INTER-PLY AND INTRA-PLY SHEAR PROCESSES IN CONTINUOUS FIBRE-REINFORCED THERMOPLASTICS

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Unlike monolithic metallic sheets. continuous fibre reinforced thermoplastic sheets are effectively inextensible in the direction of fibres, thus are severely limited in the range of possible deformations that the sheets can undergo. The inter-ply and intra-ply shear bahaviour of the reinforced sheets play a major role in determining the formability of these reinforced sheets. The present paper describes an experimental study of the shear behaviour of continuous fibre reinforced sheets in both modes employing matched-die and double diaphragm forming methods. It also presents finite element simulations that incorporate the shear characteristics, forming speed and surface tractions. Vee-bending examples are shown to highlight the significance of these variables in both matched-die and double diaphragm forming.

(Keywords: thermoplastic composites, inter-ply shearing, intra-ply shearing, matched-die forming, diaphragm forming, finite element modelling)

INTRODUCTION

With the introduction of continuous fibre-reinforced thermoplastic composites (CFRT) manufacturers have been given new opportunities and challenges in the production techniques with these materials. In order to process them, which are commonly supplied as unidirectional fibre prepregs, thermoforming processes, such as matched-die and diaphragm forming, are employed to transform the flat sheets into three dimensional components with the application of heat and pressure.

The main advantage of matched-die forming is that both sides of the laminate touch the hard die surfaces at the end of the forming stroke, thus ensuring the desired geometry is produced with acceptable surface quality. This very advantage may, however, turn into a disadvantage in the forming of CFRTs since thickness changes naturally occur due to process related flow mechanisms[1,2], such as transverse flow, inter- and intra-ply slip. Unlike the monolithic metallic sheets, these materials are effectively inextensible in the direction of the reinforcement, thus severely limited in the range of possible in-plane deformation that they can undergo. Therefore, the inter- and intra-ply shear behaviour of the reinforced sheets plays a major role in determining their formability. Another important phenomenon which has to be considered in this context is the "trellis flow", that causes considerable thickness variations in the laminate[2,3] and is commonly observed during forming of fibre cloth reinforced thermoplastics as well as multi-directional laminates. Since the matched die forming process cannot accommodate such thickness variations due to the surface contraint, the occurrence of instabilities, such as in-plane wrinkling and out-of-plane buckling appears to be unavoidable during forming of 3-D components.

In view of this apparent deficiency diaphragm forming has become a very interesting alternative to the matched-die technique. Over the last few years extensive investigations into diaphragm forming with disposable superplastic alloy and polymer diaphragms have been carried out with promising results[3-6]. Recently research on double diaphragm forming has also been carried out using two reusable silicone rubber sheets[7]. Obviously, the diaphragm forming technique can only ensure that one side of the formed laminate achieves the die contact. This means that the method doe not put any restriction on the thickness variations since the diaphragms are flaxible enough to fit the contour of the laminate.

The present paper describes an experimental work that studies the shear behaviour of CFRT sheets under inter-ply and intra-ply modes and show their significance in matched-die and double diaphragm forming processes. It also presents a finite element simulation of vee-bending that incorporates these shear characteristics and highlights their effects on instabilities under conditions of both matched-die and double diaphragm forming.

EXPERIMENTAL COMPARISON OF MATCHED DIE & DIAPHRAGM FORMING

Material Properties and Experimental Details

The thermoplastic prepreg used for all forming experiments was Plytron™, a continuous glass fibre-reinforced polypropylene (35 vol. %). The material was supplied as a 240-mm wide tape with a nominal thickness of 0.47mm. Regarding the thermal properties of this material it is to be noted that polypropylene crystallises with considerable supercooling, typically 30-40°C, depending on the cooling rate. The maximum in c_p on cooling, therefore, occurs at a much lower temperature than on heating and, in between, the c_p is different as the polymer is molten on cooling, but still solid on heating[8]. This phenomenon allowes thermoforming within a fairly wide temperature window providing the blanks are heated above melt temperature prior to forming[9].

In order to ensure the comparability of the results obtained with the two different forming techniques, only one spherical dome-shaped mould was employed for both forming series. With a diameter-to-depth ratio of 2.00 (diameter=200mm, depth=100mm) and a bend radius of 7mm at the flange corner the mould cavity represented a geometry difficult to form. Due to the thermal properties of the Plytron material, as described above, all forming experiments were conducted under non-isothermal conditions using $[0,90]_S$ laminates.

Inter- and Intra-Ply Slip Tests

Prior to the matched-die and double diaphragm forming experiments a series of shearing tests were conducted aiming to qualitatively estimate the magnitude of shear stresses required to induce inter-ply and intra-ply slip. Based on the investigations by Scherer *et al.*[10,11], experiments using three different types of specimen were conducted employing a Zwick Universal Testing Machine, Figure 1. In order to measure interply shear stresses the centre ply of a pre-consolidated three ply laminate was pulled out at a constant speed. The temperature was controlled by two heated platens surrounding but not physically touching the laminate. The pull out speed was varied from 1 to 22 mm/min and the temperatures from 180 to 220°C. The shear stress, τ, during interply-slip was calculated by dividing the measured load P(t) with the actual shearing area A(t).

Figure 2 shows that the magnitude of interply-shear stress is strongly dependent on the laminate's temperature and the speed at which the centre ply is pulled out. As expected highest shear stress levels were measured at 180°C and a pull out speed of 22mm/min.

