish an accurate relationship between deconsolidation and shear resistance. Furthermore, this work implies that, for accurate thermomechanical simulation, deconsolidation levels should be considered such that the correct shear curve matches the forming operation.

1 INTRODUCTION

In recent years, the use of fibre reinforced composite (FRC) materials has grown exponentially, due to the attractive properties that they exhibit compared with conventional isotropic materials. While they pose an attractive proposition, issues such as long manufacturing time, poor recyclability and difficult joinability all present challenges to the composites industry. Continuous fibre reinforced thermoplastic (FRTP) composites aim to meet the challenges posed by thermoset FRCs. The increasing demand for FRTP components comes with a drive for improved FRTP sheet manufacturing processes. This includes improved process modelling, with the objective to reduce the reliance on costly and time-consuming trial-and-error methods and optimise process control. These simulations are a focus of much current research on a numerical level [1-4], including the generation of reliable material characterisation data to depict accurate material forming behaviour.

The numerical characterisation and modelling of FRTPs, while similar to dry fabrics, is generally more complex due to the temperature and rate dependence of the viscoelastic material [5]. Several different modes of deformation including: intra-ply, inter-ply and out-of-plane mechanisms, are required to achieve sufficient geometric conformity in thermoforming processes [6]. While all of these modes are important, intra-ply shearing is one of the most prominent during forming of woven FRTP, as investigated by Sharma *et al*. [7]. The in-plane shear stiffness of a composite laminate is a dominant factor in the developement of wrinkles during forming, especially over areas of double curvature [8]. It is therefore important that accurate intra-ply shear characterisation is conducted for input into forming simulations.

While evaluating the shear behaviour of FRTPs has been done previously, the majority of these studies focused on single-ply shearing; therefore not including the effects of ply interaction during the shearing process. This includes an array of single-ply picture frame testing [9-14] and single-ply bias extension testing [8, 13-19]; the two most commonly used approaches to evaluate shear behaviour.

Intra-ply shear behaviour of multi-ply FRTP layups has been assessed in a select few published studies. McGuinness and Bradaigh [20, 21] conducted picture frame tests using 16 consolidated plies of Glass Fibre (GF)/PA12, evaluating laminate shear response over a range of temperatures. The authors largely focused on the development of rheological models and early methods to interpret the results of the picture frame test. Dangora *et al.* [10] evaluated the shear behaviour of a cross-ply unidirectional thermoplastic composite, consisting of 4 plies, where laminate compaction is used to enable the pin-jointed-network (PJN) assumption. Zomer *et al.* [22] conducted a similar study in which the shear behaviour of a cross-ply CF/PA6 layup (8 plies) was evaluated. Guzman-Maldonado *et al.* [23] used the bias extension test in conjunction with a 5-ply 8-harness GF/PA66 layup to propose a new constitutive model for the forming simulation of FRTP prepregs at the macroscopic scale.

While these select works consider the shearing of multiple FRTP plies, no attempt was made to compare the shear response of single- and multi-ply laminates. The aim of this study was therefore to understand the influence of laminate ply-count on intra-ply shear behaviour for a woven CF/PA6 composite layup. The authors proposed the comparison of intra-ply shear responses for a range of different CF/PA6 laminate configurations and investigated the possible discrepancies between single- and multi-ply intra-ply shear behaviour.

2 METHODOLOGY

2.1 Intra-ply Shear Characteristion

The two most common approaches adopted to evaluate FRTP laminate intra-ply shear are picture frame tests and bias extension tests. Picture frame testing describes the rhombus shearing of a laminate when tensile forces are applied across its opposing corners after being mounted in a bespoke rig. On the contrary, bias extension testing involves clamping a rectangular piece of woven or cross-ply material such that the tows are oriented at ±45° to the applied tensile force.

Due to the edge effects associated with the cool clamps in picture frame testing, difficulties maintaining perfect specimen alignment (critical for picture frame analysis) and maintaining the larger specimens at a constant temperature over the whole surface arise [10]. While work to overcome these issues is ongoing, such as that by Mattner *et al*. [11], bias extension tests can be considered a viable alternative; the yarns in the centre shear zone are all free at their ends. They therefore do not experience any tension during testing, reducing the impact of edge effects caused by the material clamping. Furthermore, bias extension specimens are usually smaller, making consistent sheet heating easier to achieve. Because of this, the bias-extension method was chosen for intra-ply shear characterisation in this work.

The fibrous nature of a woven FRTP laminate leads to three distinct shear zones: A, B and C, as illustrated in Figure 1. Zone A consists of a region of undeformed material, hence the shear angle, γ_{12} = 0. Zone C is the region of particular interest, where pure shear is enacted on the specimen due to both weft and warp yarns having free ends. Zone B is a region in which one yarn direction is clamped at its end, therefore exhibiting a shear strain approximately half that of zone C.

