INTER AND INTRA-PLY SHEARING OF UNCURED CARBON FIBRE LAMINATES

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Abstract

The shear behaviour of uncured carbon fibre prepreg is fundamental to avoiding process-induced defects during manufacturing of large-scale components. Shear tests for AS4/8552, are compared to a one-dimensional elastic-plastic model for combined intra-ply shear and inter-ply slip. The paper presents a methodology capable of determining the parameters of temperature and pressure at which minimum resistance to movement for a prepreg exists. Investigating the joint strength and friction values individually shows that friction increases with temperature, contrary to previous work, and that the new value of joint strength is predominant at lower temperatures. Rate dependency arises as an issue to be discussed in future work.

1. Introduction

Although over the past thirty years the basic advantages of composites laminates have been well proven, they are often compromised by high costs and long development times due to the inherent difficulties of manufacturing large scale components, such as those found in aerospace applications. Typically, carbon fibre composites parts are made by layering a series of thin carbon fibre layers, pre-impregnated with resin, onto a tool surface. Heat and pressure are then applied to consolidate or form the component to ensure correct seating onto the tool and promote adhesion between layers. However, the forming or consolidation of a laminate over even a simple geometry forces the layers to accommodate the imposed geometry of the tool surface. For example, consider consolidation over an external radius Fig. 1(a). As the outmost ply consolidates it is forced into a tighter geometry and to conform to the geometry layers are required to shear relative to one another. If plies are prevented from shearing or slipping interply stresses build up making manufacturing process susceptible to generating defects. These include out-plane ply wrinkling [1-2] (Fig. 1 (b)), the formation of residual stresses and part distortion [3-5] and poor consolidation [6]. To limit the possibility of such defects, the investigation of shear properties of materials is vital to understanding optimal shear conditions for manufacturability.

The mechanics of through thickness shear can be broken into two sequential stages. The initial shear response is dominated by *intra-ply shear*, whereby the shear strain is continuous across the interface between two plies. Intra-ply shear dominates until the stress within the resin rich region between plies is sufficient to yield this interface. Dislocation of the joint occurs and adjacent plies slip relative to one another, termed *inter-ply slip*. Larberg et al. [7] and Ersoy et al. [3] have investigated inter-ply slip properties of uncured carbon fibre prepregs. Each contribution generalizes the shear behaviour to interply slip only by comparing the shear behaviour with a Coulomb friction model, whereby the shear stress is independent of the shear strain. However, during forming and consolidation it has been shown that shear strains are generally relatively small (see for example Dodwell et al. [2] and or Fletcher et al. [6]), therefore the purely frictional model dramatically overestimates the associated shear stresses, in regions where intra-ply mechanics are more dominant.

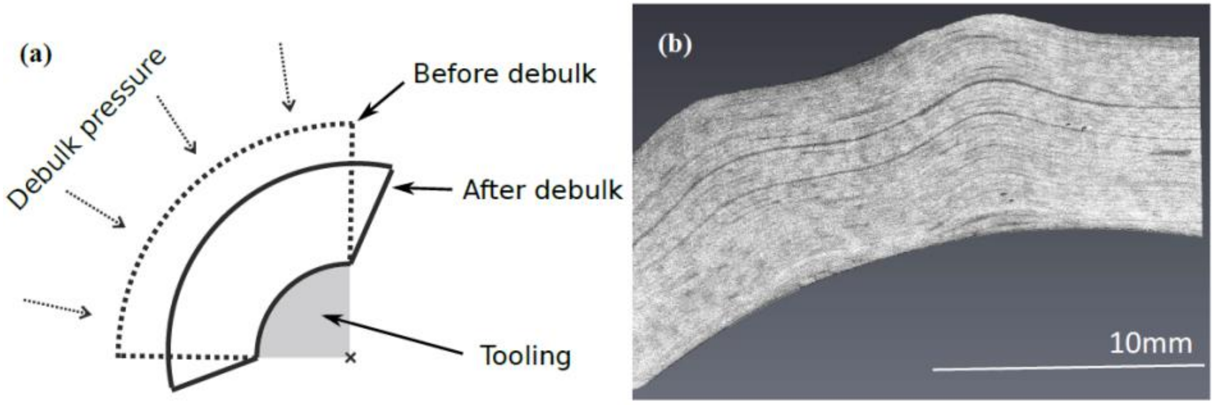

Figure 1. (a) A representation of the shear induced as a laminated is consolidated over a corner radius and layers are free to slip over one another. **(b)** CT image of a typical wrinkle defect within a corner, arising due to the inability of layers to slip over one another.

