Numerical and Experimental Investigation of Some Press Forming Parameters of Two Fibre Reinforced Thermoplastics: APC2-AS4 and PEI-CETEX.

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1- INTRODUCTION

Continuous Fibre Reinforced Thermoplastics (CFRTP) are promising materials for light weight structural components which are recyclable. Unfortunately high material and fabrication costs have so far limited their industrialisation. The press forming of CFRTP sheets has the potential to substantially reduce the fabrication times and costs [1] as compared to the much slower autoclave forming. However, successful part manufacture requires precise control of the numerous processing parameters that govern press forming. This is often difficult and time consuming to realise in practice. This paper shows how numerical simulation can greatly improve understanding of the forming process and provide a valuable computer aided design tool.

During the late 1980's computer simulation techniques where first introduced to metal stamping. The early work concentrated on developing necessary numerical tools and their validation against simple experiments. These tools have rapidly progressed and today form an essential part of the development process in many areas of metal forming and stamping [2]. By comparison the present status of thermoforming simulation is still in its infancy. However first results, some of which are presented in this paper and elsewhere [3] are encouraging, and the application of the software to fully industrial problems is now possible.

The software used here for the forming simulation of CFRTP sheets is an extension of the commercial metal stamping code PAM-STAMP™[4]. The main new developments needed for thermoforming simulation have included temperature flow modelling and implementation of new material models and techniques to represent the deformation modes in thermo-viscoelastic fibre reinforced sheets. Identification of material failure and forming limits using the material 'process window' are other important developments.

This work is demonstrated here for the forming of a specific component using two different materials; namely, APC2-AS4, prepreg with unidirectional fibre reinforcement and PEI-CETEX, prepreg with a more drapeable woven fabric reinforcement. The formability of both materials are numerically and experimentally investigated and compared.

2- DESCRIPTION OF THE PROCESS

Briefly three key phases in the press forming process may be identified. Firstly, a laminate of pre-consolidated plies is heated by some form of external heating to a temperature above the matrix melt temperature and then quickly transferred to the colder press. Secondly, the hot sheet is rapidly press formed to the required shape using either matched metal tooling, 'hydroforming', or the 'rubber pad' forming technique. Finally, the part is cooled in the tools to a temperature where it has sufficient internal stiffness to be dimensionally stable during extraction from the mould and further in cooling in air. Figure 1 shows the temperature and pressure time histories in the press forming process.

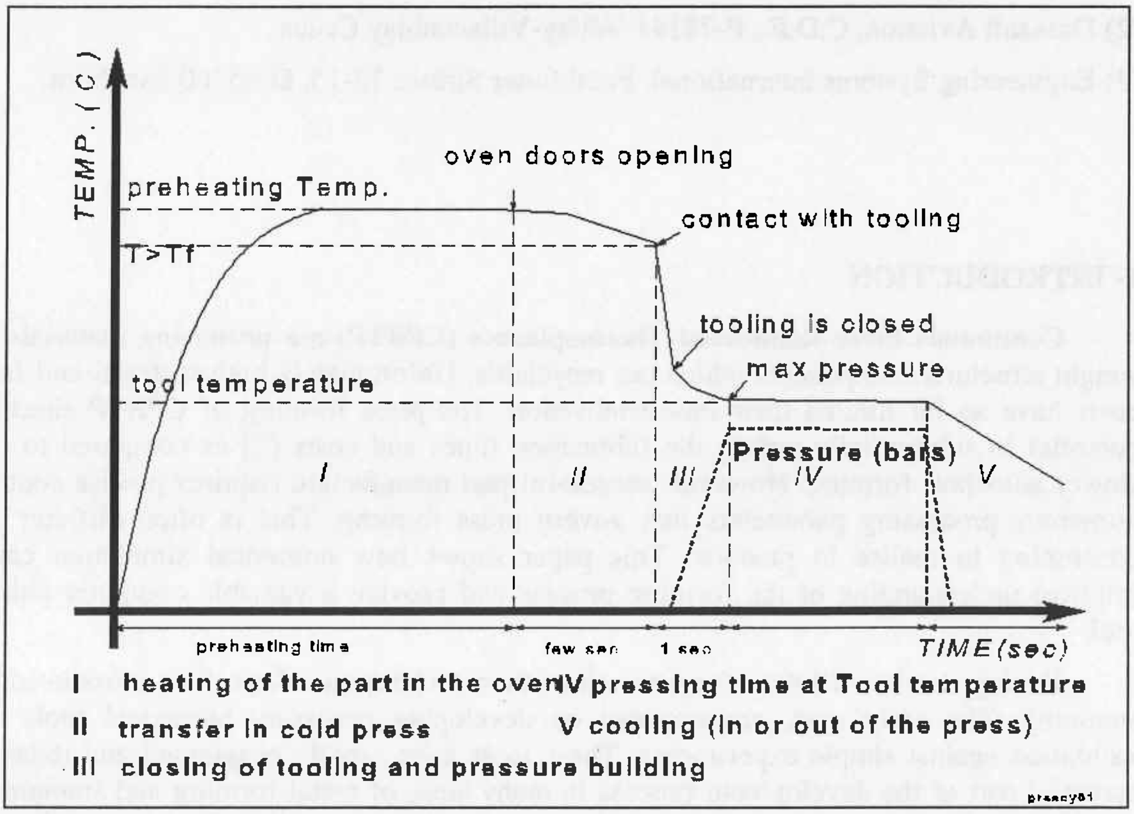

Figure 1: Principal stages of pressure and temperature evolvement in the press forming process.

In the studies to be presented here the part to be formed is a double curvature sikkens type stiffener. Geometrically this is a half cylinder with two quarter spheres at both ends. The overall dimensions are 400 mm length, 200 mm width and a total forming depth of 50 mm. The pre-heating used heated platens and the stamping operation used matched metal tooling. Two materials have been investigated:

i) APC2-AS4 consisting of a PEEK resin reinforced by unidirectional AS4 carbon fibres.

ii) PEI-CETEX consisting of a PEI resin reinforced by woven 50/50 T300 carbon fibres.

3- THE FINITE ELEMENT MODELLING

In this section a brief outline of the finite element tools to simulate the press forming process are described. Further information is also given in [5]. The conventional finite element method using shell elements is used to model the CFRTP sheet and the forming tools. The governing equations are solved as a dynamic problem using explicit integration [6]. This approach has proven to be particularly suited to highly non-linear geometric and material problems, particularly where a large amount of contact between different structural parts occurs, such as at the tool-to-sheet interfaces. Other inherent advantages of the explicit solution include the ability to handle very large three dimensional problems with comparatively low memory requirements.

