THE INFLUENCE OF FIBRE ANGLE AND RESIN PROPERTIES ON UNCURED INTERPLY SHEAR

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Abstract
Inter-ply shear is a vital mechanism when forming uncured laminates to complex geometries. Previous work focused on characterising this mechanism for $0^o - 0^o$ ply interfaces, comparing them to a visco-elasto plastic model consisting of a pre-yield stiffness and some residual post yield stiffness, connected by a Mohr-Coulomb yield criterion. These results are insufficient when considering industry standard laminates however. Work in the literature has observed ply orientation to have a significant influence on formability. Shear tests are therefore conducted for a range of interface angles and pressures. The results suggest that the geometric roughening with increasing interface angle of the fibrous region of the ply relative to the isotropic resin interface region, is responsible for both the stiffening of the pre-yield response and the weakening of the post-yield response. In the former case, this is due to improved stress transfer to the resin, whilst in the latter it is due to the reduced fibre-fibre contact between plies.

1. Introduction

Whilst the basic advantages of composite materials are well proven, they are often compromised by high costs, long development time, and poor quality due to manufacturing defects. This is particularly noticeable in the complex large scale structures found in aerospace applications. If laminates are to conform to a surface with curvature during either forming or consolidation processes, plies within a laminate must shear relative to one another. If plies are prevented from shearing the process becomes susceptible to generating various manufacturing induced defects, for example out-of-plane ply wrinkling [1-4] (e.g. Fig. 1), part distortion [5-7] and poor consolidation [8]. To limit the formation of defects it is important to characterise the shear properties of the uncured prepreg materials to determine optimal operating conditions for manufacturability, whilst also providing input parameters for predictive process simulations [3, 9] and manufacturing design methods [10].

1.1 Experimental characterisation

Over a series of contributions [10, 11] a bespoke experimental setup has been developed to determine interply shear characteristics of plies with aligned fibres. The latest version consists of a pressure cylinder which clamps two carbon fibre clad plates together, with the set-up mounted in an environmental chamber before shearing them at a constant rate using an Instron load frame (Fig. 1). It is therefore possible to control rate of deformation, applied pressure and temperature in order to assess optimum forming parameters.

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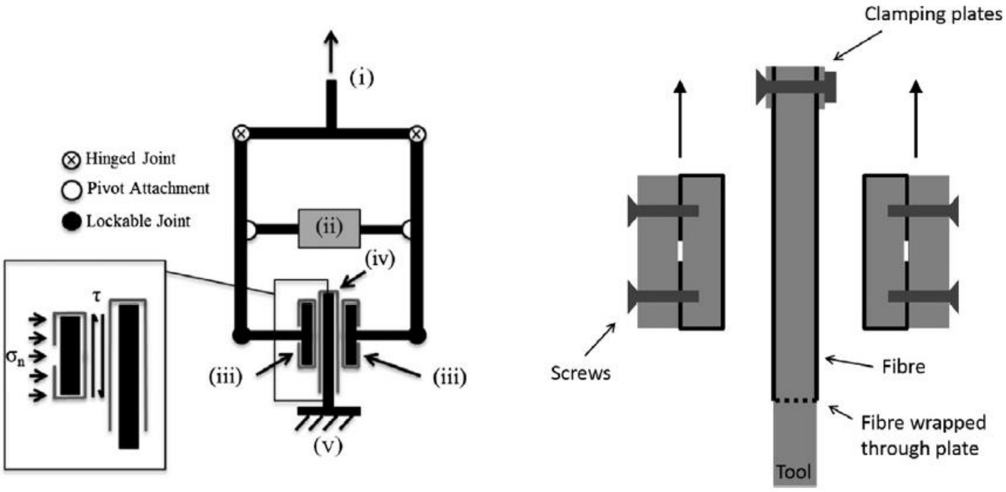

Figure 1: (Left) Schematic of the inter-ply shear rig developed in [10] in which the two independent parts move apart vertically at a constant rate and the required force recorded. Parts (i) and (v) are locked into the instron, whilst the pressure cylinder (ii) pulls the side plates (iii) into contact with the central plate (iv), at which point (i) is moved upwards at a fixed strain rate $d\gamma/dt$. (Right) Detail of the plate clamping.