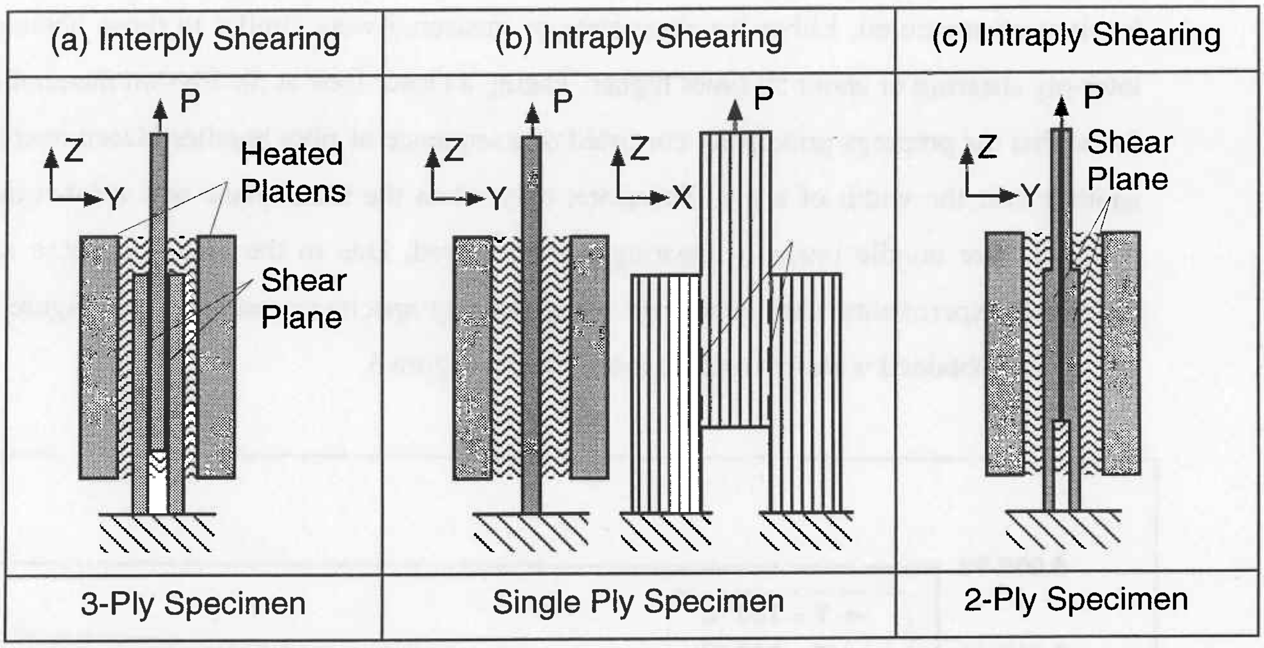


Figure 1: Interply and Intraply shearing

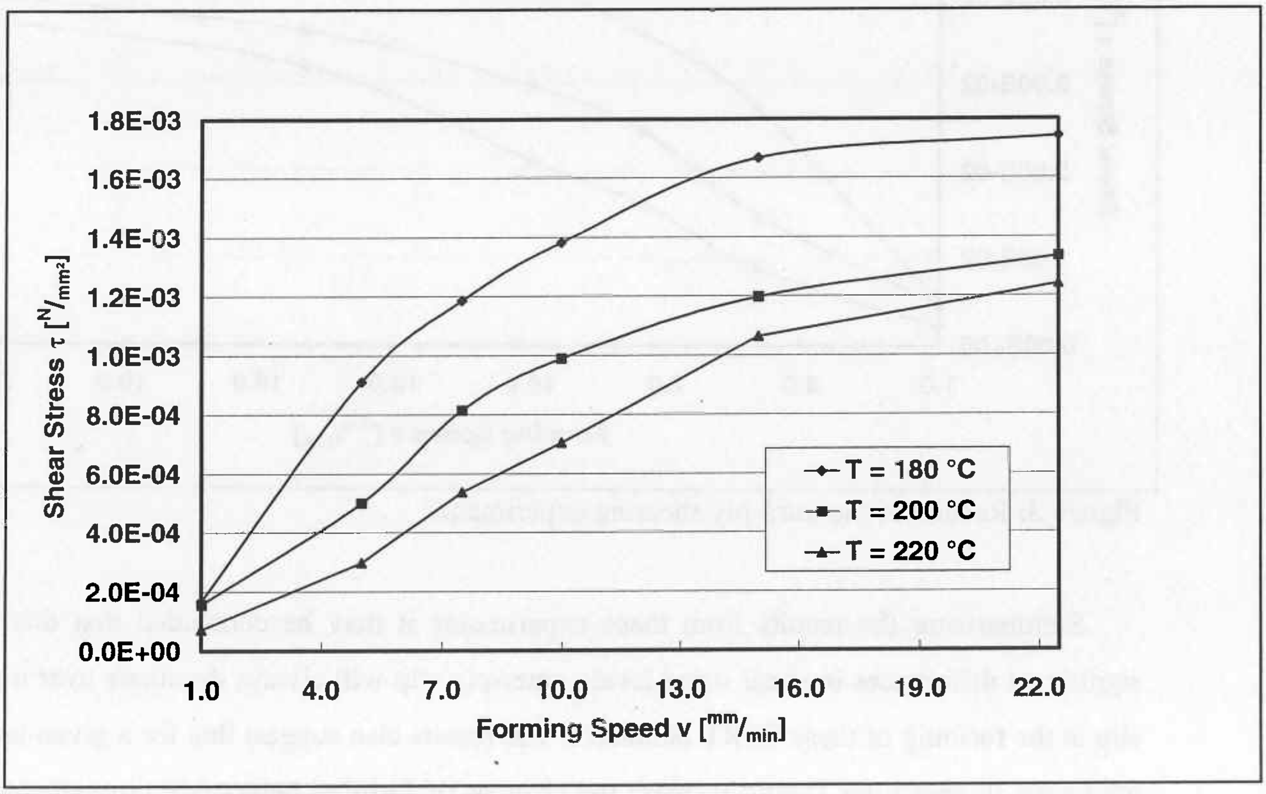


Figure 2: Results of the inter-ply shearing experiments

For the intra-ply shear tests two different specimens were used, Figure 1. The shear stresses were measured following the same procedure as for the interply shear tests. First single ply shearing was conducted using specimens as shown in Figure 1 (b). Due to the inhomogenous distribution of fibres over the width of the prepreg tape, two different shear levels were measured. Either the shear stresses measured were similar to those obtained for inter-ply shearing or about 50 times higher. Taking a closer look at the Plytron material it was found that the prepregs principally consisted of a sequence of fibre bundles placed next to one another over the width of a ply. Therefore, only when the shear plane was located directly within a fibre bundle intra-ply shearing was measured. Due to the scatter in these results, additional experiments were conducted using two ply specimens according to Figure 1 (c). The resluts obtained with this method are shown in Figure 3.

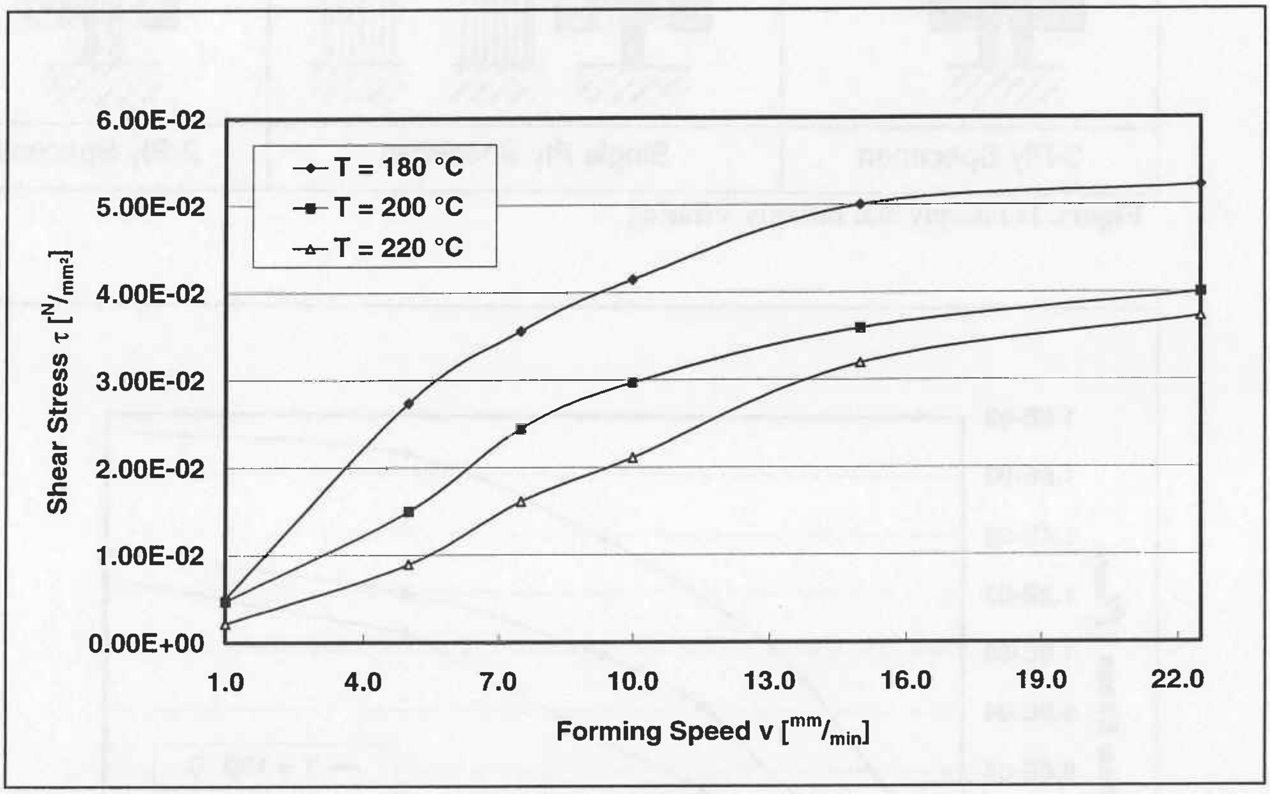


Figure 3: Results of the intra-ply shearing experiments

Summarising the results from these experiments it may be concluded that due to the significant differences in shear stress levels, inter-ply slip will always dominate over intra-ply slip in the forming of these CFRT laminates. The results also suggest that for a given laminate thickness, thinner plies should increase the chances of forming defect free components since more planes where inter-ply slip occurs can be accommodated.