The shear angle in zone C, γ_{12}, can be related to the vertical displacement of the upper gripper of the tensile tester, δ [14]:

$$\gamma_{12} = \frac{\pi}{2} - 2 \cdot \cos^{-1}\left(\frac{\delta + (H - W)}{\sqrt{2}(H - W)}\right) \tag{1}$$

Where H and W are the height and width of the specimen respectively. This equation is applicable up until slippage between individual tows (intra-ply slip) occurs; this limiting shear angle is material dependent, usually lying between 40-50˚ [13].

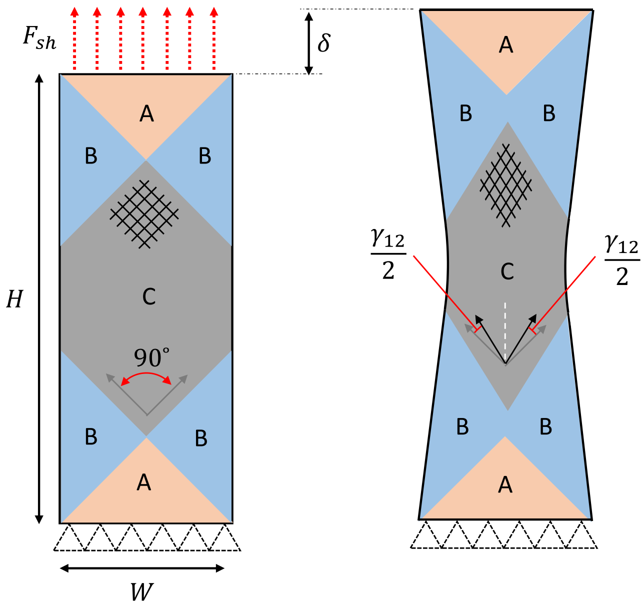

Figure 1: Bias extension intra-ply shear characterisation.

Many previous works use the derivation from Cao *et al.* [17] for the normalised shear force with respect to the shear angle, related to the specimen dimensions and applied tensile force. This relationship is rate-independent and assumes that the power produced due to the external force is dissipated in zones B and C. Harrison and Härtel [18] conducted a thorough investigation into the different normalisation methods available, concluding that for a rate-dependent material, an alternative derivation by Harrison *et al.* [13] is likely the most suitable. This derivation is based on a Newtonian fluid approximation and is aimed at reducing the 'shear softening effect' outlined by Machado *et al.* [16]. The softening effect is a phenomenon in which the shear force with respect to the shear angle is underestimated due to the region C not only dominating the shear strain response but also the shear strain rate response. The normalised shear force, F_{sh}, can therefore be expressed as:

$$F_{sh}(\gamma) = \frac{\left(\frac{H}{W} - 1\right)}{\left(2\frac{H}{W} - 3 + 2X\right)} \frac{F}{\frac{\sqrt{2}W}{2}} \tag{2}$$

Where F is the axial force. Furthermore, X, a function of shear angle, can be defined as:

$$X = \frac{1}{4}\left\{\frac{\cos^2(\gamma_{12})\left[1 + 3\sin^2\left(\frac{\gamma_{12}}{2}\right)\right]}{\cos^2\left(\frac{\gamma_{12}}{2}\right)\left[1 + 3\sin^2(\gamma_{12})\right]}\right\} \tag{3}$$

Finally, the shear stress, τ_{sh}, is defined using the following equation including sample thickness, t:

$$\tau_{sh} = \frac{F_{sh}(\gamma)}{t} \tag{4}$$

These equations enabled shear stress *versus* shear angle curves to be produced.

2.2 Material

Testing was undertaken with carbon fibre (CF) reinforced polyamide-6 (PA6) laminates, denoted 'BÜFA® WF-tex CF-PA6 (1/2/4/8)p 2x2T 0/90', produced by BÜFA Thermoplastic Composites GmbH & Co. KG. Four different laminate configurations were acquired for testing: 1-ply (0.22 mm thickness), 2-ply (0.46 mm thickness), 4-ply (0.97 mm thickness) and 8-ply (1.94 mm thickness). Individual plies were woven in a 2x2 twill pattern and stacked homogeneously at 0/90°, with each laminate exhibiting a fibre volume fraction of 50 ± 2 wt%. The specimens were waterjet cut to achieve the required dimensions; measuring 210 mm by 50 mm, allowing for 30 mm of clamping at each end. The test area was therefore 150 mm x 50 mm, exhibiting an aspect ratio of 3. The material properties, as provided by the manufacturer, are in Table 1.

Reinforcement	Fibre	Carbon fibre (CF)
	Fabric	Woven 2x2 twill
	Areal weight	200 g/m^2
	Yarn	200 tex
Matrix	Polymer	Polyamide 6 (PA6)
Laminate	Density	1.8 g/m^2
	Fibre content	50 ± 2 wt%
	Ply thickness	0.22 mm

Table 1: FRTP laminate properties.