In this paper, the influence of temperature and normal pressure on through thickness shear properties of uncured AS4/8552 prepreg is investigated. Section 2 describes the experimental test rig (Fig. 2 (a)) and procedure. The resulting load traces (Fig. 2 (b)) are fitted to a one-dimensional elastic-plastic model (Section 3) which combines intra-ply shear and inter-ply sip. The results presented in Section 4 extend past work in this area by separating the two mechanisms, where the results suggest that the overall shear resistance of AS4/8852 is minimised at approximately 90^{o}C. Section 5 discusses possible micro-mechanisms involved with intra-ply shear and inter-ply slip, the implications of the results to material selection and manufacturing process and the limitations of the analysis pesented.

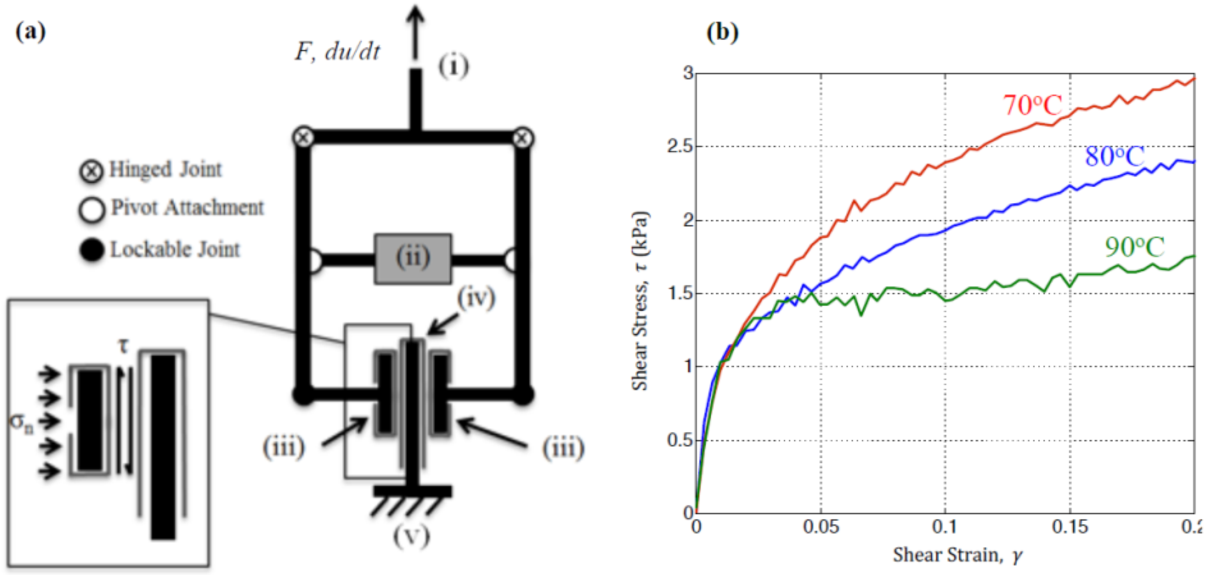

Figure 2. (a) Schematic of interply test rig in which the two individual parts moving apart at constant rate *du/dt* and the required force *F* recorded. **(b)** Load traces for shear tests, for 70, 80 and 90^{o}C with a normal stress (σ_n) of 75kPa.

2. Experimental Procedure and Initial Results

2.1. Experimental Procedure

Fig. 2 (a), shows a schematic of the test rig which consists of two independent components. Firstly a lock-able hinged array, connected to an Instron load cell at (i), consists of a pneumatic cylinder (ii) which pulls together two plates (area, A = 50x50 mm^2) wrapped in carbon fibre prepreg (iii). These plates clamp either side of a central plate (iv), also wrapped in carbon fibre prepreg, which is fixed to the bottom mounting of an Instron testing machine (v). The rig is mounted within an environmental chamber, allowing the temperature of test to be controlled. The test procedure is as follows: (1) test temperature is achieved in the environment chamber (2) the pressure in the pneumatic cylinder is controlled to generate a normal clamping stress σ_n between the side and central plates. (3) The Instron pulls the upper part of the rig at a constant rate *du/dt*, whilst the load cell records the force *F*.