Matched-Die Forming

The principal set-up of the matched-die forming device which was mounted onto a Zwick Universal Testing Machine is illustrated in Figure 4. When forming a spherical dome part, the pre-heated blank was placed on top of the female die and held in place with a clamping plate. In order to prevent quenching before the inception of forming, a heat insulation plate was placed inbetween the blank and the clamping plate. The clamping force was adjusted by the number of disc springs located between the upper cross-beam and the clamping plate. All components were formed at a speed of 30mm/s.

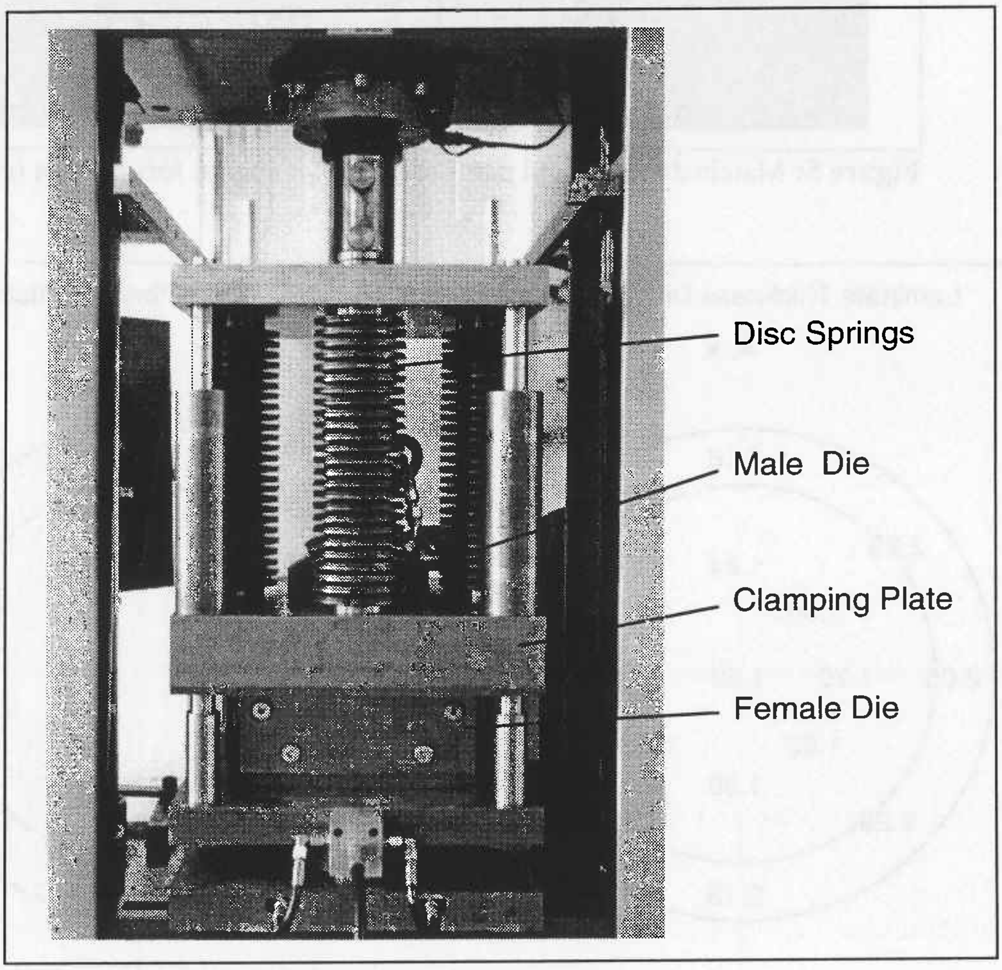


Figure 4: Matched-die forming set-up

As can be seen in Figure 5 (left, expectedly the resulting parts from matched-die forming exhibit a very smooth and glossy surface finish around the apex of the dome section due to the smooth surface of the matching dies. Towards the flange area, however, the situation changes dramatically and severe out-of-plane wrinkling in both surfaces are observed.

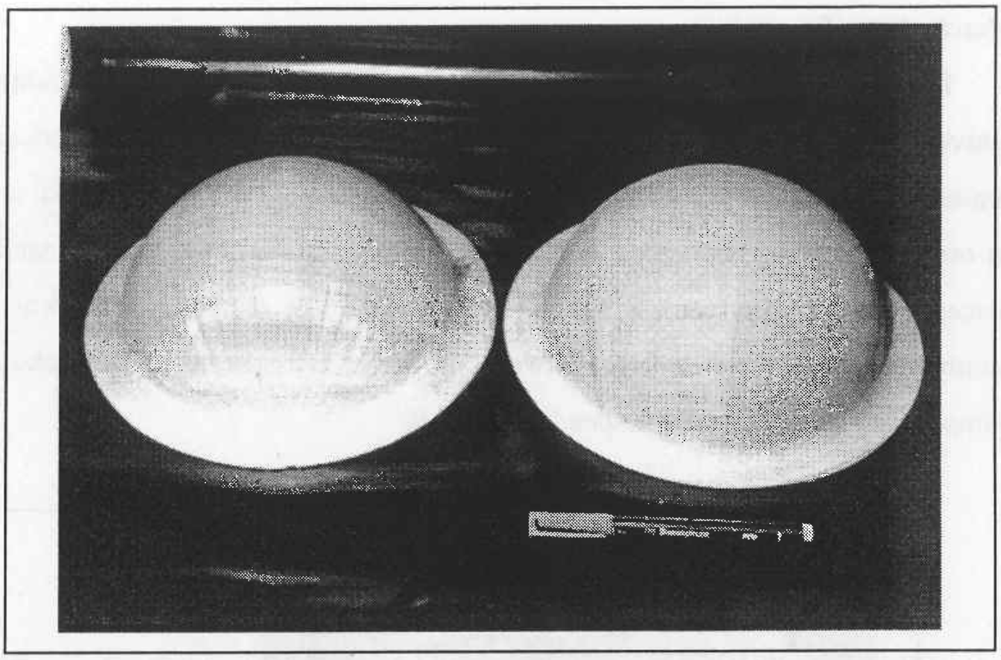


Figure 5: Matched-die formed part (left) and diaphragm formed part (right)