The thermal behaviour of the CF-PA6 laminates was determined using differential scanning calorimetry (DSC). A small sample of the chosen FRTP was heated from 50 ˚C at 10 K/min up to a maximum of 300 ˚C, from which it was cooled at the same rate back down to 50 ˚C. It was deduced that the sample was fully melted at a temperature of approximately 223 ˚C, and for a cooling rate of 10 K/min, the onset of crystallisation is shown to be approximately 190-195 ˚C. The crystallisation onset point for PA6 is however, heavily linked to the cooling rate, as shown by Kugele *et al*. [24].

2.3 Experimental Procedure

Bias extension tests were conduced using an Instron 5581 Universal Testing Machine, equipped with a 1 kN load cell. To achieve the desired specimen temperature, an Instron 3119-607 environmental chamber was equipped with closed-loop temperature control. Specimens were clamped in place using four sprung bolts to compensate for the slight reduction in laminate thickness during heating that causes normal fastenings to become loose. The experimental setup is illustrated in Figure 2.

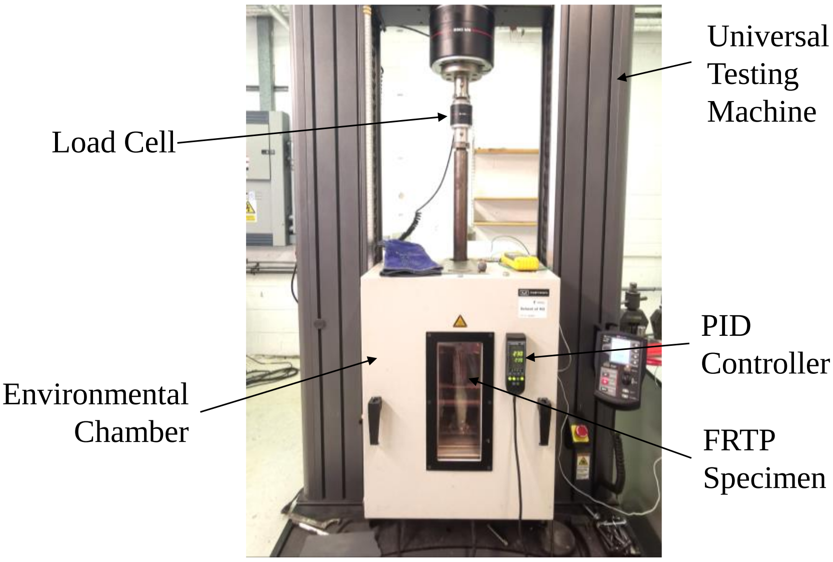

Figure 2: Experimental apparatus.

For the purposes of this work, bias extension tests for the four individual laminate configurations were conducted at a fixed temperature of 230 ˚C (above the melt temperature dictated by the DSC analysis) and fixed rate of 100 mm/min. Testing was conducted following a 10 minute dwell at the prescribed test temperature to ensure the specimens were fully molten. Two repeats was undertaken for each sample to improve the confidence in obtained results.

3 RESULTS

The output from the bias extension tests for each individual study was a force *versus* displacement curve, as recorded by the universal testing machine. Normalised shear force *versus* shear angle curves were obtained utilizing Equations 1-3. Figure 3a illustrates this for the single-ply laminates, in which the three datasets (two repeats) are plotted. Each curve can be broken down into three distinct sections: an initial realignment of fibre yarns at low forces resulting in a steep initial gradient in force response (i), followed by a steady-state section of laminate shearing (ii), and ending with a steep upturn in recorded force as the laminate approaches its locking angle (iii).

A high level of repeatability was observed between repeats, especially prior to the occurrence of intra-ply slip around 45˚, verifying the suitability of the test method.

To combine the three datasets, a 5th order polynomial in the form of Equation 5 was fitted using a Levenberg-Marquardt algorithm, also illustrated in Figure 3a. The fitting process was completed without the inclusion of shear angle data greater than 45˚ due to the uncertainty surrounding results upon the incidence of intra-ply slip. Therefore, for the rest of this work, these data are not included.

$$\tau = [a_1\gamma^5 + a_2\gamma^4 + a_3\gamma^3 + a_4\gamma^2 + a_5\gamma] \tag{5}$$

This procedure was repeated for the three multi-ply laminates in order to compare between them. To eliminate the thickness dependence of the normalised force output, Equation 4 was implemented for each polynomial to produce the desired shear stress *versus* shear angle curves for each laminate thickness. These experimental *versus* shear angle curves are illustrated in Figure 3b.

To quantify the absolute difference between each laminate ply-count, each curve was normalised by dividing it by its respective mean value, thus centering each curve around a ‘relative shear stress’ value of 1. A master polynomial was then calculated once again using a Levenberg-Marquardt algorithm, resembling Equation 5. This is illustrated in Figure 3c.