All experiments were carried out using Hexcel's AS4/8552 [8], which were wrapped around each plate so that the fibres were oriented vertically (i.e in the direction of loading). Furthermore, for each test, the rate of deformation *du/dt* was kept at a constant 0.1mm/min, a recommended shear rate for manufacturing processes [7]. Tests were carried out across a range of temperatures (40-100^{o}C) and confining pressures σ_n (25-100kPa). The test program is summarised in Table 1.

Temp. (^{o}C)	40	50	60	70	80	90	100
σ_n (kPa)	25/50/75/100	75	25/50/75/100	75	25/50/75/100	25/50/75/100	75

Table 1. Test Program, showing range of temperatures and pressures investigated.

2.2 Comparison of initial experimental results with existing literature

Fig. 2 (b) shows the 3 typical load traces obtained from the shear tests. Each trace shows a similar response to those displayed by Larberg et al. [7], whereby each graph has two distinct regions. The first region, characterized by an initial stiffness, can be attributed to the shear behavior at small strains, primarily dominated by *intra-ply shear*. The secondary stiffness is the stiffness post yield, which appears to have a typical *strain-hardening* response, which is pronounced at lower temperatures. From similar load traces, Larberg et al derive a coefficient of friction. Not only does such a model ignore the initial small strain shear response but due to the post yield stiffness, it is unclear how a simple coulomb friction type model could be fitted. In the following section we introduce a one-dimensional elastic-plastic model, which captures the initial intra-ply shear behaviour at small strains, and the post yield stiffness.

3. One-dimensional elastic-plastic model for combined inter and intra-ply shear

We consider the initial shear response to be the elastic response to intra-ply shear, characterized by

$$\tau = G\gamma, \tag{1}$$

where G is the elastic intra-ply shear modulus, $\gamma = du/dv$, where dv is double ply thickness, du is in-plane deformation, and $\tau = F/2A$ where A is the area of a plate (see Section 2). The onset of inter-ply slip is defined by the Mohr-Coulomb yield criterion

$$\tau_c = \mu\sigma_n + j, \tag{2}$$

such that μ is the coefficient of friction, σ_n is the normal stress and j is a measure of interface/joint strength. Suppose that yield has occurred (i.e. $\tau \geq \tau_c$) then an additional strain increment is applied $\Delta\gamma$. This strain increment can be decomposed into an elastic $\Delta\gamma_e$ and a plastic (frictional) contribution $\Delta\gamma_p$, so that $\Delta\gamma = \Delta\gamma_e + \Delta\gamma_p$. It follows from Eq. (1) that

$$\Delta\tau = G\Delta\gamma_e = G\left(\Delta\gamma - \Delta\gamma_p\right) \tag{3}$$

The hardening rule is then defined by

$$\Delta\tau = H\Delta\gamma_p, \tag{4}$$

for which H, the *strain-hardening parameter*, describes how the yield criterion changes due to inter-ply slip. Combining the Eq. (3) and Eq. (4) the post yield response is given by

$$\Delta\tau = G_t\Delta\gamma \qquad \text{where} \quad G_t = G\left(1 - \frac{G}{G+H}\right) \tag{5}$$

where G_t is termed the *consistent tangent stiffness*. Rearranging Eq. (5) for the strain-hardening parameter gives the expression

$$H = \frac{GG_t}{G - G_t}. \tag{6}$$

This gives an idealized bi-linear response, as shown in the stress-strain plot Fig. 3 (a). The modelling parameters can be approximated from the experimental stress-strain data by firstly constructing two tangents lines with gradients G and G_t (see Fig. 3 (a)), and then calculating the yield stress τ_c as the shear stress at which these lines intercept. Repeating shear tests for a range of normal stresses σ_n, the Mohr-Coulomb friction law, Eq. (2), is approximated. This process is shown in Fig. 3 (b), a plot of σ_n against τ_c, whereby the gradient gives the coefficient of friction μ and the y-intercept the joint strength j.