In the three dimensional shaping of stacks of CFRTP material two predominant forming mechanisms occur. These are intra-ply shearing of the individual plies and inter-ply shearing between the plies. A single shell element representing the stacked plies cannot capture correctly these two deformation modes. Consequently the approach used here is to model each ply of the laminate separately with shell elements and use appropriate material law for intra-ply shearing and viscous-friction laws between shells for inter-ply shearing [7].

The material model is a 'biphase model' in which the elastic fibre and viscous matrix components are treated separately. The matrix has a thermo-viscous behaviour and the fibres are treated as either unidirectional or woven elastic [8,9]. The fibres are assumed to be embedded in the elements and move with the element intra-ply shear deformation. The shell formulation and material model is able to reproduce ply buckling caused by fibre locking at a critical angle, or due to excessive inplane compressive loading. The inter-ply shearing between adjacent plies is handled using specialised viscous-friction and contact constraints. The friction laws are material dependant and are a function of temperature, contact pressure, and relative fibre orientation and sliding velocity between adjacent plies [10,11].

The various modes of heat transfer are modelled. Heat transfer occurs as the hot sheet contacts the colder tools and is predominantly a one dimensional (through-the-thickness) flow. This tool-to-ply and ply-to-ply heat transfer is modelled through the mechanical contact using a finite volume approach [12]. Limited anisotropic in plane heat conduction will also occur and is modeled using conventional anisotropic heat conduction [13]. This treatment has been extensively validated against analytical solutions and experimental tests [14]. From the temperature analysis the correct material viscosity and viscous-friction values may be computed and used in each element in the material and friction laws.

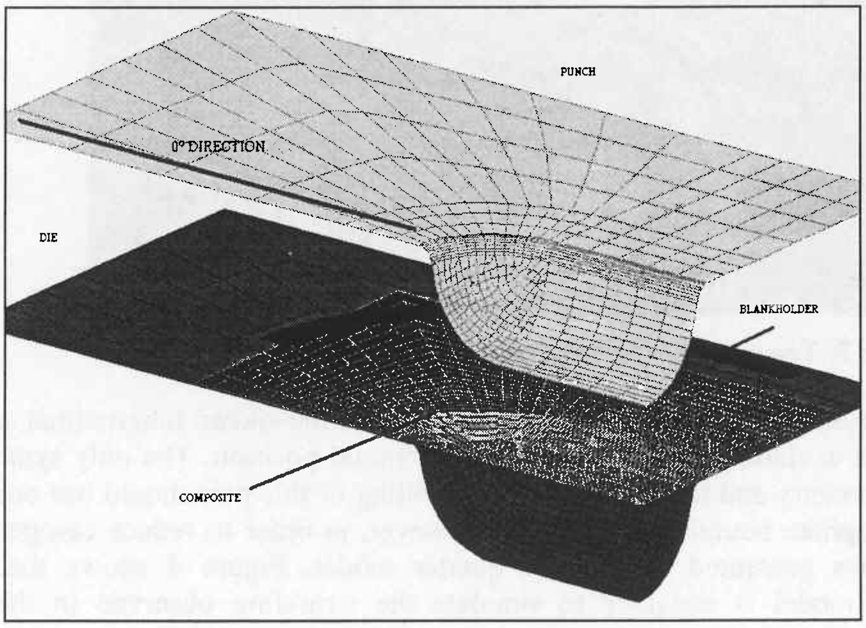

Figure 2: Finite element modelling.

be computed and used in each element in the material and friction laws.

Figure 2 shows details of the finite element model used for the sikken studies to be presented here. Two possible laminate types are considered, these are:

i) 20 plies of APC2-AS4 material with each ply having 2047 shell elements (Section 4.).

ii) 8 plies of PEI-CETEX material with each ply having 1743 shell elements (Section 5.).

4- APC2-AS4 STUDIES

These parts have 20 plies and use a quasi-isotropic lay-up $[+45°,90°,-45°,0°,45°,90°,-45°,0°,45°,-45°]_2$ giving a total laminate thickness of 2.8 mm. This material and layup is known to have limited formability and one of the main aims of the investigations was to study the influence of the blankholder to suppress wrinkling. The punch velocity used is 40 mm/s.

4-1 The quasi-isotropic part

Figure 3 shows experimentally formed APC2-AS4 part. It may be seen that wrinkles are present all around the radius of the spherical area and in the straight area in the 90° direction. From a regular grid of white lines drawn on the initially flat sheet it is possible to see a high level of fibre buckling and fibre reorientation due to movements in the grid.

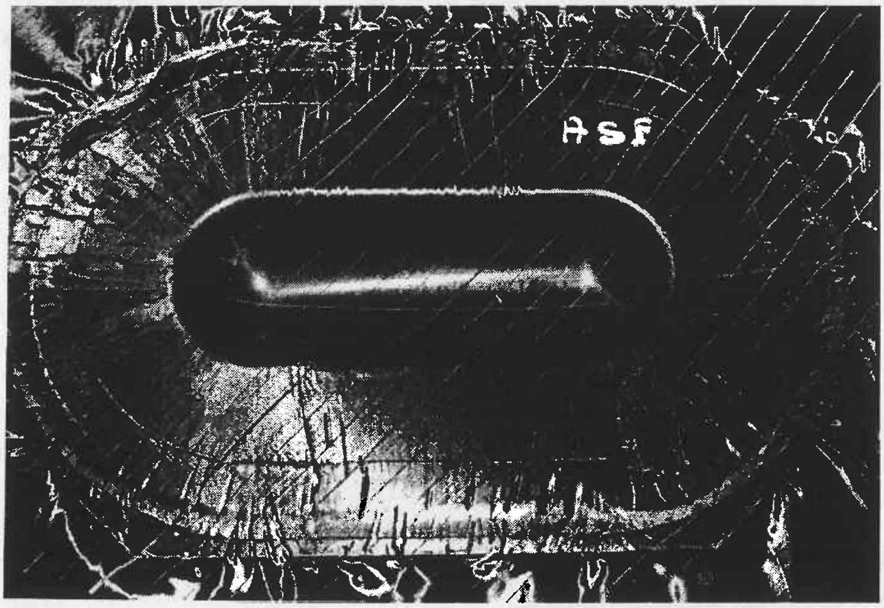

Figure 3: Top view of the quasi-isotropic APC2-AS4 part.