Finally, this master polynomial was subsequently fitted to each result curve by multiplying it by a shifting factor, C, as per Equation 6. While this procedure does naturally induce a small amount of error in the shear stress *versus* shear angle results, the error is limited to a maximum of $\approx \pm 5\%$. Moreover, this process further simplifies the mathematical procedure since each curve can be represented by a single value, C. These fitted curves are plotted in Figure 3d.

$$\tau = C \cdot [a_1\gamma^5 + a_2\gamma^4 + a_3\gamma^3 + a_4\gamma^2 + a_5\gamma] \tag{6}$$

The four shifting factors for each laminate configuration are in Table 2. To provide a more useful representation of the individual shifting factors, it is beneficial to reference them about a fixed point. Since the vast majority of previous literature concerning FRTP bias extension testing is conducted using single-ply laminates, the single-ply result is chosen as the reference value. Therefore, the calibrated shifting factor, C_{Ref}, is deduced by dividing the original shifting factors by that of the 1-ply laminate. These calibrated shifting factors are also in Table 2.

Table 2: Absolute and reference shifting factors for the master polynomial.

	1-ply	**2-ply**	**4-ply**	**8-ply**
C	0.129	0.061	0.050	0.049
C_{Ref}	1	0.44	0.36	0.35

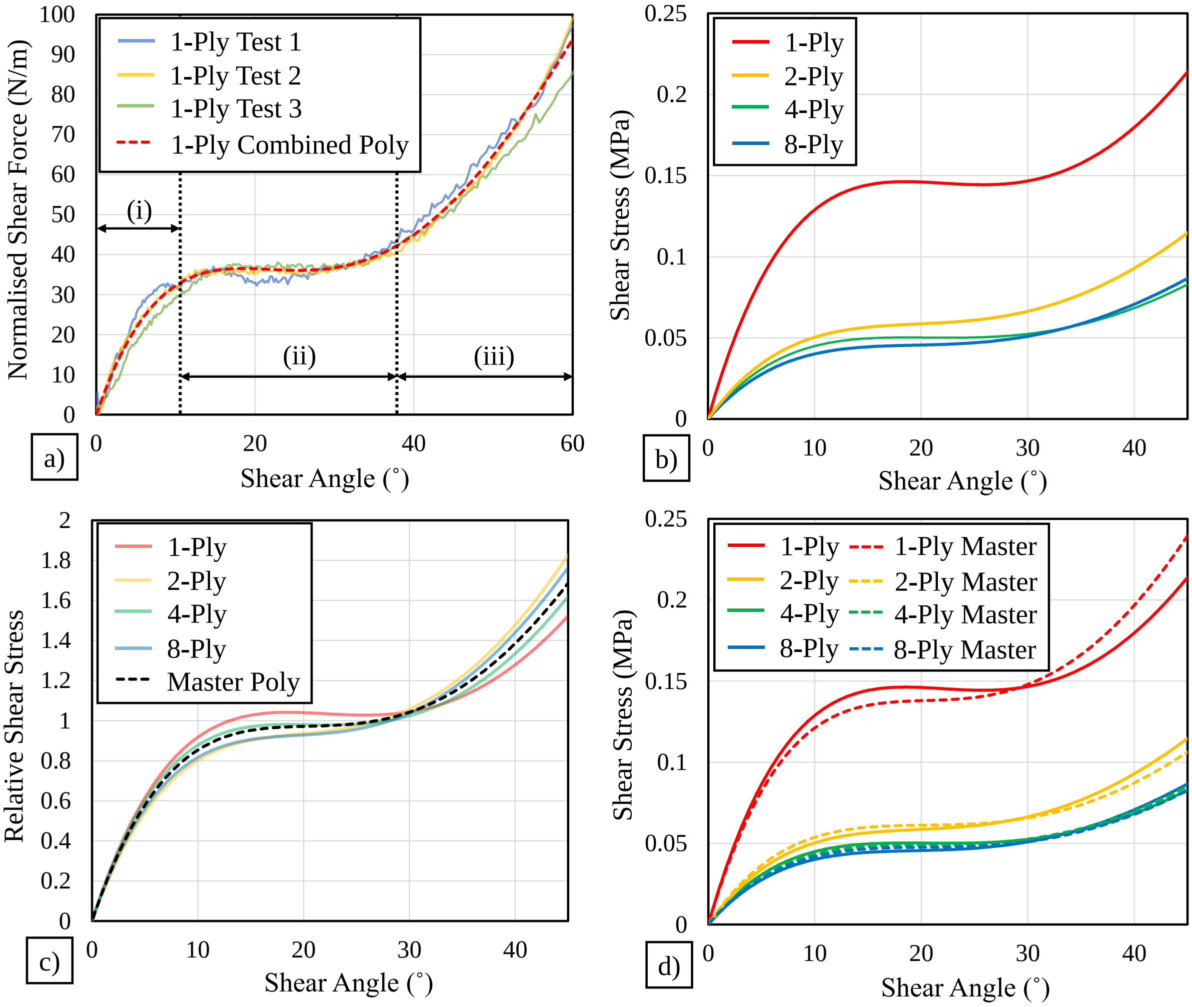

Figure 3: a) 1-ply normalised force *vs* shear angle results b) Shear force *vs* shear angle results c) Master polynomial fitting d) Master shear stress *vs* shear angle results

To understand why the shear response of a single-ply laminate exceeded that of all the multi-ply laminates under the same conditions, the thermal response of each laminate was evaluated.