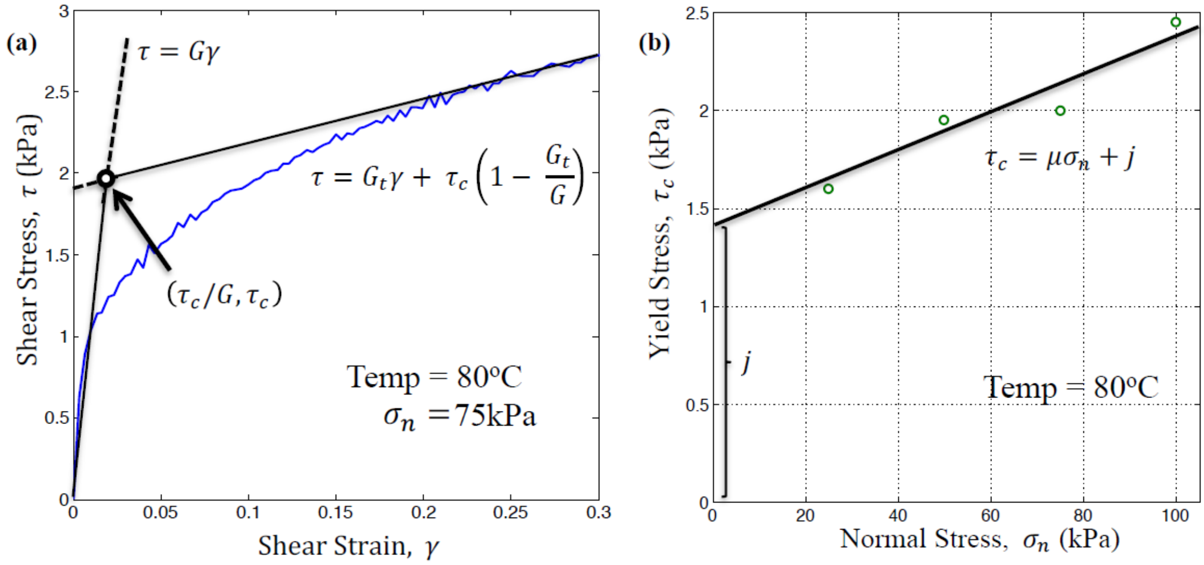

Figure 3. (a) The bi-linear stress-strain response for the one-dimensional elastic-plastic model with combined inter and intra-ply shear. The plot is characterized by two lines, which describe the shear response pre and post-yield ($\tau > \tau_c$) respectively. **(b)** Plot of yield stress against normal stress for a given temperature, coefficient of friction and joint strength can be approximated by calculating the gradient and y-intercept respectively.

4. Results

The load traces have been discussed in Section 2, we now present results in light of the modelling parameters introduced in section 3. As described in Section 2, shears test were carried out for a range of temperatures (40-100°C) each at four different normal stresses (25-100kPa). At each temperature, the average yield stress was plotted against the normal stress as shown in Fig. 3 (b). A straight line of best fit provides experimental values for each model parameter, joint strength j and coefficient of friction μ. Fig. 4 shows how each quantity changes with increasing temperature. Joint strength (Fig. 4 (a)), a measure of the limit of intra-ply shear deformation, strictly decreases with increasing temperature. However, the coefficient of friction strictly increases with temperature (Fig. 4 (b)).