From figure 3 the asymmetry of the wrinkles with respect to the sikken longitudinal axis is noticeable together with a deviation of the 0° axis from its initial position. The only symmetry that exists is a central symmetry and therefore correct modelling of this part should use one half of the sikkens with appropriate boundary conditions. However, in order to reduce computation times the first simulations presented here use a quarter model. Figure 4 shows that this geometrically simplified model is adequate to simulate the wrinkling observed in the test specimens.

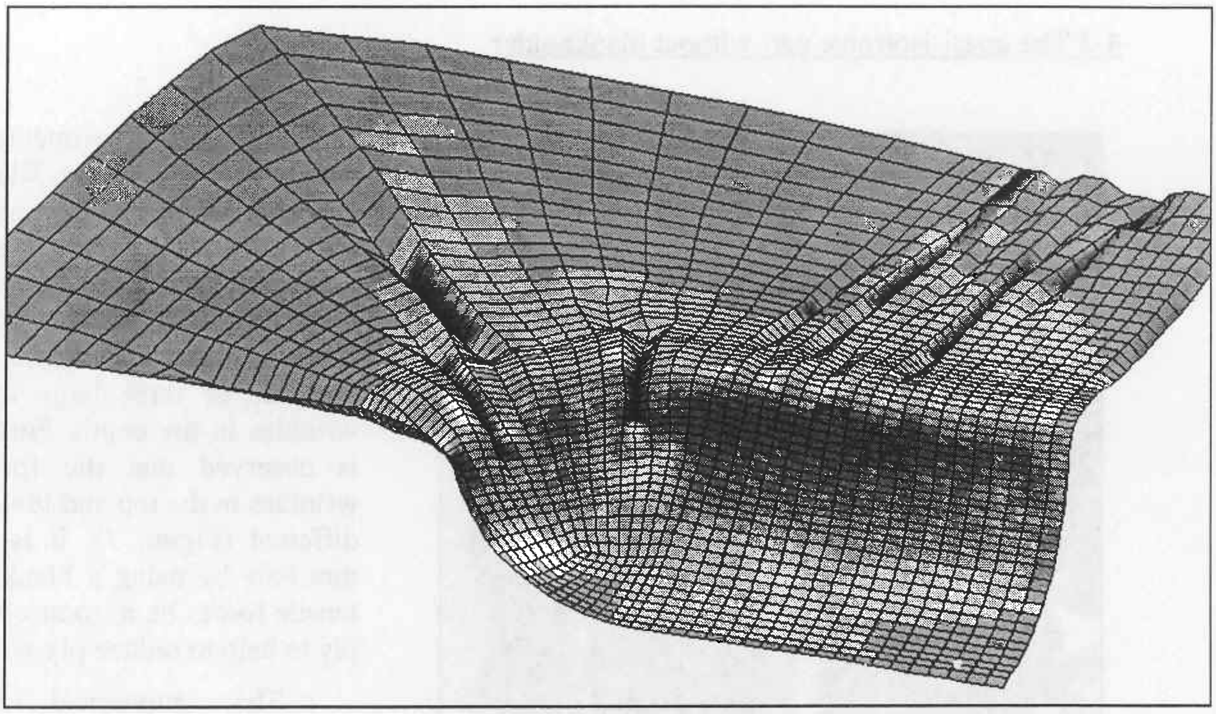

Figure 4: Quasi-isotropic APC2-AS4 numerical simulation: View of the top ply.

For completeness the ability of the software to predict the wrinkling pattern found in test specimens must be validated using a one half model. For this model detailed numerical results concerning the temperature prediction have been previously reported [15]. The main observation concerning the half model simulations is that asymmetry of the wrinkles is correctly predicted (Figure 5).

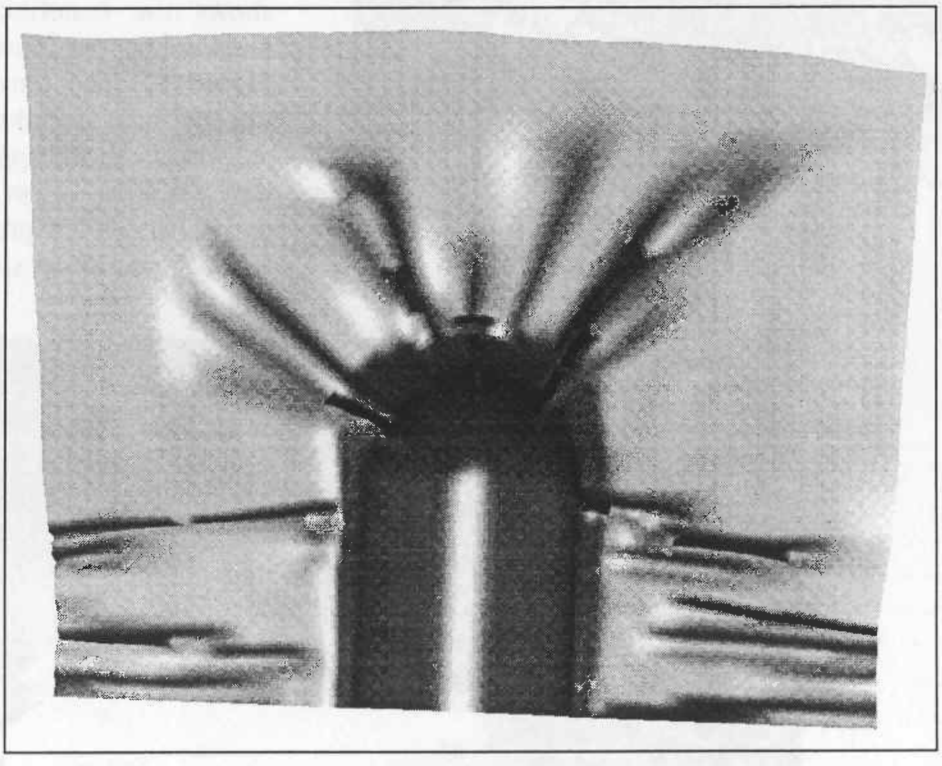

Figure 5: Quasi-isotropic APC2-AS4 part:
View of the top ply for the half model calculation.