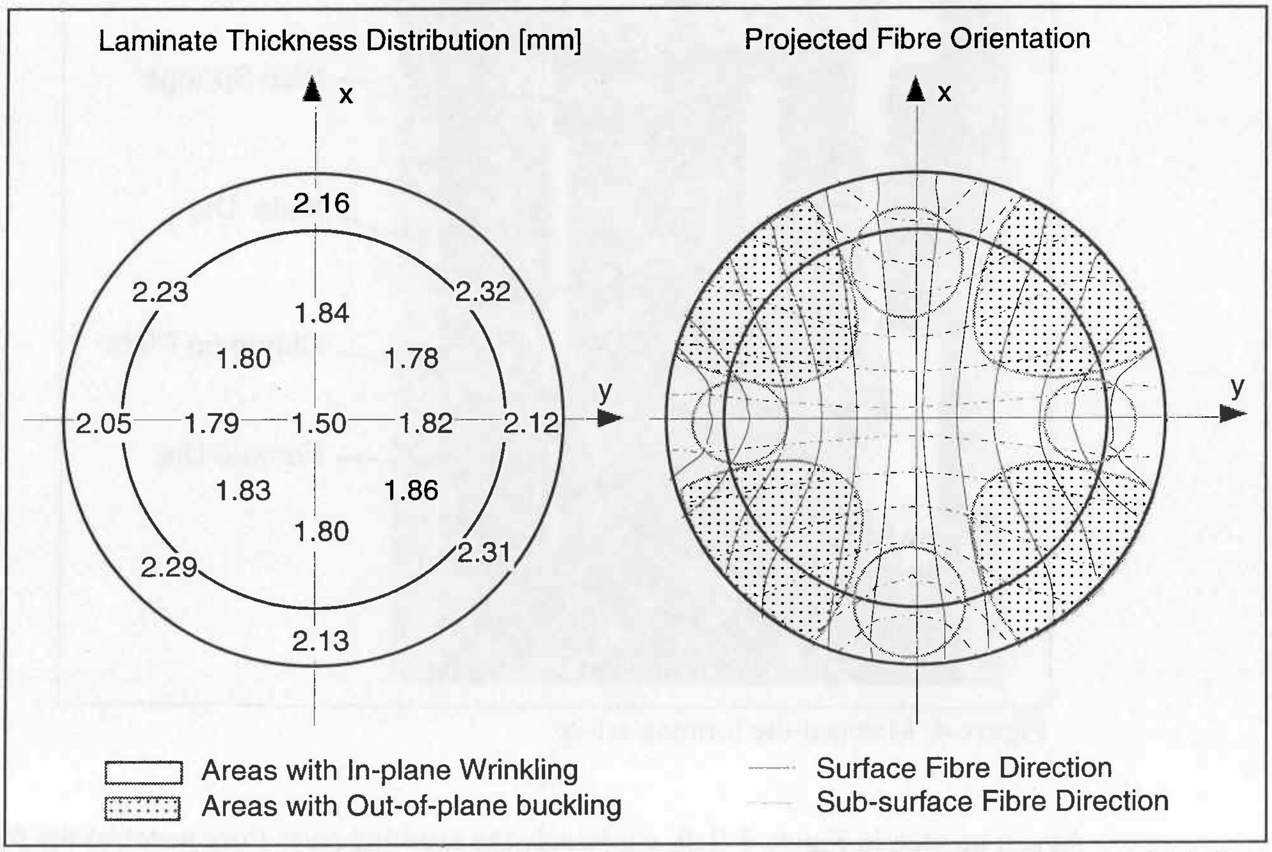


Figure 6: Laminate thickness distribution and projected fibre orientation of a matched-die formed component

A projection of the thickness distribution measured by slicing the part into thin strips along the surface fibre direction, 0°, is shown in Figure 6. Starting with a blank thickness of 1.88mm considerable thinning is observed around the apex of the dome section. The flange exhibits fairly uniform thickness with an overall tendency to thicken. This result may be explained by examining the individual sections of the forming process in conjunction with the deformation mechanisms they induce.

At the first stage of forming the male die or the stamper touches the centre of the clamped laminate, starting to push it down into the cavity of matching die. This means that the initially flat laminate is shaped by draping it onto the surface of the male die. As the male die is moves towards its matching counterpart, the virtually inextensible laminate has to travel with it, which is, however, severely hampered by the clamping frame. The induced tension leads to excessive transverse flow away from the centre of the laminate consequently resulting in substantial thinning in the apex of the dome section, Figure 6. In order to achieve satisfactory die conformity, the laminate has to alter its shape through inter- ply rotation, inter- and intra-ply slip. Since the shear stresses necessary to induce inter-ply shearing was lower, it was identified to be the dominant forming mechanism in this process. Projecting the resulting fibre orientations of a dome shaped part onto a flat plane the severity of inter-ply rotation that occurred during forming becomes evident. In Figure 6 the black lines represent the fibre orientation in the surface ply and the dotted lines give that of the sub-surface ply. It can be seen that the initially straight and orthogonally orientated fibres become curved after forming with the bending radius gradually decreasing as the fibres move away from the apex of the dome. This phenomenon may be explained with the inextensibility of the reinforcing fibres in the laminate, which makes fibre movement necessary for the geometrical conformance. When being draped onto the apex of the dome, the inhomogeneously distributed fibres in the surface plies drag along the orthogonally orientated fibres of the sub-surface plies. During this process the fibres within a sub-surface ply also move relative to one another thus leading to the in-plane wrinkles in the neighbouring surface ply. This phenomenon apparently suggests that substantial intra-ply slip and transverse flow have occurred. A closer look at the fibre distribution within a single ply, however, shows that Plytron consists of a sequence of spread fibre bundles placed next to one another rather than individual fibre filaments being homogeneously distributed over the width of the prepreg tape. This means that in-between to adjacent fibre bundles there is a matrix-rich zone that practically enables “inter-ply”- slip to occur within a single ply. The in-plane wrinkling observed in the sub-surface plies, as marked in Figure 6, are caused by the surface plies following the same procedure as described above. The same process also occurs in the perpendicular direction with the fibres in the sub-surface plies dragging along those of the surface plies. Furthermore, in the direction away from the fibres, the trellis flow leads to thickening in the flange area as shown in Figure 6. However, since the matched-die forming process cannot accommodate laminate thickening, these areas are getting squashed at the end of the forming stroke leaving out-of-plane wrinkles in the surface of the flange.

Double Diaphragm Forming

The diaphragm forming experiments were conducted using a modified forming set-up with the same female die as before. The stamper and the clamping plate were replaced by a vacuum frame and a top plate through which the forming pressure was applied, Figure 7.

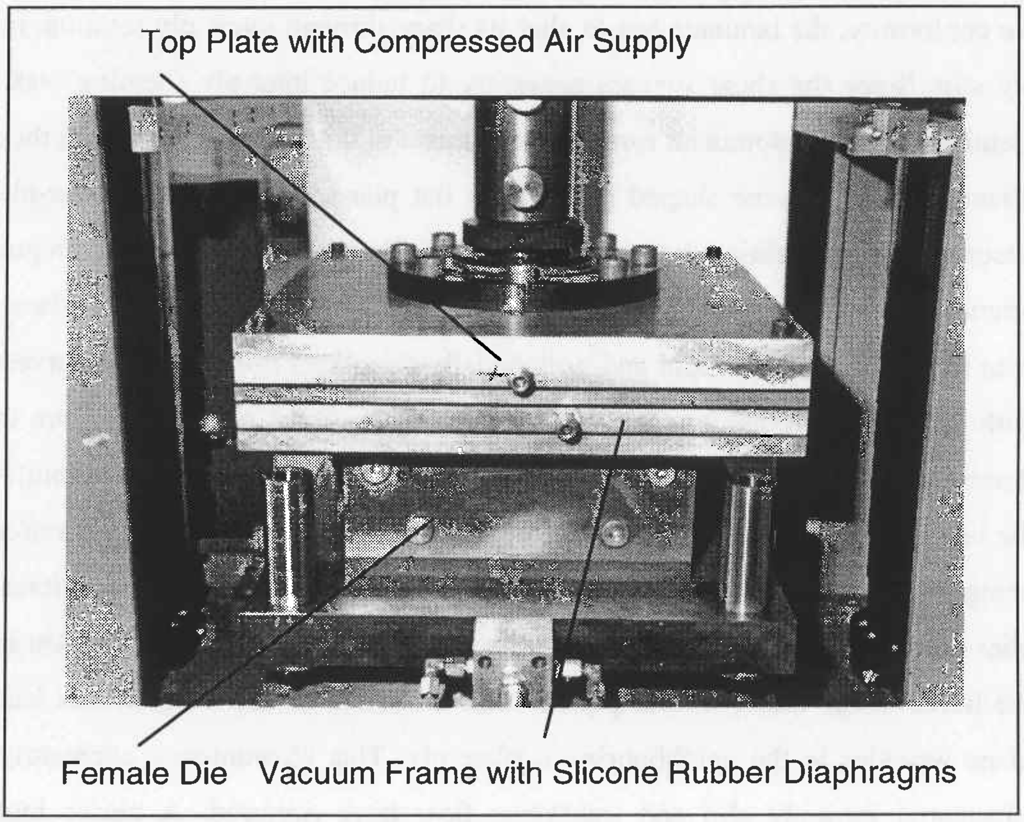


Figure 7: Double diaphragm forming set-up

For all experiments reusable silicone rubber diaphragms were employed with a stretchability of 500% and a temperature resistance of up to 250°C. In order to form a dome-shaped part, a loosely stacked sequence of plies was placed in a vacuum inbetween the two diaphragms and heated to forming temperature in an external oven. The vacuum frame was then transferred onto the mould whilst keeping the blank vacuum-bagged. Forming was then initiated by driving the top plate onto the vacuum frame after which the forming pressure was applied.