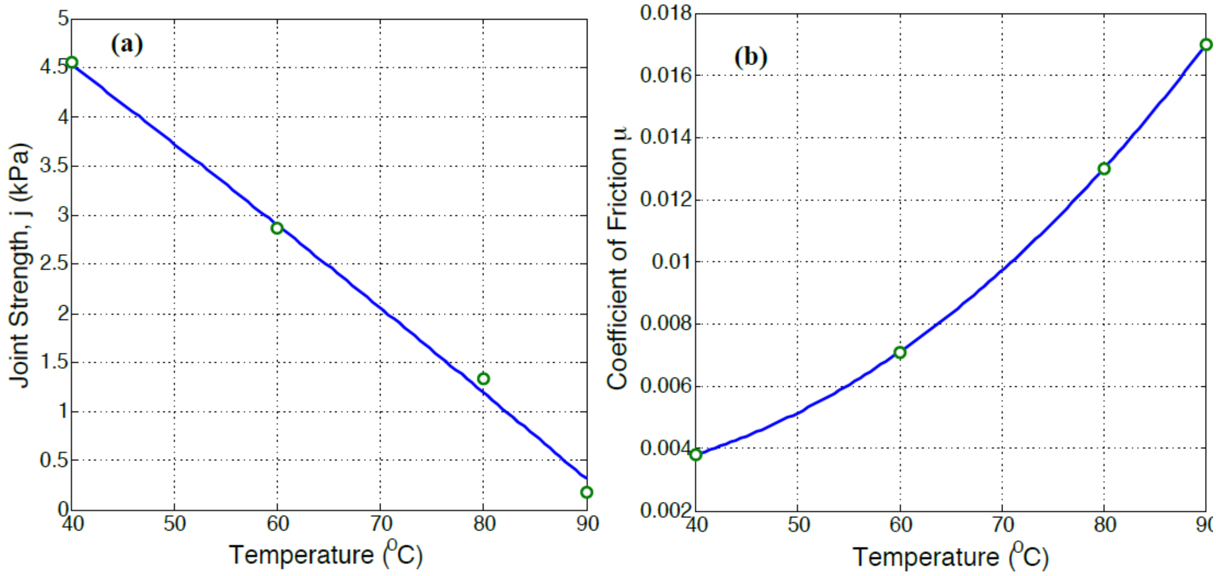

Figure 4. (a) Joint stiffness against temperature **(b)** Coefficient of friction against temperature.

The overall shear response is a combination of both joint strength and interply friction. Fig. 5 (a) shows a plot of yield stress against temperature, whereby the combination produces a minimum yield stress at approximately 90°C. The strain-hardening parameter, H, is calculated using G and G_t as described in section 3. Fig. 5 plots H against temperature, reaching a maximum at approximately 60°C before approaching 0 at 100°C.

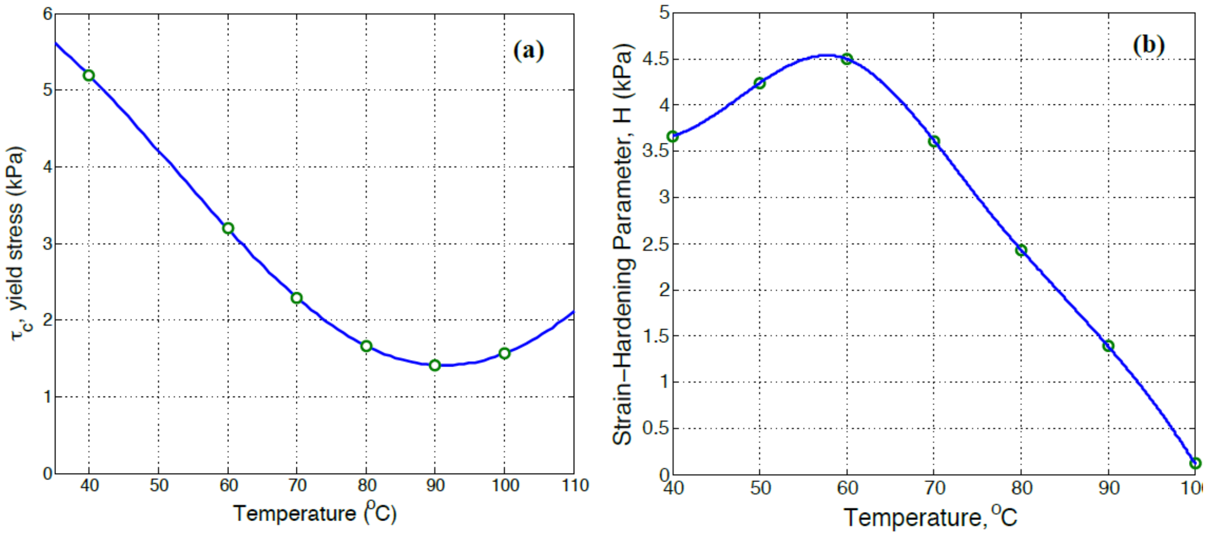

Figure 5. (a) Yield Stress against temperature at 75kPa normal stress **(b)** Strain-Hardening against temperature at 75kPa normal stress.