4-2 The quasi-isotropic part without blankholder

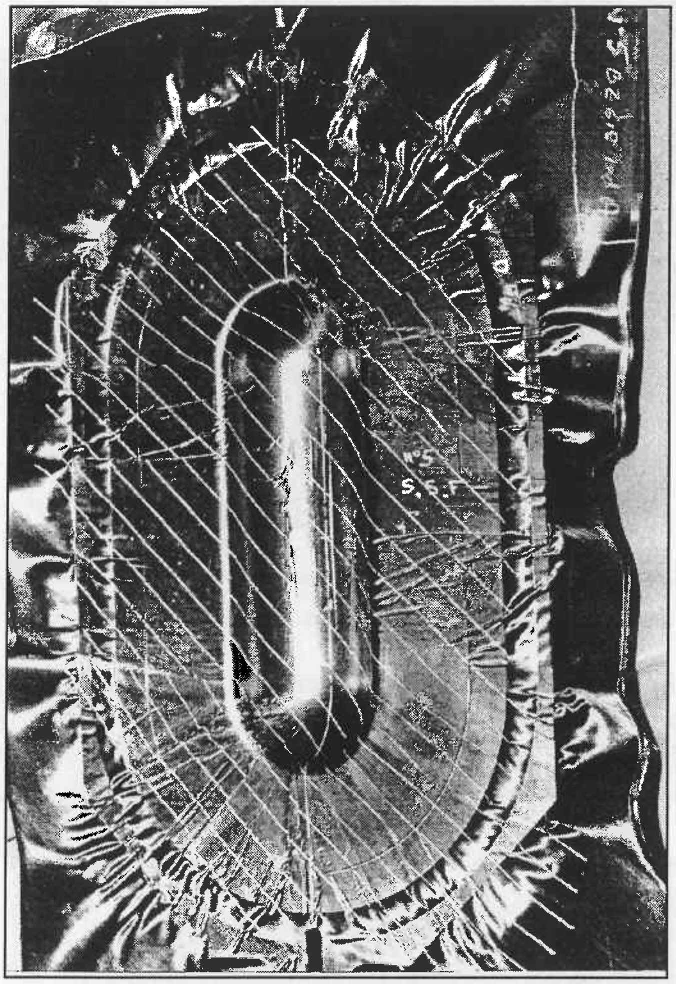

Figure 6: Top view of the quasi-isotropic APC2-AS4 part formed without blankholder.

This experimental study considered the same sikkens with different forming conditions in which the blankholder is removed. In this case many more transverse wrinkles may be observed in the top ply (Figure 6). The major difference is the presence of three large longitudinal wrinkles in the depth. Furthermore it is observed that the formation of wrinkles in the top and lower plies are different (Figure 7). It is concluded that only by using a blankholder can tensile forces be introduced to the top ply to help to reduce ply wrinkling.

The numerical simulation correctly predicts the increase of the wrinkling in the top ply (Figure 8) and the difference in wrinkling behaviour between the upper and lower plies (Figure 9), when the blankholder is removed. Further investigation of the stress distribution in the top ply shows the beneficial effect of the blankholder to limit ply wrinkling Figure 10. The tension areas of the top ply formed without a blankholder are limited to the spherical part where the wrinkles occur, whereas, high tensile forces are present all over the vertical area of the sikkens.

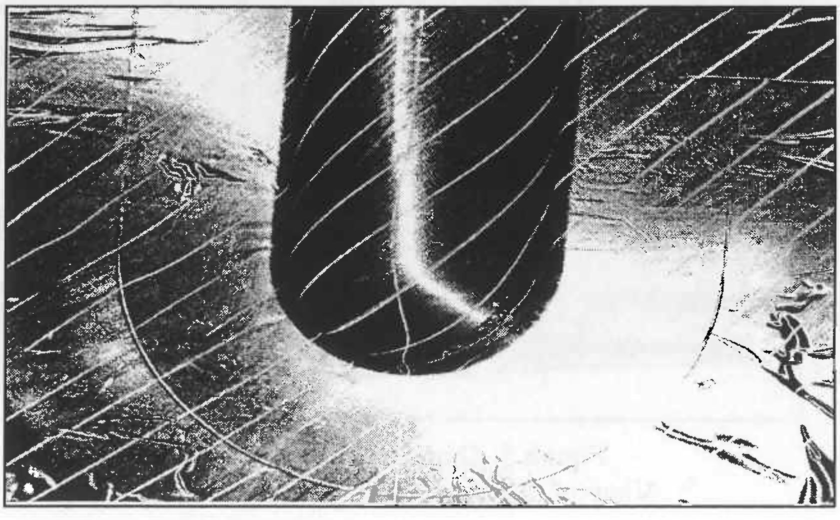

Figure 7: Bottom view of the quasi-isotropic APC2-AS4 part formed without blankholder.

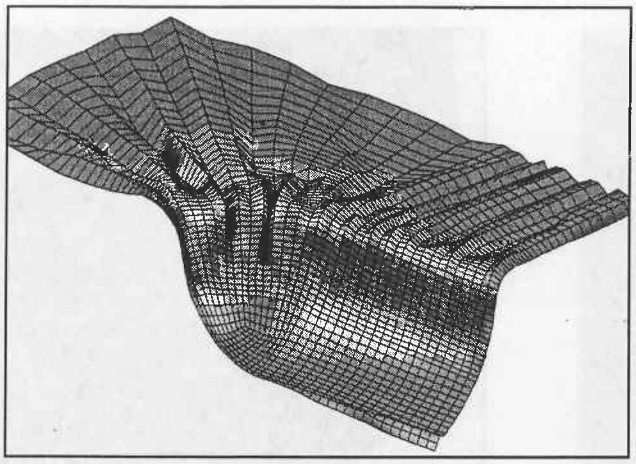

Figure 8: Quasi-isotropic APC2-AS4 part. Top ply. No blankholder case.

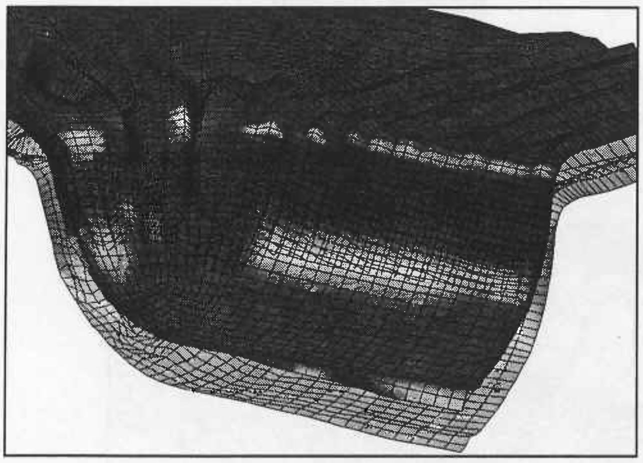

Figure 9: Quasi-isotropic APC2-AS4 part. Bottom and top ply. Noblankholder case.