Upon heating a thermoplastic composite laminate, deconsolidation occurs resulting in an increase in the thickness of the laminate [25, 26]. This phenomenon can be attributed primarily to the release of internal laminate stresses that were locked into the laminate during its production [27]. To evaluate the deconsolidation behaviour of the different laminate configurations, a small specimen of each was heated to 230˚C and dwelled for 10 minutes to allow deconsolidation to occur, before cooling below the re-crystallisation temperature. These specimens therefore represent the same laminate conditions experienced during the bias extension tests.

Figure 4 illustrates visually the thermal response on the outer surface of a 1-, 2- & 4- ply laminate after the occurrence of deconsolidation. Due to the visual similarity between 4- and 8- ply laminates, only the 4 ply configuration is depicted. For comparison purposes, also included in the figure is a fully consolidated laminate, compacted at 30 bar. From these tests, it became evident that the amount of deconsolidation a laminate undergoes (measured as a percentage change in laminate thickness) is dependent on the number of laminate plies.

To understand why the different laminates exhibit such contrasting behaviour, microscopy was used on a cross-section of both a consolidated and deconsolidated laminate. Figure 5 illustrates the results of microscopy, with the deconsolidated laminate exhibiting large voids, particularly between individual plies.

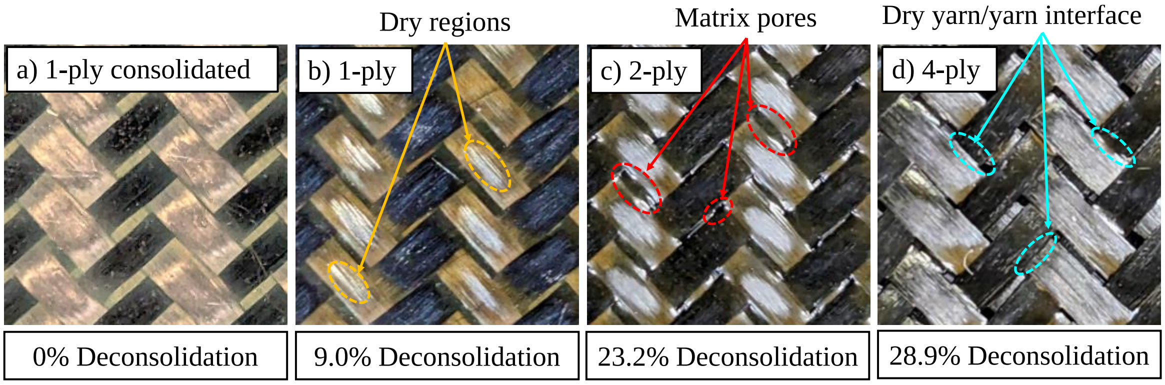

Figure 4: Deconsolidation behaviour of different laminate configurations.

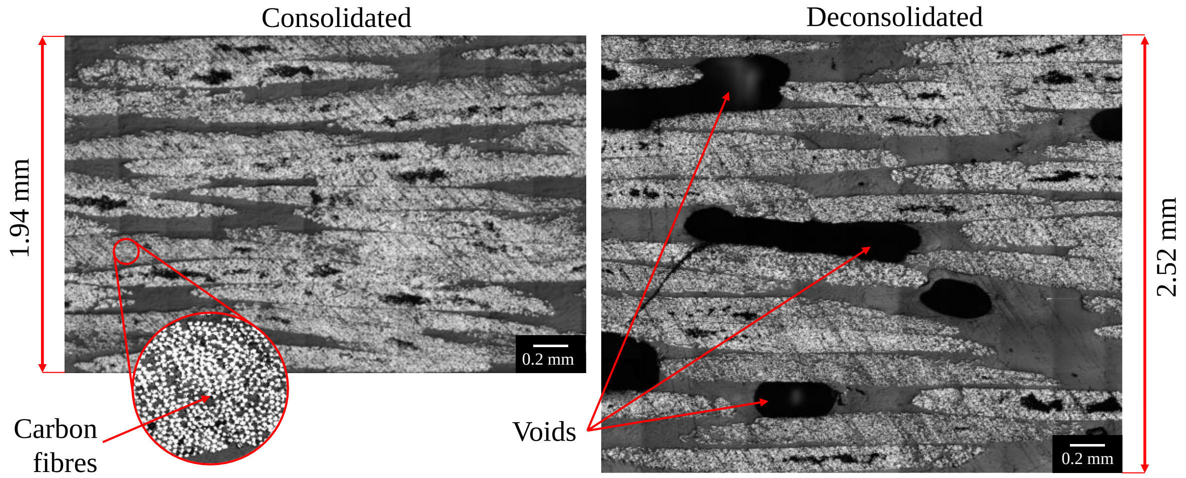

Figure 5: Microscopy of the cross-section of a consolidated and deconsolidated 8-ply laminate.