5. Discussion

5.1. Combined intra and interply shear behavior

Fig. 5 (a) appears similar to results presented by Larberg et al. [7] and Dodwell et al. [9], who both plotted coefficient of friction at yield against temperature. This plot differs in that τ_c is a combination of the effects of friction, μ, and the new parameter, joint stiffness j. The plot shows an initial decrease in τ_c as temperature increases, reaching a minimum at 90°C, after which τ_c increases with temperature. The general shape of the curve agrees with Larberg et al. and Dodwell et al. [7-9]. Dividing the shear into two separate mechanisms, as shown Fig. 4, gives a better insight into the combined mechanics which contribute to τ_c.

Comparing the values of j in Fig. 4 (a) with the values of τ_c in Fig. 5 (a) we see that the parameter j dominates at lower temperatures, where the contribution to τ_c from μ , Fig. 4 (b), is very small. This suggests that intra-ply shear plays a more significant role at low temperatures. However, μ increases with temperature, whilst the value of j decreases. From Fig. 5 (a) the minimum reached at 90°C marks the point at which inter-ply slip becomes the dominant mechanism. The behaviour of μ is particularly important. Previous work presented μ as a value with behaviour similar to the value of τ_c in this work, suggesting that μ is initially high at low temperature then falls to a minimum value before increasing again with temperature. This new model shows μ to be minimal at low temperatures then strictly increasing as temperature increases.

This suggests that at low temperatures the fibres within each ply are separated by a thick layer of resin, formed from the resin rich zones present on the surface of each ply. This reduces the inter-ply friction between fibres and the response is dominated by the shearing of the resin rich region. As temperature increases the resin layer is initially maintained, with the softened response being due to the lower shear modulus of the material at elevated temperature. As the temperature rises further the resin redistributes into the dry core of the plies, increasing fibre-fibre contact between adjacent plies. At this stage the increased level of fibre-fibre contact means that the results are almost purely frictional. Figure 6 (a) shows a cross section of unconsolidated 8552 prepreg and Figure 6 (b) shows a cross-section of the same material after it has been heated to 80 °C and had a normal stress of 100kPa applied to it.

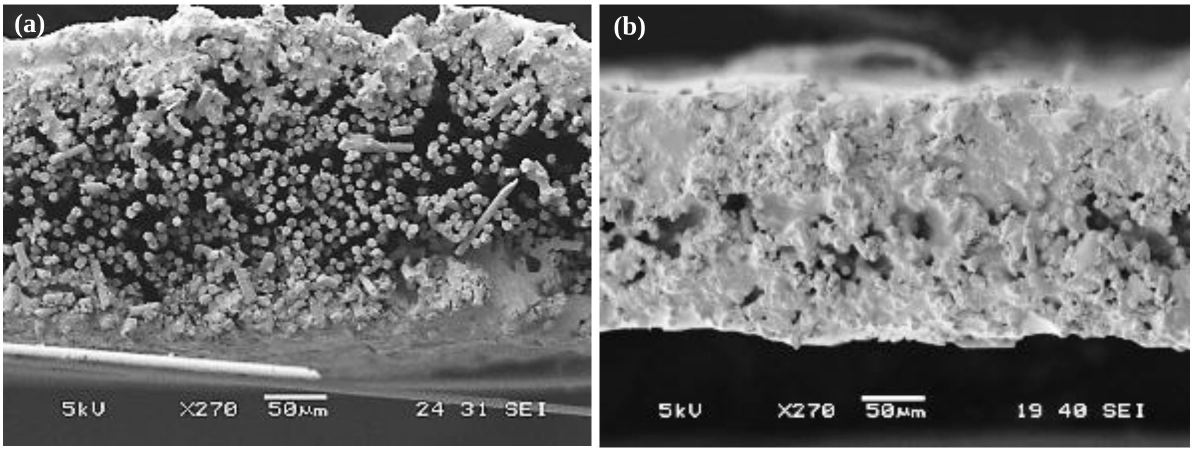

Figure 6. (a) Cross-section of uncured, unconsolidated AS4/8552 prepreg (x270) **(b)** Cross-section of AS4/8552 prepreg post consolidation at a temperature of 80°C (x270)