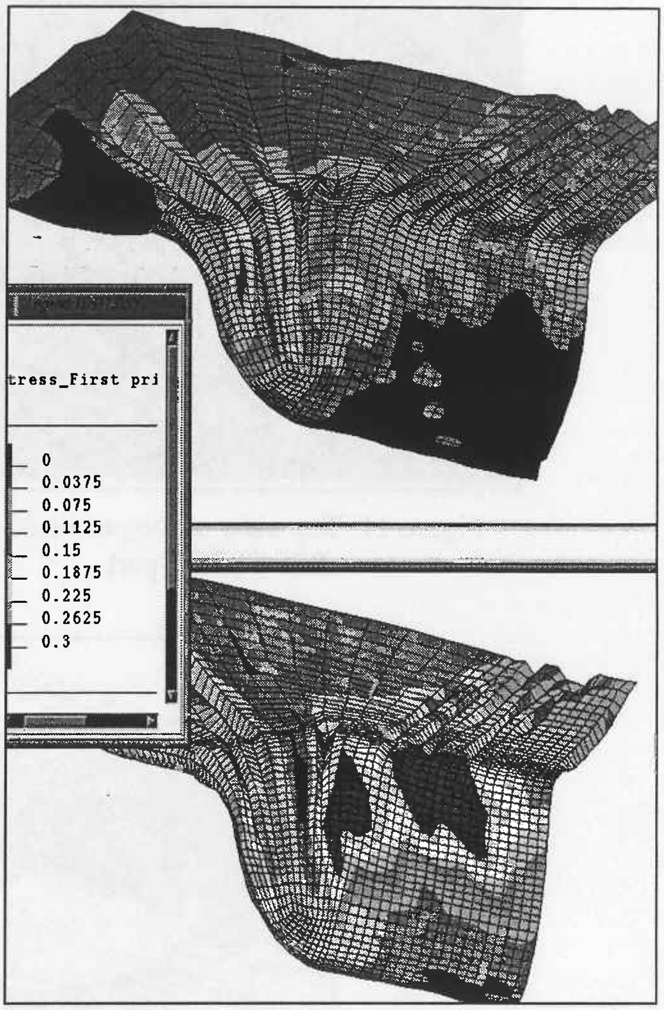

Figure 10: Top ply (45°) 1st principal stress (Gpa). Comparison without (top) / with (bottom) blankholder.

5- PEI-CETEX STUDIES

These parts are fabricated using 8 plies of PEI-CETEX giving a total laminate thickness of 2.6 mm. Studies have investigated the influence of the stacking sequence, the forming velocity and the clamping system.

<u>5-1 The quasi-isotropic part</u>

The stacking sequence of the quasi-isotropic part is $[(+45°,-45°),(0°,90°)]_2$. The forming velocity is 40 mm/s. Experimental results in Figure 11 show that there are less wrinkles than with APC2-AS4 parts particularly in the 90° flat area. However, there is still some buckling which may be easily seen in figure 11 from the line discontinuities. There is also some fibre rupture on the bottom ply, especially in the spherical area where there is a high level of stress (figure 12). Figure 13 and 14 show the numerical simulation results which indicate similar trends to the experiments.

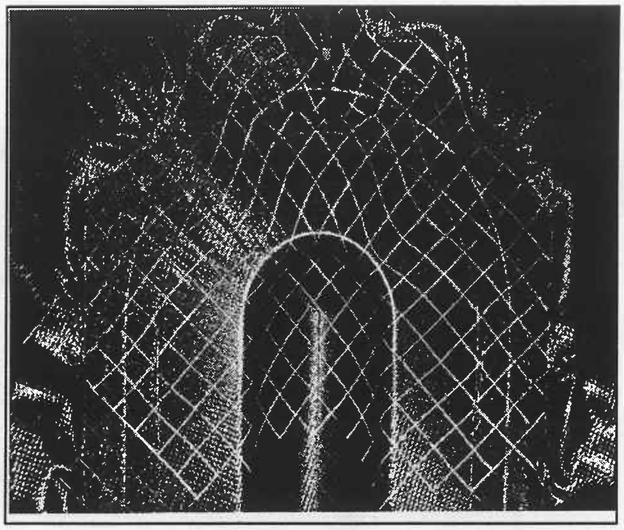

Figure 11: Top view of thequasi-isotropic PEI-CETEX part.

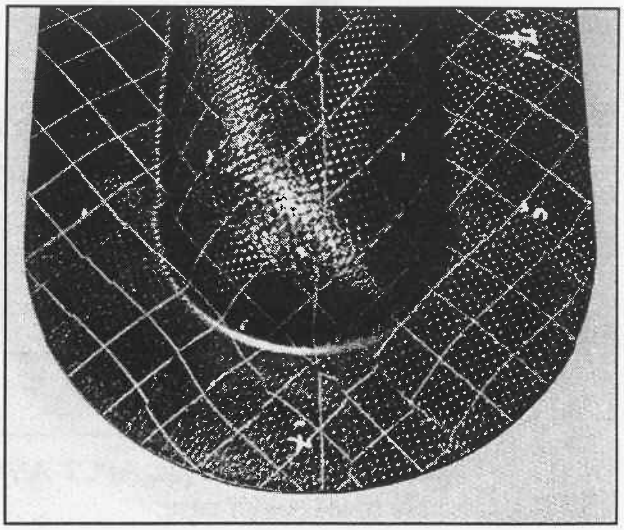

Figure 12: Bottom view of the quasi-isotropic PEI-CETEX part.