1.2 Modelling material response

Initially simple coulomb friction models of the form $\tau_c = \mu\sigma_n$ were proposed for inter-ply shear, where τ_c is critical shear stress, μ is coefficient of friction and σ_n is normal pressure [11, 12]. Erland et al. [10] showed that the inter-ply shear has a strong dependence on both rate and magnitude of shear. Previous inter-ply shear models do not capture the pre-yield response or post-yield hardening typically observed. Erland et al. [10] therefore proposed a one-dimensional viscoelasto-plastic model for inter-ply shear (Fig. 2).

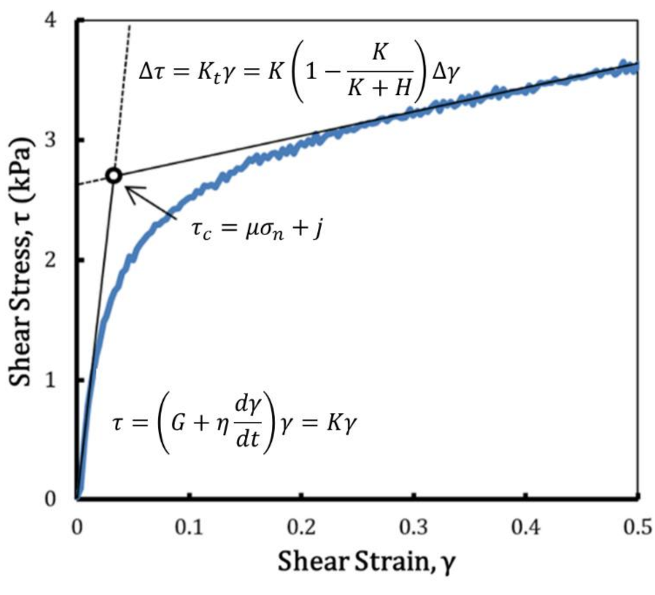

Figure 2: The bi-linear stress-strain response for the visco-elasto plastic model overlays a typical experimental load trace from [10]. The plot is characterised by two lines, which describe the shear response pre and post-yield response.

The initial response, of gradient K, comprises of an elastic initial stiffness, G, and a rate dependent component governed by a viscoelastic coefficient, η. The transition to the second response occurs around a Mohr-Coulomb yield event, differing from the simple coulomb model in its addition of a resin

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dominated joint strength, j. The post yield response is then characterised by a strain hardening parameter, H, which allows the stiffnening mechanism observed in testing to be represented.
When compared with the experimental data, the model enables a thorough interrogation of the individual contributions of the resin and fibres to the overall interply shear response. This work suggests at low temperatures (<50°C for 8552 resin) shear is dominated by the resin due the presence of a relatively thick resin-rich interface between plies. At higher temperatures, (>90°C for 8552 resin), the resin redistributes towards the fibre core, leaving a thin interface region consisting of mostly fibres. Contact between fibres of adjacent plies leads to a friction dominated response. The compromise between these two conflicting responses leads to an optimum temperature, which minimises the critical shear stress of the interface. For two AS4/8552 plies, with fibres oriented in the same direction, this optimum temperature is approximately 80-90°C.

1.3 Understanding the interaction at the ply-ply interface

Work to date has focused solely on the shearing at a 0-0° interface. Whilst this has provided a great deal of insight into the mechanisms behind interply shear, the behaviour of interfaces consisting of dissimilar angles must be considered if the results are to be applied to any laminate used in industry. Work by Hallander et al. [13] clearly highlights that altering the stacking sequence of angled plies has a noticeable effect on formability of a part, with laminates with large numbers of orthotropic interfaces forming more readily than those with blocks of similar plies. From the discussion in [10], it is clear that the shear behaviour at the interface of two plies is heavily influenced by the manner in which the fibrous regions of the two plies interact at the interface. Whilst the two resin films will readily combine into a single layer, the fibrous regions, particularly when angled, will remain as two distinct bodies. The frictional behaviour will therefore be dependent upon the apparent roughness of these bodies, which will be a function of the dimensions of the fibres, and their relative angle to one another. Investigation of the topography of a ply using a Talyscan surface roughness measurement device should therefore allow a greater understanding of the interaction. In section 2 we discuss the modifications to the methodology presented in [10] required to be able to investigate angled interfaces and the methodology employed for the surface roughness measurements, before presenting results in section 3. The implications of these results and the mechanics driving them are discussed in section 4 before conclusions are drawn in section 5.