Figure 6 (a) shows a large amount of resin towards the edge of the ply, with a very noticeable dry core. By contrast, in figure 6 (b) the resin appears to be distributed fairly uniformly following consolidation at temperature, with more fibres on the outer edge. There is also a noticeable reduction in ply thickness as the resin has redistributed. This supports the hypothesis that low temperature interaction will be dominated by the resin layer, whereas high temperature interactions will be increasingly influenced by fibre-fibre contact.

The degree to which resin contributes at lower temperatures shows limitations with the elasto-plastic model, as resin is a visco-elastic material and therefore rate of deformation will affect the material response. In order to understand the viscoelastic behaviour of the resin it will therefore be necessary to investigate this rate dependency. This is an area for future investigation.

5.2. Post yield hardening

The post yield hardening is of particular interest. Fig. 3 (a) displays the load trace for a test conducted at 90°C with a normal pressure of 75kPa. The initial intra-ply elastic region discussed in section 2 can be observed as the steep initial gradient, before the yield point leads into the region of post-yield hardening. The phenomenon of this post yield stiffness or hardness can also be observed in the load traces presented by Larberg et al. [7]. Confidence in the rig function has been obtained by conducting a test whereby PTFE was wrapped around the plates rather than CFRP, resulting in a flat post yield response as expected of a frictional material, with a coefficient of friction of 0.096 which falls within the expected range for this material. This confirms that the post yield hardening is due to the material and not the test setup. It is thought that this hardening effect is due to the relatively slow rate at which the tests are conducted. This could result in the liquid resin reforming the joint once it has failed, progressively increasing the resistance to load as the reformed joint must be continuously yielded. Fibre pullout tests conducted by Dodwell et al. [9] employed a much higher rate of deformation of 1mm/min, and the load traces obtain showed little or no evidence of post yield hardening, suggesting the rate was sufficient to prevent reforming of the interface.

6. Concluding Remarks and Future Work

A new model has been presented that combines elastic and plastic behaviour. This model avoids the overestimation of yield stress acquired from a purely frictional (plastic) model, and avoids the underestimation presented by a purely elastic model. The combination of these two behaviours allows for increased accuracy when considering shear strain levels encountered during the forming of production parts. The model is a first step however as the yield point predicted and subsequent change in gradient of the stress/strain trace is instant, whereas experimental load traces show a more gradual transition. As a result the model slightly overestimates the yield stress.

The test methodology has successfully identified the point at which minimum resistance to slip occurs. For AS4/8552 prepreg this is at a temperature of 90°C. For other materials it is expected that a similar minimum resistance point will also be temperature dependent. Defining the optimum pressure for minimum resistance to slip is more complex. At 90°C we can see that the response is friction dominated, therefore it can be assumed that slip would be best achieved at zero pressure. Certain applications require the use of pressure however. In the example discussed in Section 1 the aim is to achieve maximum consolidation through the use of pressure. As such the pressure effectively both drives and restricts the slip. It therefore becomes necessary to balance the pressure required to consolidate the part against the pressure required to allow plies to slip within the laminate.

Further tests will be carried out at elevated temperatures in excess of 100°C in order to attempt to capture the increase in resistance described by both Larberg *et al.*[7] and Dodwell *et al.*[9]. Future proofing of the developed model will also require the investigation of different materials of varying generations of thermoplastic reinforcement.

An area of further interest is the investigation of combined load scenarios, in particular the bending and shearing of an uncured laminate. This process results in significant amounts of both inter and intra-ply shear, with these mechanisms contributing to the work done in bending the laminate. Investigations will begin on a ply level looking at how intra-ply shear contributes to bending stiffness using a combination of Dynamic Mechanical Analysis and the Pierce Cantilever test. Once the behaviour of a single ply is understood it will be possible to isolate intra and inter-ply characteristics during the bending of an uncured laminate.

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