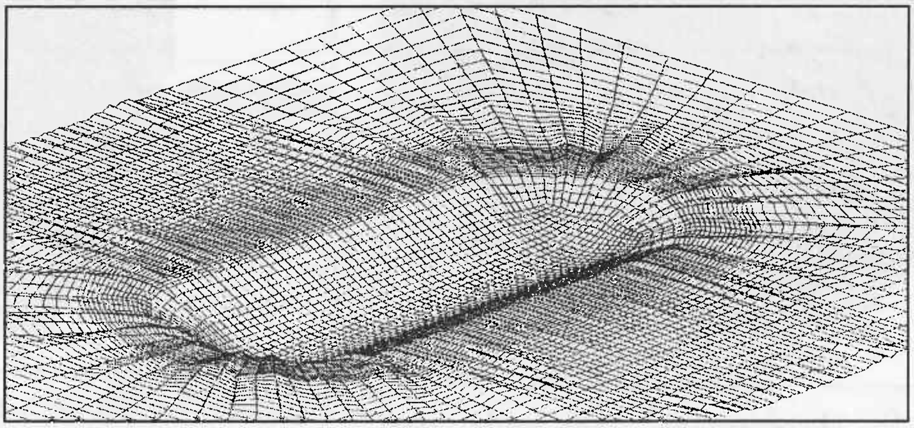

Figure 13: Intermediate deformed state of the quasi-isotropic PEI-CETEX part.

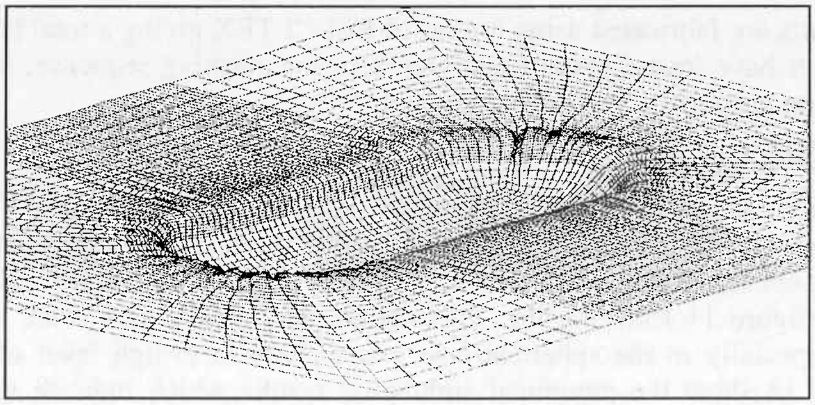

Figure 14: Final state of the quasi-isotropic PEI-CETEX part.

5-2 Influence of the forming velocity on the quasi-isotropic part

Due to the importance of the viscous effects on material formability it is anticipated that the forming velocity will play a major role in the forming process. A lower loading velocity will generate lower viscous forces at the inter-ply sliding between plies and the intra-ply shearing of individual plies. This will minimise the difficulty for a plies to conform to a given shape and should lead to less wrinkling. This has indeed been observed experimentally for the sikkens part.

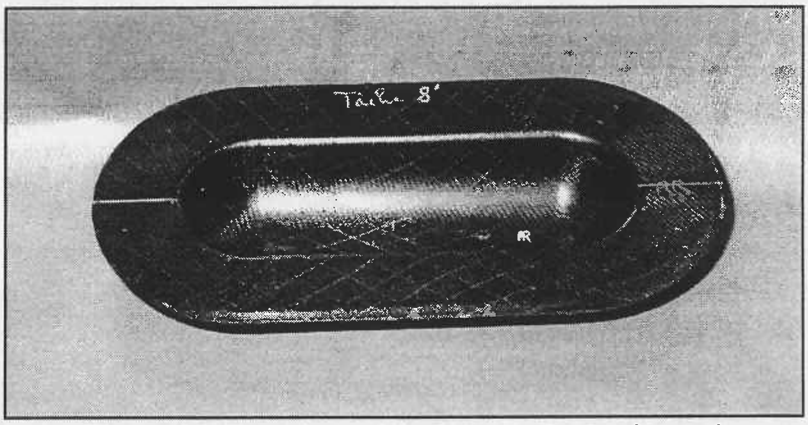

Figure 15: Top view of the lower velocity formed quasi-isotropic PEI-CETEX part.

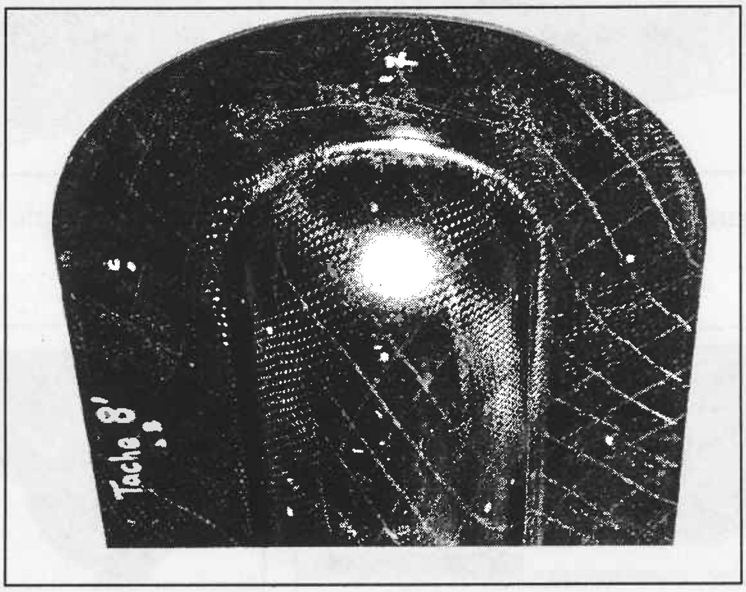

Figure 16: Top view of the lower velocity formed quasi-isotropic PEI-CETEX part.

The quasi-isotropic PEI-CETEX part is formed with a lower forming velocity of 5 mm/s compared to 40 mm/s as used in section 5-1. Figures 15 and 16 show that using a lower rate of loading produces good quality parts without wrinkling or rupture of the fibres. From figure 16 it may be seen that there is a locking of the fibre angle which is more pronounced than with the high forming velocity. Finally, the thickness distribution is found to be much smoother using the lower forming velocity.

The numerical simulation shows the same trends that using a lower loading velocity will generally reduce ply wrinkling. It should be noted that even the low velocity press forming gives a much faster cycle time than typical autoclave forming which can lead to significant cost saving in series production.