2. Methodology

The methodology presented in [10] was strictly adhered to, along with the operational caveats. The only deviation in methodology was the rotation of the side plates, resulting in their resembling diamonds rather than squares. In order to ensure that this change in leading edge geometry did not influence the results a proofing experiment was run whereby the plates were kept in the square orientation, with the fibre wrapped at a 45° angle. Comparisons with the results from the rotated side plate at a similar angle showed an insignificant variation, within the standard error range. As the rotation of the side plates was significantly easier to set up this was chosen for the final methodology. A brief description of the methodology is presented in section 1.2, with the detailed methodology being available in [10]. Initial testing on angles > 45° showed a tendency towards excessive intra-ply shear, with the ply disintegrating rather than slipping as a single body, rendering the methodology unsuitable for angles in the range of $45^o < \theta \leq 90^o$. The full range of tests conducted can be seen in Table 1, with each result being repeated 3 times.

In order to help better understand the interaction at the interface of two plies, a series of surface roughness measurements have been taken using a Talyscan 150 non-contact imaging machine, capable of providing a 3D image of the surface of a sample to a resolution of 1µm. Whilst this will not show a perfect image of the fibrous region due to the resin layer, it should give some indication as to the structure at the fibre-resin interface, allowing a better understanding of the physical interaction between plies at the interface. The tests were performed on a single ply of unconsolidated 8552/AS4 prepreg cut to be 6x6mm, at room temperature.

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3. Results

All values of initial stiffness, *K*, strain hardening parameter, *H*, and critical shear stress, τ_c gathered during the tests are shown in Table 1. Typically, *K* increases with angle, *H* reduces with angle and τ_c remains unaffected.

Table 1: Experimentally derived values of K, H and τ_c for varying pressure, σ_n, temperature, and interface angle, θ. Tests were conducted at a rate R = 0.1mm/min.

		Temperature (ºC)											
		40			**60**			**70**			**90**		
θ	σ_n (kPa)	K	H (kPa)	τ_c	K	H (kPa)	τ_c	K	H (kPa)	τ_c	K	H (kPa)	τ_c
0-0	**50**	81.3	1.08	5.20	66.0	3.19	2.86	-	-	-	-	-	-
	75	81.2	1.47	5.15	64.6	4.10	3.09	62.2	4.14	2.85	54.8	1.30	2.89
	100	77.9	2.13	5.26	63.5	4.91	3.46	-	-	-	-	-	-
0-10	**50**	-	-	-	75.1	2.40	3.41	-	-	-	-	-	-
	75	90.0	1.32	5.29	71.9	2.92	3.61	69.2	2.93	2.79	59.1	1.01	1.83
	100	-	-	-	73.3	3.42	3.75	-	-	-	-	-	-
0-20	**50**	-	-	-	82.5	1.47	3.68	-	-	-	-	-	-
	75	93.9	1.24	5.49	84.3	2.66	3.85	-	-	-	62.4	0.85	1.82
	100	-	-	-	78.6	3.13	4.07	-	-	-	-	-	-
0-45	**50**	95.3	0.97	5.36	81.6	1.48	3.87	-	-	-	-	-	-
	75	95.6	1.46	5.34	82.5	2.33	4.14	80.6	2.20	2.92	65.6	0.57	1.96
	100	92.4	1.86	5.49	85.9	2.86	4.20	-	-	-	-	-	-

The change in joint strength *j* and coefficient of friction μ with increasing angle is shown in Table 2. μ strictly decreases with angle, whereas *j* increases. Regression coefficients are also displayed.

Table 2: Experimentally derived regression coefficients for values of *j* and μ.

	Temperature (ºC)						
	60				**40**		
θ	μ	j (kPa)	R^2	θ	μ	J (kPa)	R^2
0	0.0071	2.86	0.915	**0**	0.0038	4.95	0.960
10	0.0082	3.01	0.885	**10**	-	-	-
20	0.0042	3.54	0.919	**20**	-	-	-
45	0.0039	3.83	0.731	**45**	0.0027	5.2	0.669

A plot pre-yield stiffness *K* against interface angle θ at 60ºC and pressure $\sigma_n = 75$kPa is shown in Fig. 3 (Left). The test response shows an initially rapid increase in *K* with changing θ with the response plateauing as it approaches 45 degrees. Strain hardening parameter, *H* is plotted against θ for three different pressures at 60ºC in Fig. 3 (Right), showing an initial rapid reduction with increasing θ before plateauing as it approaches 45 degrees. Increased pressure results in increased values of *H*.