Figure 5 shows a $[0,90]_s$ diaphragm formed part. In contrast to the matched die formed components, here the surface finish is not as glossy which is directly related to the surface roughness of the diaphragms. It has to be noted, however, that despite the considerable high blank-to-dome-diameter ratio of 1.80 none of the diaphragms ripped during forming. The finished parts do not show any out-of-plane buckling and only minor in-plane wrinkling around the flange area exists similar to what was observed during the matched-die forming experiments. The thickness distribution is shown in Figure 8 and it is interesting to note the large increase in thickness in the flange area, especially away from the fibres.

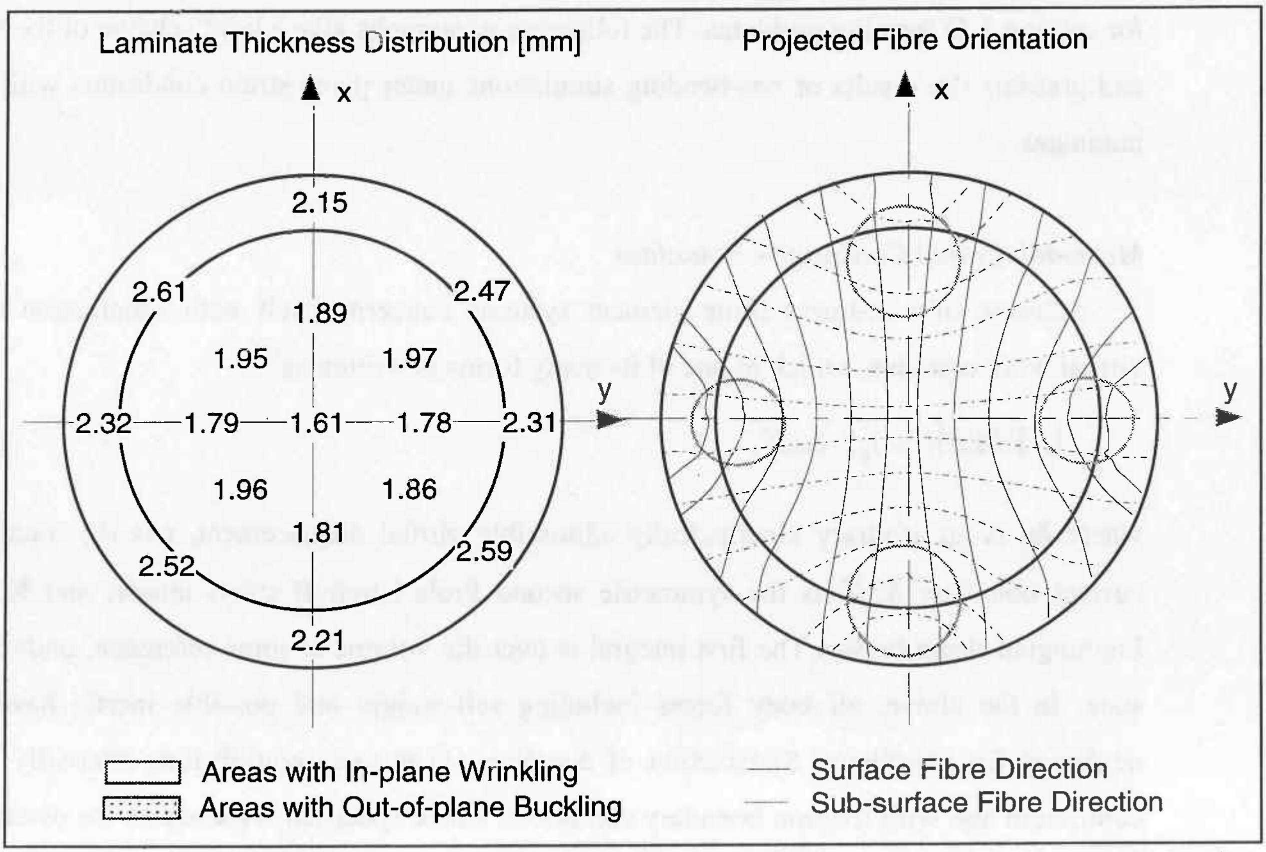


Figure 8: Laminate thickness distribution and projected fibre orientation of a matched-die formed component

Unlike with matched dies, the double diaphragm forming process does not hamper laminate thickening in areas where excessive trellis flow occurs. Another fundamental difference between the two forming techniques is that diaphragm forming shapes a laminate by drawing it into a female die in contrast to matched die forming that drapes it onto a stamper. This way, even in the absence of a clamping plate, sufficient clamping forces are obtained since the outer regions of the sandwiched laminate are pressed onto the flange of the die before the central part is drawn into the cavity. Furthermore, additional tensile stresses are superimposed by the diaphragms due to their ability to stretch, which can reduce or even out compressive stresses in the laminate during forming and thus prevent instabilities from occurring.

FINITE ELEMENT MODELLING

The thermoforming simulation program used for comparing and analysing the matched-die and the double diaphragm forming process has been specifically developed by Christie[12] for solving 3-D forming problems. The following paragraphs give a brief scheme of the theory and presents the results of vee-bending simulations under plane-strain conditions with 4-ply laminates.

Methodology and Constitutive Equations

Solution of non-linear finite element systems concerns itself with satisfaction of the virtual work equation, which in one of its many forms is written as[13]

$$\int_{V_0} \tilde{\mathbf{T}}:\delta\mathbf{E}\,dV_0 = \int_S \mathbf{t}\cdot\delta\mathbf{u}\,dS, \qquad (1)$$

where $\delta\boldsymbol{u}$ is an arbitrary kinematically admissible virtual displacement, $\boldsymbol{t}$ is the traction on current boundary S, $\tilde{\mathbf{T}}$ is the symmetric second Piola-Kirchoff stress tensor, and $\mathbf{E}$ is the Lagrangian strain tensor. The first integral is over the volume at some reference, undeformed state. In the above, all body forces including self-weight and possible inertia have been neglected for simplicity. Satisfaction of equation (1) ensures equilibrium internally in the continuum and with traction boundary conditions where specified. Procedures for discretising and iteratively solving equation (1) are well known[14,15] and will not be discussed here.

Completing the picture is the constitutive equation relating the stresses in the material to the strains or strain rates occuring. Assuming the plies to be transversely isotropic and hyperelastic, a strain energy function is defined in terms of the undeformed fibre direction vector, $\boldsymbol{a}_0$, and the deformation tensor[13]:

$$C_{IJ} = \frac{\partial x_k}{\partial X_I}\frac{\partial x_k}{\partial X_J}, \tag{2}$$

where capitals refer to reference or material coordinates, and small letters to spatial co-ordinates. An appropriate strain energy function is:

$$\begin{aligned} W &= K_1\left(I_1 - 3 - ln(I_3)\right) + K_2\left(I_2 - 3 - 2ln(I_3)\right) + K_3\left(I_3 - 1\right)^2 \\ &\quad + K_4\left(I_4 - 1\right)^2 + K_5\left(I_5 - 1 - 2ln(I_4)\right) \end{aligned} . \tag{3}$$

where the five strain invariants are[17]:

$$I_1 = tr\boldsymbol{C}, \qquad I_2 = \tfrac{1}{2}\left\{(tr\boldsymbol{C})^2 - tr\boldsymbol{C}^2\right\}, \qquad I_3 = \det\boldsymbol{C} = \left(\rho_0/\rho\right)^2,$$

$$I_4 = \boldsymbol{a}_0 \cdot \boldsymbol{C} \cdot \boldsymbol{a}_0 = \lambda^2, \qquad I_5 = \boldsymbol{a}_0 \cdot \boldsymbol{C}^2 \cdot \boldsymbol{a}_0. \tag{4}$$

Equation 2 was chosen for several reasons. If material constant K_3 is given a high value, the material is nearly incompressible. Similarly, the ply stiffness in the fibre direction is approximately $E_f \approx 8K_4$ if K_4 is much higher than other constants. The other 3 constants combine to allow other "initial" elastic moduli to be controlled, hence:

Transverse Young's modulus,	$E_T \approx 8(K_1 + K_2)$,	
Longitudinal shear modulus,	$G_L \approx 2(K_1 + K_2 + K_5)$,	(5)
Transverse shear modulus,	$G_T \approx 2(K_1 + K_2)$	

Also, if $K_4 = K_5 = 0$, and K_3 is high, the Mooney material is very closely approximated with K_1 and K_2 as Mooney constants. The isotropic Mooney material is suitable for modelling many natural rubbers and will be used for the diaphragms in pressure forming examples described later.