Figure 17 shows the intermediate and the final deformed states of the quasi-isotropic PEI-CETEX part formed using the lower velocity. Further investigations of the stress levels reached in the plies for the two cases shows that significantly greater stresses are present in the 40 mm/s forming velocity case (figure 18); this explains the fiber rupture observed in the spherical part. Figure 19 shows the comparison of the shear stress distribution obtained in the two cases. As anticipated the lower loading velocity generates lower viscous dependant inter- and intra-ply stresses which enables the laminate to deform more easily to the required sikkens shape (see the higher shear stresses obtained in the low velocity case).

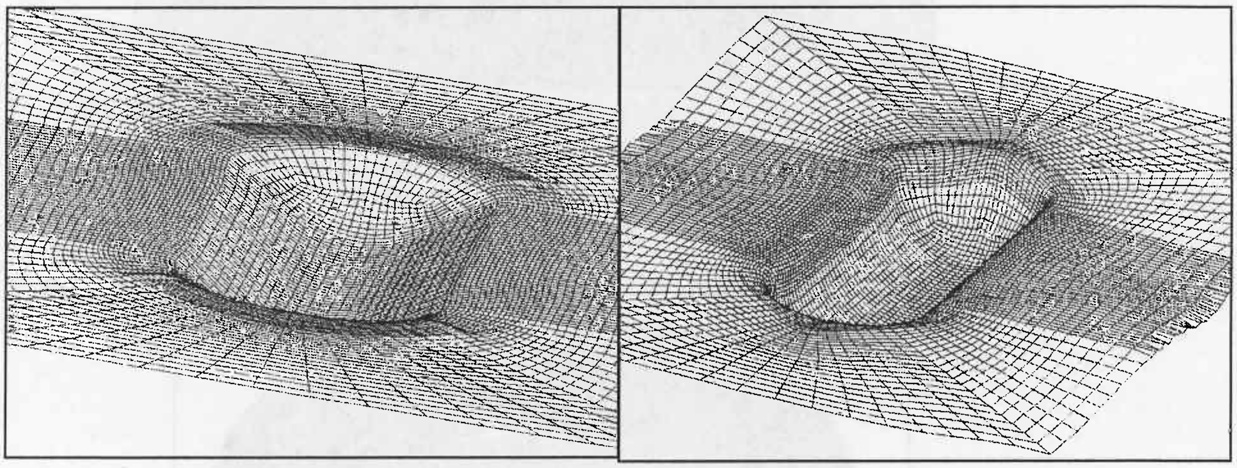

Figure 17: Intermediate and final state of the quasi-isotropic PEI-CETEX part.

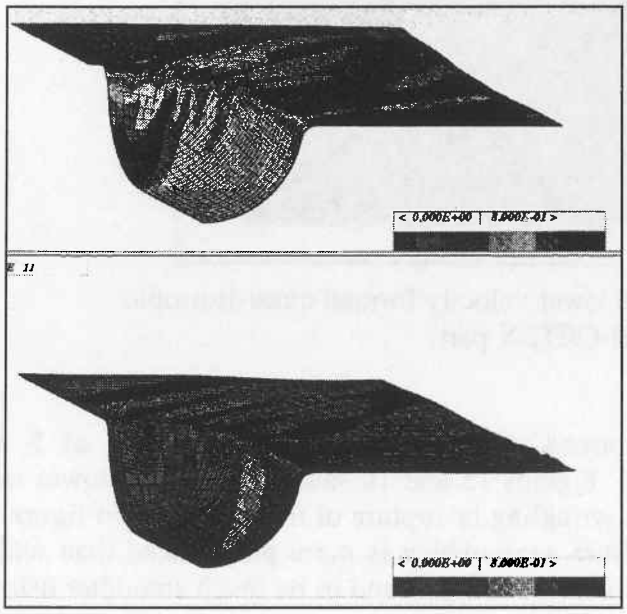

Figure 18: Bottom ply fibre stress. Forming velocity= 40 mm/s (top) and 5 mm/s (bottom).

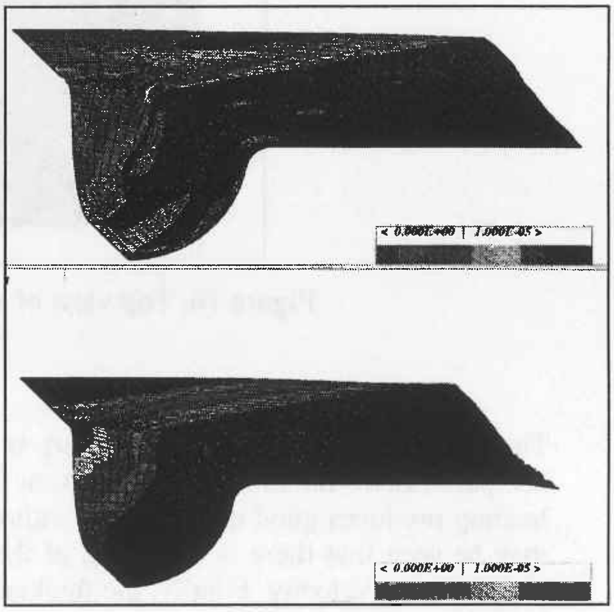

Figure 19: Bottom ply shear stress. Forming velocity = 40 mm/s (top) and 5 mm/s (bottom).

5-3 Influence of the laminate stack-up

The laminate formability is investigated using the higher forming velocity of 40 mm/s and an alternative stacking sequence of $[(0^\circ,90^\circ)]_8$.. Figure 20 shows that in this case there are no wrinkles or ply delaminations. This indicates that the formability of this stacking sequence is improved, but as may be expected the structural mechanical properties will be reduced. Figure 21 shows the numerical simulation results which gives similar deformations to the tests.