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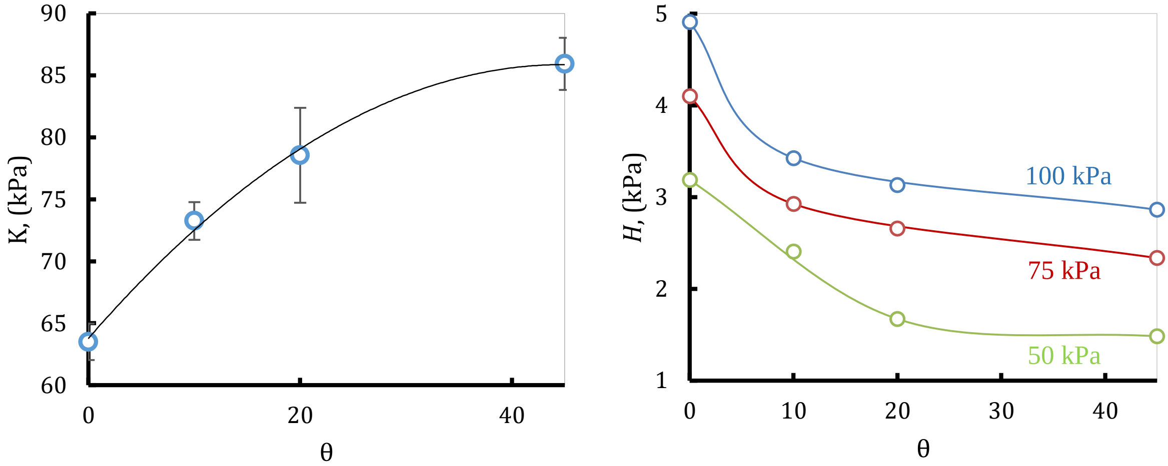

Figure 3: (Left) Initial shear stiffness, K, against interface angle, θ. Tests were conducted at a temperature of 60ºC, rate R = 0.1mm/min and normal pressure σ_n = 100kPa. **(Right)** Strain hardening parameter H against interface angle θ. Tests were conducted at a temperature of 60ºC and rate R = 0.1mm/min.

4. Discussion

4.1 Initial Stiffness and Critical Shear Stress

The initial stiffness recorded is the shearing of the two ply structure prior to the yielding of the resin interface. In [10] it is observed that the initial response is resin dominated, being dependent upon rate of deformation and temperature. The observed increase in initial stiffness as θ increases from 0º to 45º (Fig. 3 (Left)) is a result of the manner in which the rigid fibre bed transfers load to the viscous resin interface. Shear stress in the resin is generated as the fibres are drawn through it. In the $0^{\text{o}} - 0^{\text{o}}$ configuration the applied load from the test rig is aligned with the fibre orientation, so the resulting movement occurs along the surface interface of the fibrous region. If we consider a cross-sectional view with the 0º fibre running from left to right this can be simply visualised as a smooth rigid body moving through a smooth viscous body (Fig. 4 (Left)). In this instance stress transfer to the resin interface occurs as purely as a result of the surface roughness of the fibres, and the sizing applied to it.