The level of deconsolidation appeared to be the only differentiating factor between the tested laminates that were exposed to the same conditions. Because of this, it was hypothesised that the four laminate thicknesses, once re-consolidated, would exhibit equalized intra-ply shear responses.

To test this theory, the bias extension apparatus was modified such that the laminate could be consolidated during the intra-ply shear process. Figure 6a illustrates the modified experimental apparatus. The samples were placed within a silicon bag, in which a vacuum could be pulled, thus consolidating the respective laminate. Previous work on deconsolidation prediction was used to verify that 1 bar would be sufficient to achieve complete consolidation [27].

Since the recorded axial force for each of the consolidated tests also included the force required to stretch the silicon bag, it was necessary to subtract this foreign force constituent, as a result leaving the force to extend solely the laminate. This was calculated by re-running a test without a laminate present. The results of this ‘dry’ test are illustrated in Figure 6b. Since the silicon material is highly elastic, it responds with a mostly linear relationship between force and displacement. Although some non-linear behaviour is exhibited after 25 mm displacement, this occurs after the critical intra-ply slip cut-off and so does not influence the results.

An example of the raw output data from the consolidated bias extension test, for the three tested 4-ply laminates, is illustrated in Figure 7a. Once again, a 5th order polynomial (in the form of Equation 5) was fitted to the three datasets in order to combine them.

Figure 7b illustrates the reduction procedure for the 4-ply laminate, in which the raw consolidated data, reduction curve, corrected reconsolidated data and deconsolidated data (from the previous experiment) are all plotted. This procedure was repeated for the 1-, 2- & 8- ply laminates.

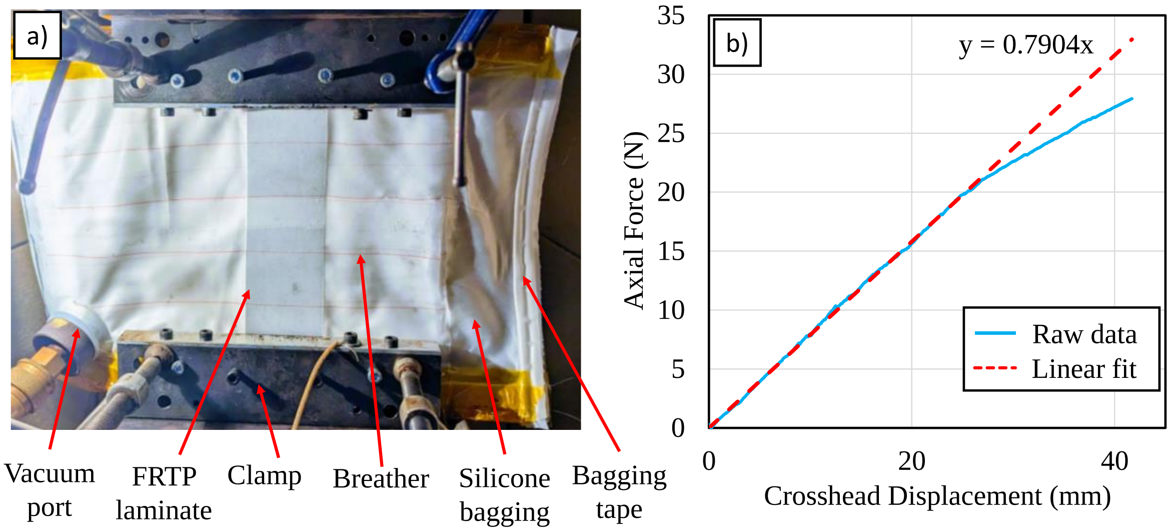

Figure 6: a) Reconsolidated bias extension test setup b) Vacuum bag reduction curve