Finally, second Piola-Kirchoff stresses are obtained from the strain energy function using:

$$\tilde{T}_{RS} = \frac{\partial W}{\partial C_{RS}} + \frac{\partial W}{\partial C_{SR}} = \sum_{\alpha=1}^{5}\frac{\partial W}{\partial I_\alpha}\left(\frac{\partial I_\alpha}{\partial C_{RS}} + \frac{\partial I_\alpha}{\partial C_{SR}}\right). \tag{6}$$

Contact Modelling

An essential step in modelling a laminate consisting of independent plies is to simulate the contact and friction behaviour as the plies move against and past each other. From a computing point of view the contact model must couple together the deformations of neighbouring plies which would otherwise result in a singular system matrix.

Conceptually, we may divide the surfaces of each ply into an array of small areas, each represented by a contact point in the centre, as depicted in Figure 9.

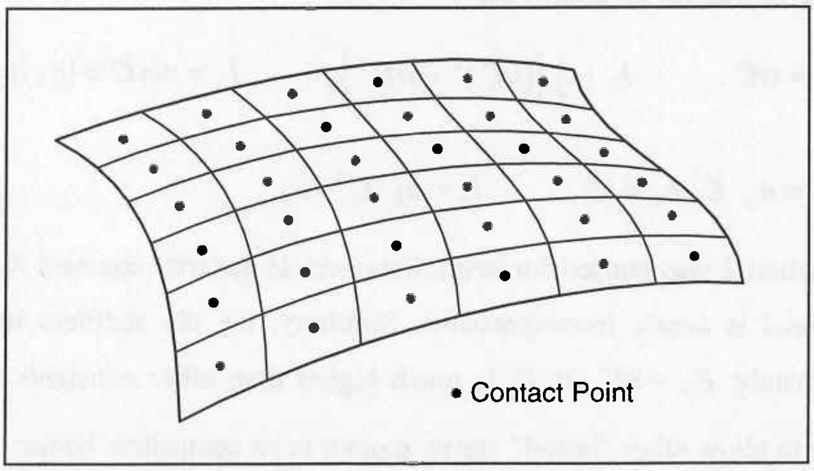


Figure 9: Contact element surface discretisation

Each of these points may be in contact with any other surface, be it on another deformable body or some fixed tool, or in contact with nothing at all. If $\boldsymbol{n}$ is the surface normal at the point on the other surface nearest to the contact point, then we seek to eliminate any relative displacement $\Delta\boldsymbol{u}$ between the two surfaces along this normal, using the constraint equation:

$$C(\boldsymbol{u}) = \boldsymbol{n} \cdot \Delta\boldsymbol{u} = 0. \qquad (7)$$

Immediately there is a problem when one considers the mechanics of fitting together discretized surfaces perfectly - it is not possible. A solution, apart from infinitely fine meshes is to only approximately satisfy equation (7) by use of a penalty method. Any variational principle Π can be modified to be constrained by some functions $C(\boldsymbol{u})$ such as equation (7) by creating a modified variational principle using[15]:

$$\overline{\Pi} = \Pi + \alpha\int_{\Omega} C^T(\boldsymbol{u})C(\boldsymbol{u})d\Omega, \qquad (8)$$

where α is a penalty number; the higher its value is, the closer equation (7) is satisfied. More specifically for this problem, the variation of the new term in equation (8), using equation (7) is included in the virtual work equation.

Physically, the application of contact constraints by a penalty method amounts to no more than setting up a series of springs between the two surfaces, with the stiffness proportional to α. From a numerical viewpoint, these springs are the coefficients coupling the separate blocks of the system matrix representing the deformation in each separate ply. The lack of satisfaction of equation (7) will be evidenced by coupled surfaces tending to overlap or drift apart. However, considering effects such as fibre migration and out-of-plane ply buckling in real laminates, this behaviour may not be unrealistic in many circumstances.

Tangential forces are applied analogously except that they are adjusted to apply a force appropriate to the friction model in use. In the work presented here, shear stresses linearly proportional to the relative sliding velocity of one surface over another are applied, simulating the viscous resistance of a thin layer of Newtonian fluid of constant thickness between the plies (the matrix-rich inter-layers). This allows inter-ply slip to be realistically modelled.

The detail of procedures involved in modelling contact behaviour are very involved and will be left to a later publication.

Simulation of Matched-Die Forming

For evaluation of the influence of inter- and intra-ply slip on the occurrence of shear instabilities in matched-die forming processes, simulations were performed using a 4 ply laminate. Each ply was modelled to be 0.4mm thick with 0.05mm space on each side to simulate the interlayer thickness. The friction condition between adjacent plies was defined as 2.00×10^7 times the relative sliding velocity. The variables for the strain-energy function were $K_1 = 5.00\times10^4$, $K_3 = 5.00\times10^6$ and $K_4 = 1.00\times10^8$. It has to be noted that for all simulations isothermal forming conditions were assumed.

In Figure 10 the laminate is formed at 7mm/sec which is a fairly slow forming rate. At this speed, the stresses in each ply are not affected by friction from the neighbouring plies and remain relatively similar. The normal contact stresses against the tools are shown by the thin lines.