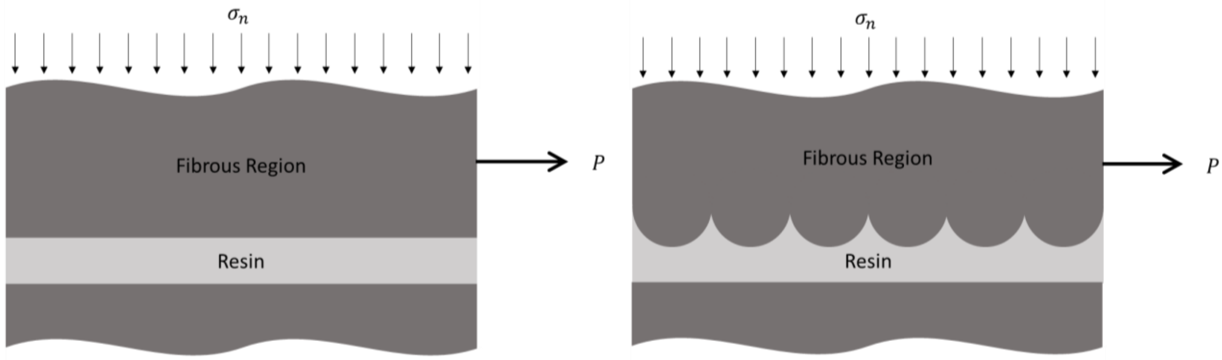

Figure 4: (Left) Cross sectional view of fibre-resin interface for a 0º ply and (Right) a 90º ply. The geometry induced roughening of the surface of the fibrous region is of particular importance.

As θ approaches 90º the fibrous bed begins to move at an angle to the fibre orientation. This results in a non-flat geometry at the interface, which becomes increasingly rough as θ increases. Stress transfer therefore becomes influenced not just by adhesion and fibre roughness, but the geometry of the fibre-resin interface in the plane of movement.

From Table 2 we can see that τ_c is not significantly influenced by interface angle. For some temperatures there appears to be a slight increase, whilst others show a slight decrease. The variation falls within the expected error range however, leading to the assumption that no change occurs. This supports the

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suggestion in [10] that this yield is a physical debond in the isotropic resin layer, and thus occurs at the same shear stress regardless of interface angle and the apparent stiffness of the resin. This is in contrast to the findings of Scherer et al. [14], however it should be noted that the yield value they report is from a comparatively simple model which does not consider both pre and post-yield response.

It is important to note that this behaviour assumes the fibres act together as a rigid body and do not pull apart as a result of the increasing tendency towards intra-ply shear as θ approaches 90^{o} discussed in Section 2. For this test setup the rigid body assumption can be considered valid due to the manner in which the fibres are clamped.

4.2 Post-yield Response

Plotting strain hardening parameter, H, against interface angle, θ, displays a reduction in hardening with increasing θ (Fig. 3 (Right)). Work from [10] suggests that the post yield region is influenced by the level of fibre-fibre contact between plies arising during intermingling. The observed decrease in H seen in Fig. 9 is considered to be due to fibre packing at the interface. A 0-0^{o} interface provides optimum packing density, and therefore the greatest degree of fibre-fibre contact. Even a slight misalignment between plies will drastically reduce the amount of fibre-fibre contact, resulting in the sharp decrease in observed hardening. A tendency for increased hardening at around 60-70^{o}C was also noted in [10] and observed in Table 1 with the hypothesis being that if the resin is free to flow, it may allow some reforming of the interface post yield. If the flow of resin is hindered by angled interfaces, as suggested in the initial stiffness response, this could impede joint reformation, promoting the physical dislocation of ply interfaces which was considered to lower post-yield stiffness.

The values of coefficient of friction, μ, and joint strength, j, displayed in Table 2 appear to support the discussion. We can see that μ strictly decreases as θ approaches 45^{o}, supporting the hypothesis that increasing geometrically induced surface roughness leads to a reduced frictional contribution to the critical shear stress. Countering this we see a constant increase in j with θ, this time supporting the idea that the surface roughness aids in stress transfer from the fibrous region to the resin interface. It should be noted that the regression coefficients shown in Table 2 are significantly worse than those gathered for similar values in [10]. This is in part due to being drawn from just three different pressures rather than the preferred four, but also due to the effect of investigating another variable, orientation, and the error related to the more complex sample preparation.

4.3 Surface Roughness Measurements

The talyscan generates a 3D data cloud which can be visualised as a grayscale image (Fig. 5 (Left)). The topology shows several peaks and troughs, with a maximum amplitude of ~60μm and a wavelength ranging from 500 to 1000μm. The almost periodic nature of these features appear to be the result of some form of 'combing' to orientate the fibres during the manufacture process, as the diameter of the individual fibres is only ~8μm. By taking sections at various angles across the plot we can observe the change in roughness with fibre orientation (Fig. 5 (Right)).