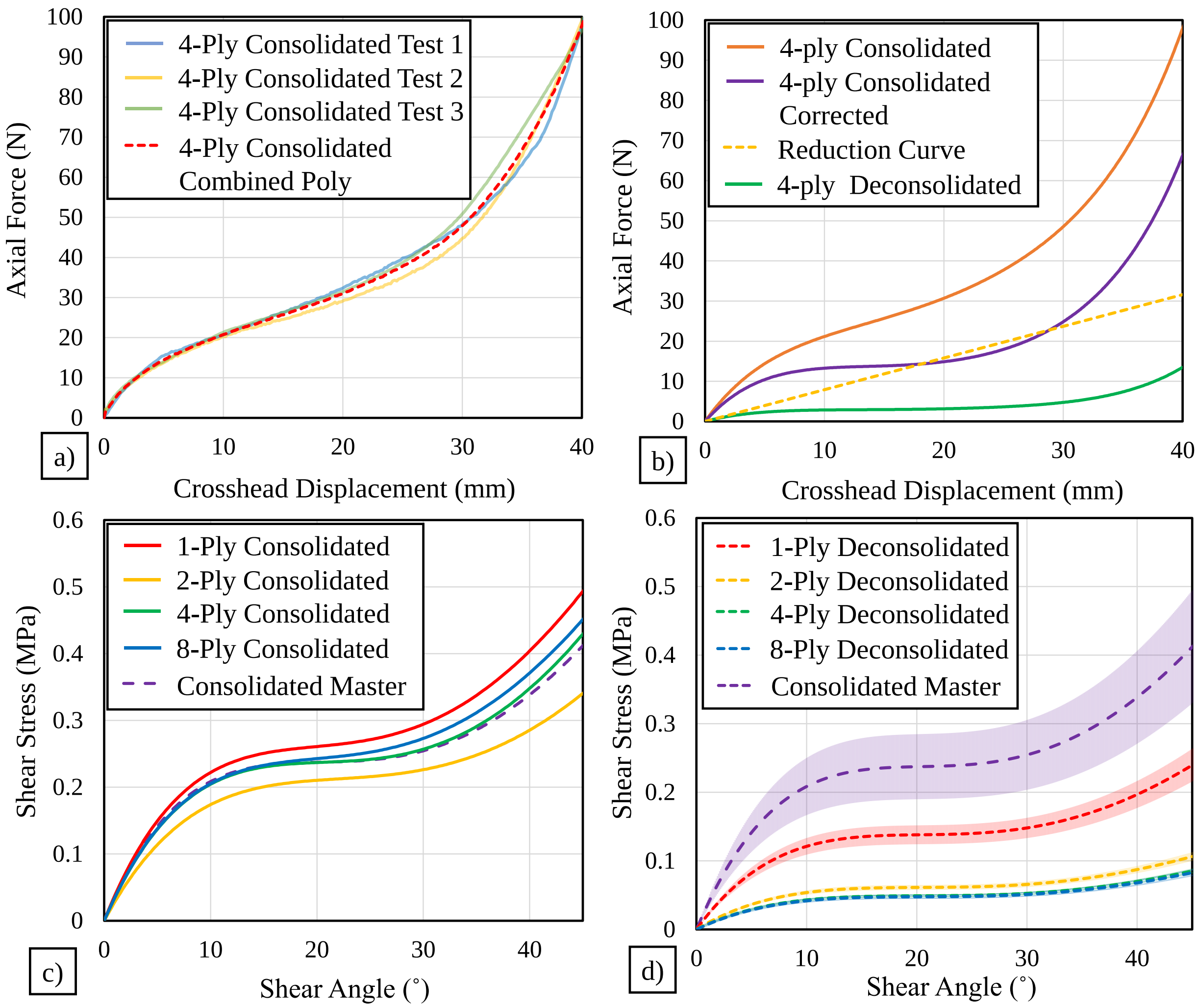

Figure 7: a) 4-ply reconsolidated raw data b) Corrected 4-ply reconsolidated curve calculation c) Consolidated shear curves and master fit d) Consolidated *vs* deconsolidated shear curves.

The corrected consolidated curves for each laminate configuration were again normalised and converted into shear stress *versus* shear angle curves using equations 1-4. Figure 7c illustrates the four shear stress *versus* shear angle curves for the four consolidated datasets. As before, the master polynomial was fitted to the four curves to resemble a master reconsolidation curve, in the form of Equation 6. The value of C_{Ref} for this curve was $1.72 \pm 20\%$. To compare between the reconsolidated and deconsolidated shear responses, Figure 7d illustrates the four deconsolidation master curves (from Figure 3d) and the new reconsolidated master curve, each with confidence intervals based on the combined experimental repeatability and master polynomial curve fitting accuracy.

4 DISCUSSION

The initial bias extension results illustrate that there is a large difference in shear behaviour between single- and multi-ply laminates. Polynomial curve fitting allowed for quantification of the difference between the shear response of each laminate; single-ply shear response being at least twice that of all multi-ply configurations. The 4- and 8-ply laminates exhibited very similar responses, suggesting that the shear response had converged at this point, roughly one third the response (0.36x and 0.35x for 4- & 8-ply respectively) of a single-ply laminate.

Studying laminate deconsolidation allowed the authors to hypothesise a cause for this unexpected behaviour. For a 1-ply laminate, the amount of deconsolidation was considered small; the only evidence being in the centre of the weft yarns (on the upper face), where localised dry regions existed. Upon the existence of multiple plies, however, the amount of deconsolidation experienced by the laminate was much greater, being 23.2%, 28.9% and 29.9% for 2-, 4- and 8- ply laminates, respectively. Voids were present between the majority of parallel yarns for all multi-ply laminates, with large dry regions present in the centre of each exposed yarn. Furthermore, some yarn/yarn interfaces also appeared completely dry for 4- and 8-ply laminates.