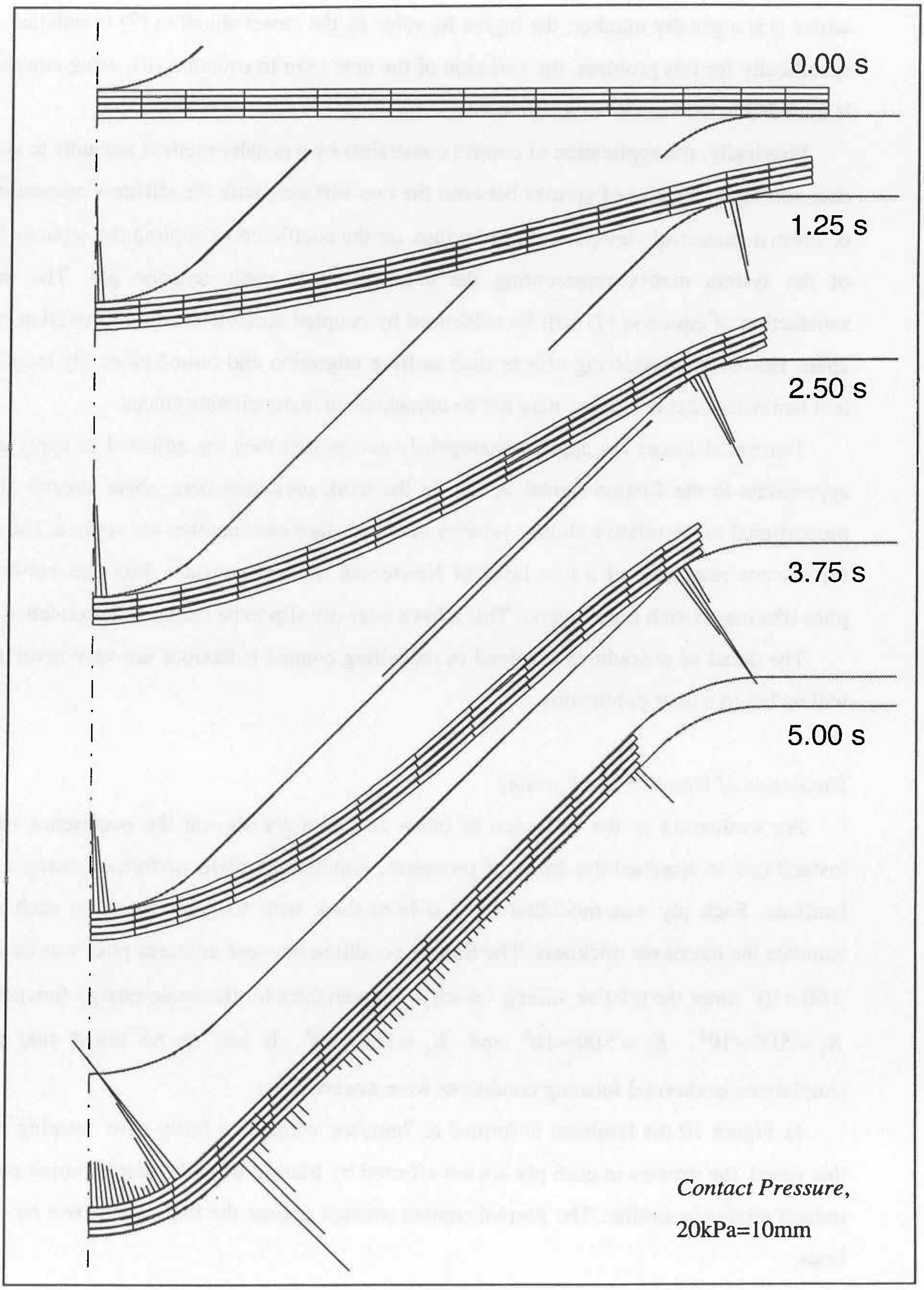


Figure 10. Matched-die forming a 90 degree bend.

In Figure 11 the same part has been formed at 70mm/sec which is closer to a realistic forming situation. Here, compressive stresses in the sub-surface ply build up immediately leading to out-of-plane buckling throughout the laminate. Figure 12 shows the fibre stresses in the above two cases at approximately the same stage of deformation. It is interesting to note that in the fast forming example, the inner ply is already in full compression even at this early stage of deformation.

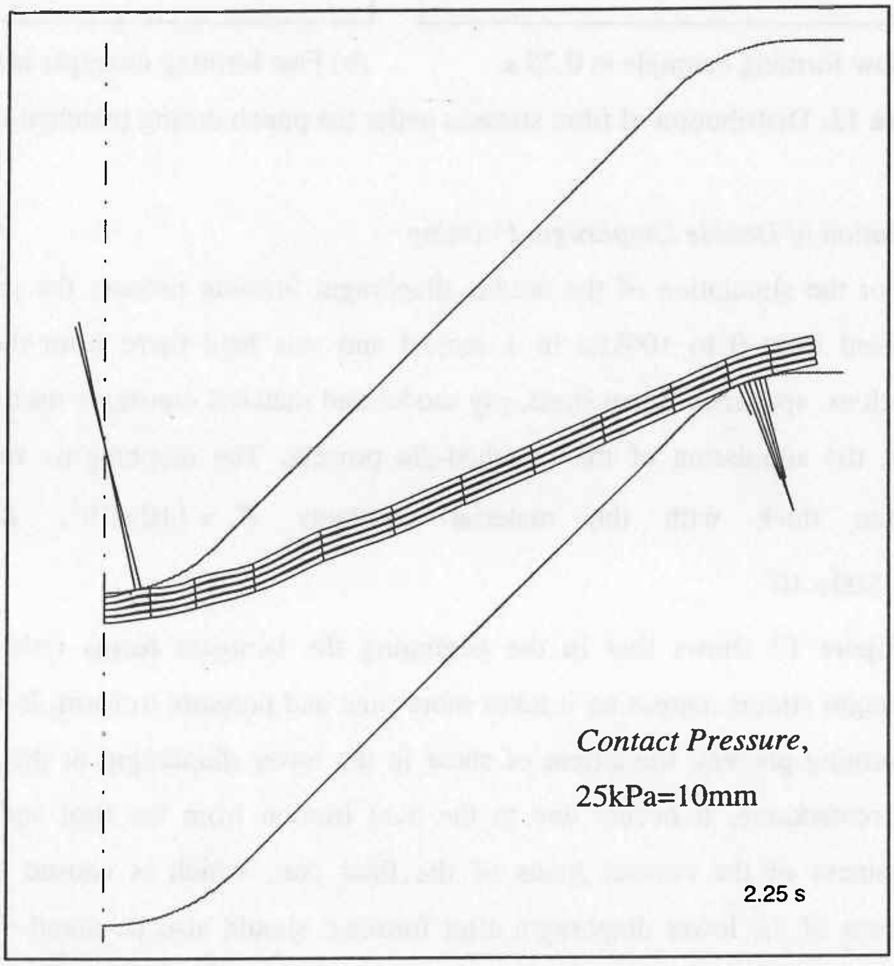
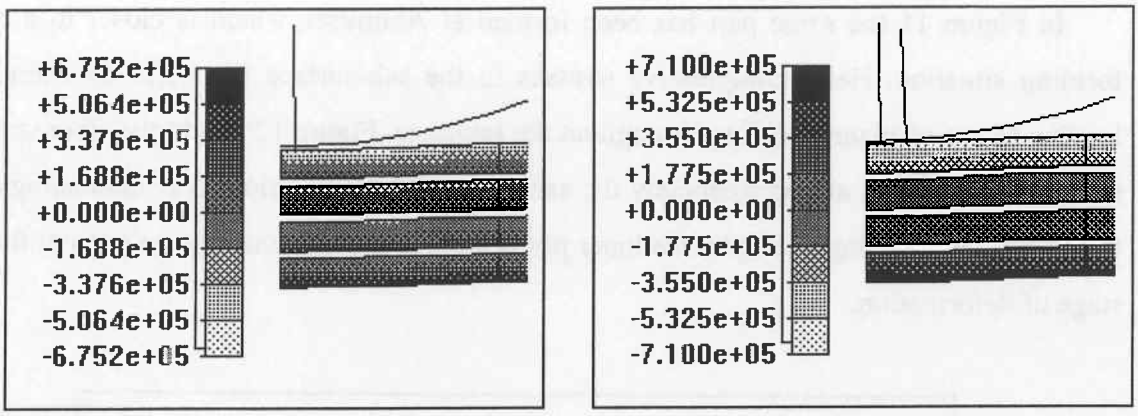


Figure 11: Matched-die forming at high velocity showing buckling

The main disadvantage of matched-die forming for FRTPs that was experimentally observed has been vindicated by the simulations as well. Unless forming speeds are impractically low so that inter-ply slip freely occurs, the early development of compressive stresses is unavoidable with this technique. As a consequence these compressive stresses lead to instabilities, such as out-of-plane buckling and in-plane wrinkling[17-19].



(a) Slow forming example at 0.25 s. (b) Fast forming example at 0.025 s.

Figure 12: Distribution of fibre stresses under the punch during matched-die forming

Simulation of Double Diaphragm Forming

For the simulation of the double diaphragm forming process the pressure was linearly increased from 0 to 100kPa in 1 second and was held there from then on. The friction conditions, specimen dimensions, ply model and material constants used here were the same as for the simulation of the matched-die process. The diaphragms were modelled to be 0.75mm thick with the material constants $K_1 = 1.10 \times 10^5$, $K_2 = 0.25 \times 10^5$ and $K_3 = 5.00 \times 10^6$.

Figure 13 shows that in the beginning the laminate forms rather rapidly, but with diaphragm strains increasing it takes more time and pressure to form. In the middle stages of the forming process, the extent of shear in the lower diaphragm at the bend-over region is quite remarkable. It occurs due to the dual friction from the tool and the laminate,. The unevenness of the contact loads of the final part, which is caused by the non-uniform thickness of the lower diaphragm after forming, should also be noted. Figure 14 shows the stress distribution in the laminate at a forming stage comparable to that shown in Figure 12. In contrast to the situation of matched-die forming, where compressive stresses occur in all plies, here tension is dominant in the laminate. This result supports the notion that in the double diaphragm forming technique the stretching diaphragms transfer highly desirable tensile stresses onto the laminate, thus reducing the tendency of buckling instability. This corresponds well with the experimental results presented in this paper and is also supported by the findings of Smiley[20].