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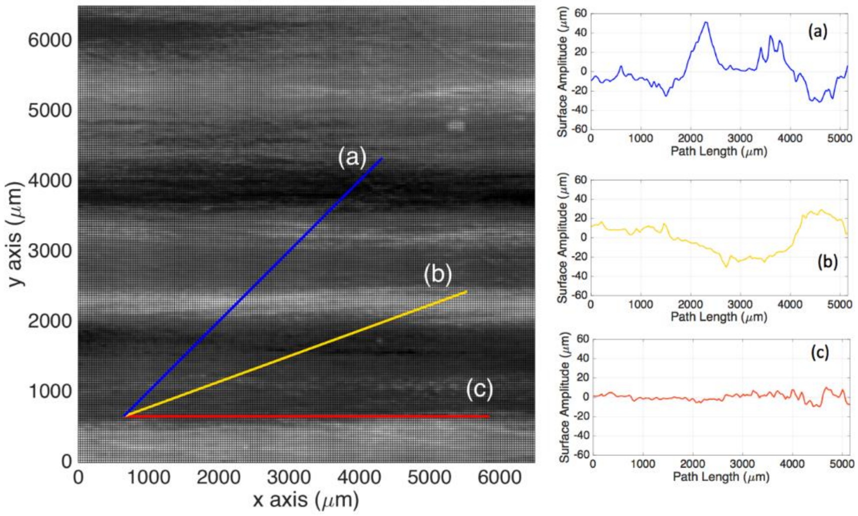

Figure 5: (Left) Talyscan image of 8552/AS4 prepreg, with the fibre orientation running from left to right across the page. The plots on the right show the surface roughness at varying angles. Line (a) runs at 45° to the fibre orientation, line (b) at 20° and line (c) at 0°

As the orientation of the slice approaches 90° we can see an increase in both the number and severity of features. The roughness increase with interface angle is therefore a result not just the fibre cross-section, as suggested earlier, but also of the cross-section of the structure those fibres form at the interface.

4.4 Implications for forming

The influence of the increasing initial stiffness with θ appears to have a negative impact, however this is tempered by the angle independent response of τ_c. This independence from angle means that so long as the required shear strain γ is greater than the critical shear strain γ_c, change in initial stiffness will have no bearing on the overall shear stress required to form. The reduction in post yield hardening with increasing angle θ is naturally beneficial to forming. This agrees with the findings of Hallander *et al.* [13], in which it is suggested that the presence of orthotropic interfaces in a laminate improves formability

5. Conclusions and Future Work

The test methodology and modelling techniques developed in [10] have successfully been used to investigate a range of angled ply scenarios. The effects of angled interfaces are significant, with a change of ~20% in values of K and H from a 0-0° interface to a 0-45°. The results of these tests have given some insight into the effects of an angled interface within a laminate, suggesting that dissimilar angles are desirable at the interface for large strain situations, as per the findings of Hallander et al. [13], but detrimental to very small strain scenarios. Importantly for the former case, increasing the angle does not increase τ_c, making control of the interface angle very effective in combatting post yield hardening. This could influence the degree to which ply blocking is utilised in the design of a laminate. The main impact of this research is its potential to influence laminate stacking sequence design. Prior to this work the output was predominantly focused on controlling the forming and manufacturing parameters, such as temperature and debulk pressure. This angled ply work now allows an insight into how the actual structure of the laminate can be manipulated in order to improve its formability. A key consideration in these tests is that the manner in which the angle plies is sheared might be considered to be unrealistic, as the angle remains constant and there is no 'scissoring' as would be expected on account of the Poisson's ratio effect when loading angled plies. Work has been planned to investigate this more complex process using a bi-axial test frame, however the simplified test presented in this paper provides a valuable insight into not just the mechanics involved in the shearing of an angled interfaces, but also several of the parameters determined in [10], principally the strain hardening parameter, H.

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A particularly interesting and complex problem presents itself when we consider the influence of pressure on formability. Data in [10] suggests that reducing pressure in turn reduces resistance to shear deformation, improving formability. However, in these tests shear deformation is imposed using an instron, whereas in reality shear deformation in a curved geometric component is driven by the very pressure that restricts it. Work in [16] investigates this effect using a custom built rig which allows the accurate measurement of the pressure driven consolidation of a laminate with some curvature, and comparing the results back to an energy minimisation model capable of predicting consolidation strain around the radius of the tool.

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