To understand why the different configurations appeared so visually different, microscopy analysis yielded an insight into the behaviour within a deconsolidated laminate. The consolidated laminate contained no obvious pores or voids which would have been eliminated during the compaction process. After deconsolidation had occurred, however, there was a large increase in laminate thickness, attributed to the presence of voids within the laminate structure. The majority of these voids appear to have occurred between individual plies (inter-ply) rather than within the ply itself (intra-ply), explaining why deconsolidation levels are much higher for multi-ply laminates. It is highly likely that the amount of deconsolidation is related to the number of internal interfaces; a 2-ply laminate has one internal interface, whereas a 4-ply laminate has twice the number of plies but three times the number of interfaces.

Consolidated bias extension tests were used to test this theory, with the final consolidated results illustrated in Figure 7c. While the experimental repeatability had a similar percentage error to the standard tests, since the absolute force values were so much higher, much greater experimental uncertainties ($\approx \pm 20\%$) were present in the corrected shear curves. The authors do believe, however, that upon consolidation, laminate shear behaviour does tend to equalise the shear response of the four laminates. This is reaffirmed by the lack of any obvious relationship between laminate thickness and consolidated shear response, with the four curves appearing to be spread at random.

Figure 7d compared the master consolidated result with the deconsolidated curves, including confidence intervals, illustrating that the shear response of a consolidated laminate was greater than that of any of the deconsolidated laminates. Compared to a reference 1-ply laminate, the shear response was $72 \pm 20\%$ greater. This therefore confirms that a laminates shear response is related to the laminate thickness as a secondary effect, with deconsolidation being the primary influencer.

Subsequently, a relationship between the relative shear resistance (relative *versus* a single-ply response (Table 2)) and the laminate consolidation (Figure 4) could be created, such to correct a laminates intra-ply shear curve dependent on its consolidation state. Figure 8 illustrates this relationship, including confidence intervals. A first order exponential curve, in the form of Equation 7, was fitted; x is equal to the laminate deconsolidation, and p & q are constants.

$$C_{Ref} = p \cdot e^{-qx} \tag{7}$$

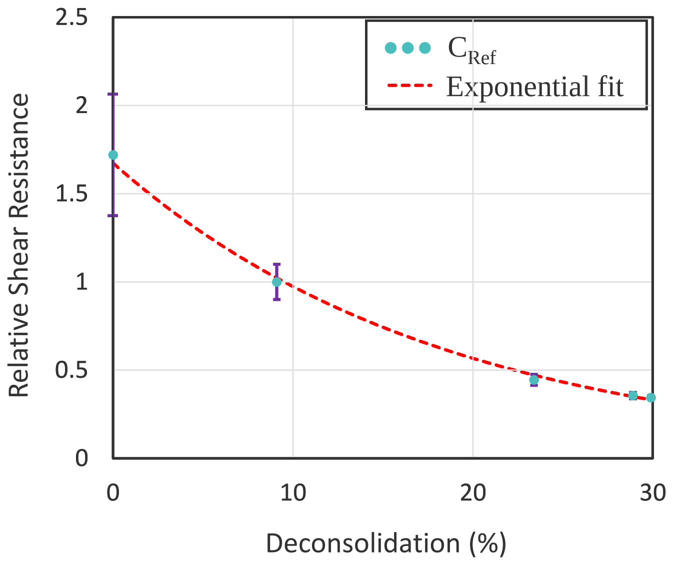

Figure 8: Exponential relationship between a laminates relative shear resistance (compared to a single-ply laminate) and its level of deconsolidation.

5 CONCLUSIONS

It can be concluded that the shear response of a laminate is heavily influenced by its ply-count, by virtue of the level of thermal deconsolidation. Laminate ply-count and thermal deconsolidation are intrinsically linked; voids occur mostly between laminate plies, meaning that an increase in the number of ply-ply interfaces leads to a subsequent increase in the amount of deconsolidation. This relationship was verified by conducting pressurised bias extension tests, thus consolidating each laminate during the shearing process. The shear response of laminates of different thicknesses, once consolidated, was roughly equalised around a value approximately 70% higher than that of a single-ply laminate. This reaffirmed the authors' initial findings, that the variation in shear response between different ply-counts is attributed to the level of deconsolidation. However, owing to the high force required to stretch the silicon vacuum bag, coupled with the complexity of the experimental setup, there was substantial error in the absolute value of the consolidated shear response.

The implications of these results indicate the importance of accounting for the level of laminate deconsolidation during the simulation of FRTP thermoforming operations. It is not a poor assumption to make, that during matched-die forming, a laminate undergoes complete deconsolidation during the shearing operation. This work therefore suggests that the fitted shear curve for accurate matched-die simulation should be approximately a third that of a reference 1-ply laminate. Likewise, forming operations that reconsolidate the target laminate during the shearing operation, such as diaphragm forming, require an elevated shear curve for accurate thermomechanical simulation.

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