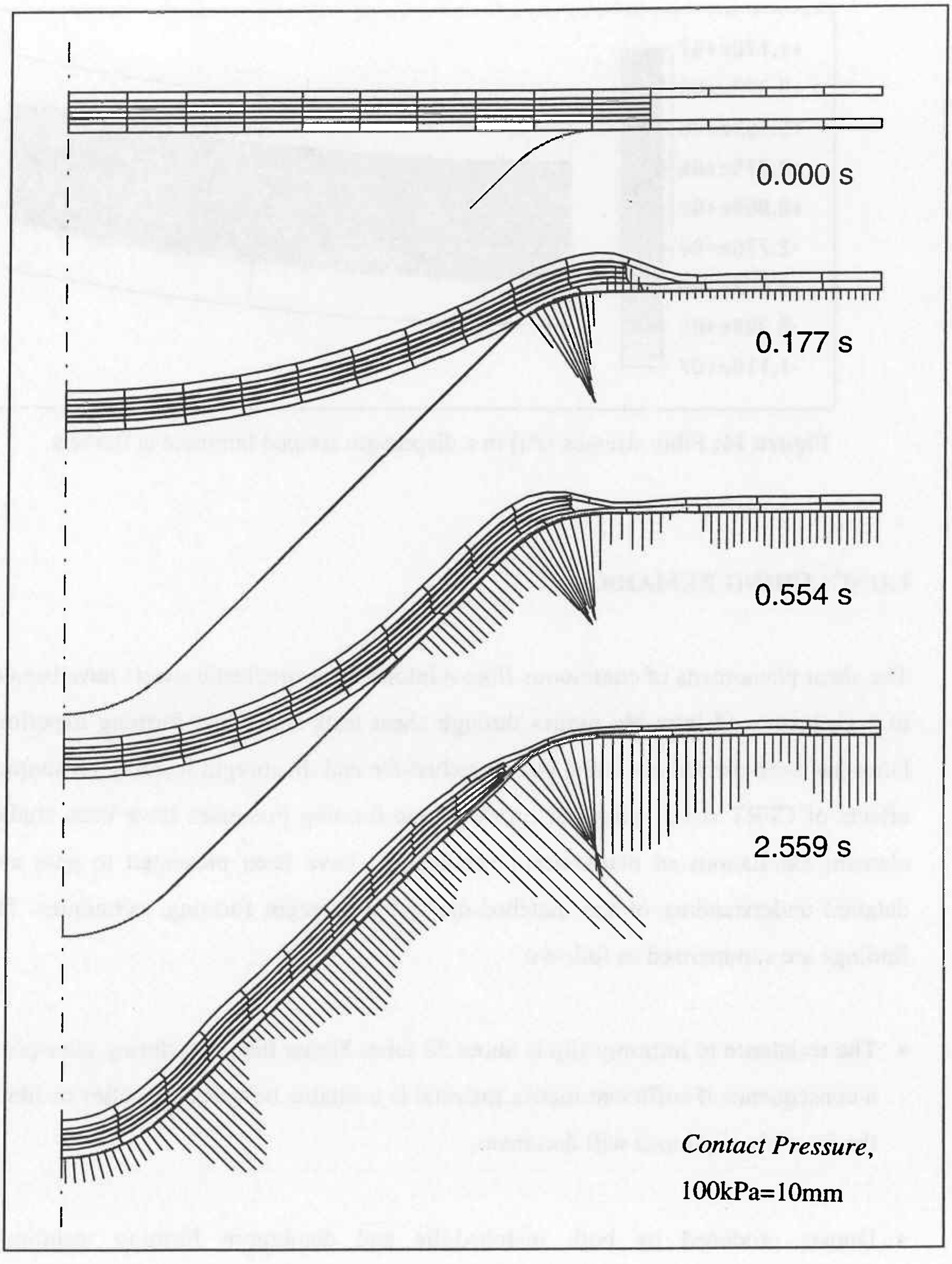


Figure 13: Double diaphragm forming a 90° bend

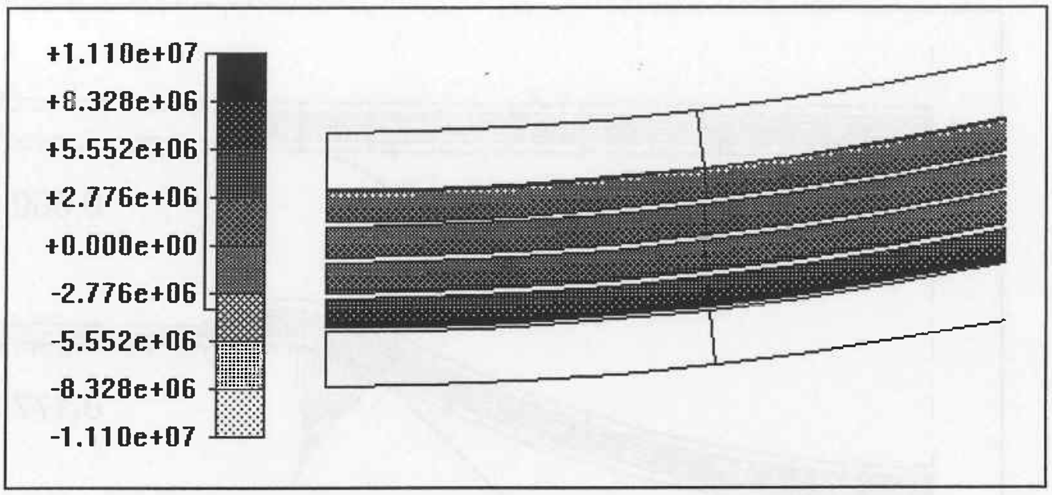


Figure 14: Fibre stresses [Pa] in a diaphragm formed laminate at 0.554 s

CONCLUDING REMARKS

The shear phenomena of continuous fibre reinforced thermoplastic sheets have been examined in both inter- and intra-ply modes through shear tests and dome forming experiments. The latter has been carried out using both matched-die and diaphragm forming techniques and the effects of CFRT shear behaviour on these two forming processes have been studied. Finite element simulations of plane strain vee-bending have been presented to gain some more detailed understanding of the matched-die and diaphragm forming techniques. The salient findings are summarised as follows:

- The resistance to intra-ply slip is about 50 times higher than that during inter-ply shear. As a consequence if sufficient matrix material is available between two plies or fibre bundles, the inter-ply slip mode will dominate.

- Domes produced by both matched-die and diaphragm forming techniques reveal considerable thinning around the apex area and as expected some thickenning in the flange. Due to the constraints imposed by the matching dies the surface finish is generally better in matched-die forming and the flange thickness variation is slightly less severe compared to that for double diaphragm forming which allows free trellis-flow. However, at the same time the matched-die forming restricts the material movement that generally leads to severe out-of-plane buckling in the produced components. In-plane wrinkling is present in domes produced by both techniques and its reason may be attributed to the relative movements of the fibres in two adjoining layers of a deforming laminate.

- Finite element simulations of vee-bending give good understanding of the underlying deformation mechanisms in both forming methods by highlighting the effects of inter-ply shear, deformation speed and surface traction imposed by the deforming diaphragms. It appears that in matched-die forming compressive stresses are generated almost through the entire laminate thickness at an early stage of forming unless the forming speed is very low. However, in diaphragm forming, the tension provided by the frictional stresses existing between a diaphragm and the blank laminate is decisively beneficial to nullify the effects of compressive stresses and avoid out-of-plane buckling. Consequently a reasonably defect free part might be produced if the forming depth does not demand excessive diaphragm stretching. The varying contact pressure in diaphragm forming may lead to some product unevenness.

ACKNOWLEDGEMENTS

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