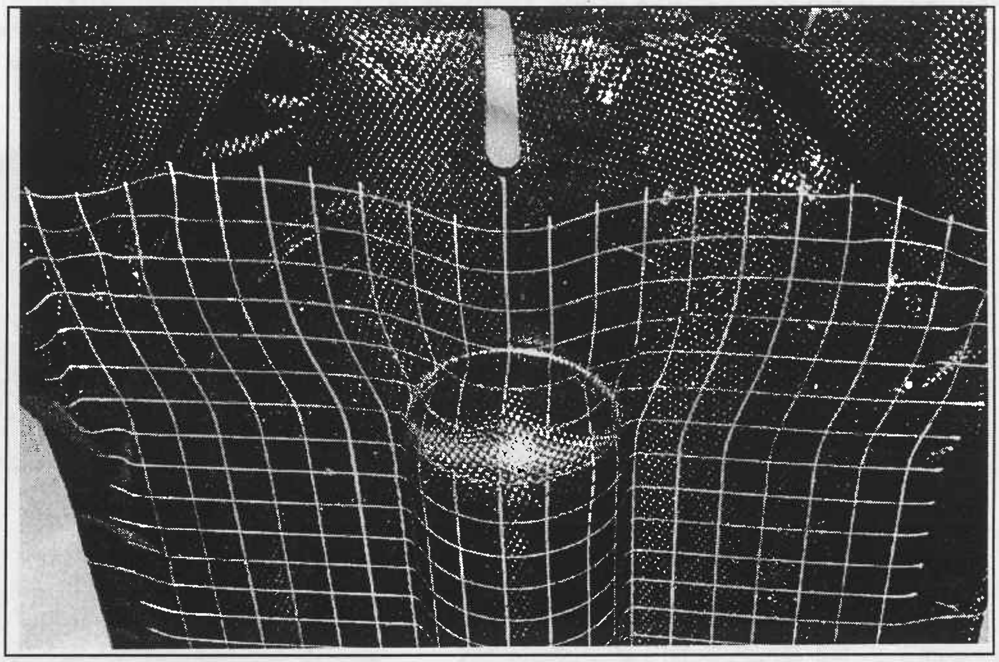

Figure 20: Bottom view of the $[(0^\circ,90^\circ)]_8$ PEI-CETEX part

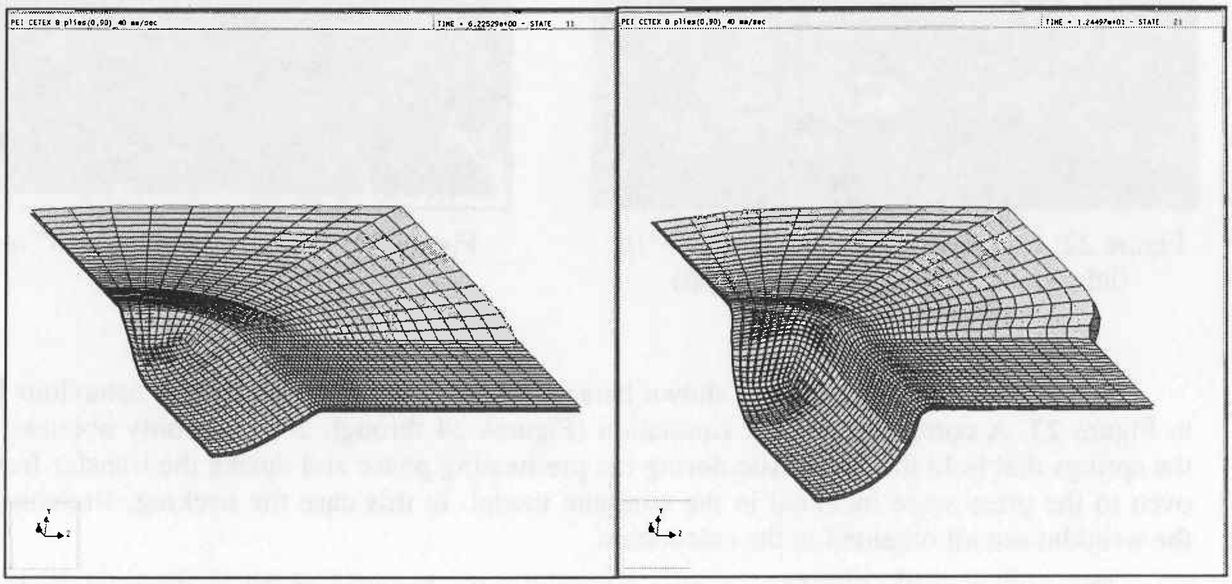

Figure 21:Intermediate and final state of the $[(0^\circ,90^\circ)]_8$ PEI-CETEX part.

5-4 Influence of the clamping system using the [(+45°,-45°)]$_8$ part

The final investigation considers the influence of the clamping system using the cross-ply [(+45°,-45°)]$_8$ PEI-CETEX part. This stacking sequence is considered to have high formability. The forming velocity used is 40 mm/s.

The part is different from the previous examples described. Particularly noticeable is the large necking and associated stretching that develops in the 0° direction (Figure 22). Another manifestation of this structure is shown in Figure 22 where large shear strains may be seen in the rounded section. Some wrinkling is also visible in the flat area in the 90° direction. The reason of this phenomenon was not understood from testing, but a detailed study of the numerical solutions has helped provide the answer.

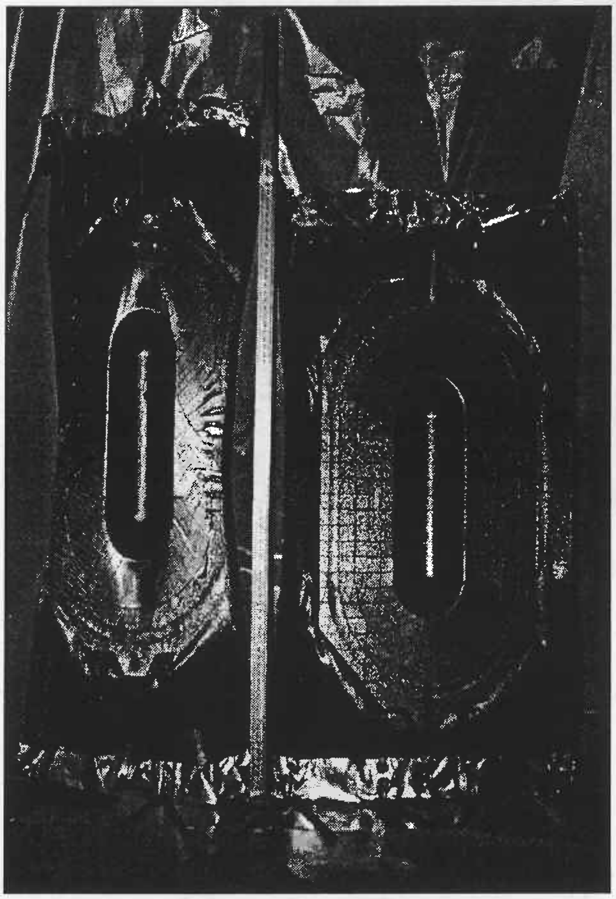

Figure 22: Comparison of the [(+45°,-45°)]$_8$ (left) and the quasi-isotropic (right) PEI-CETEX part.

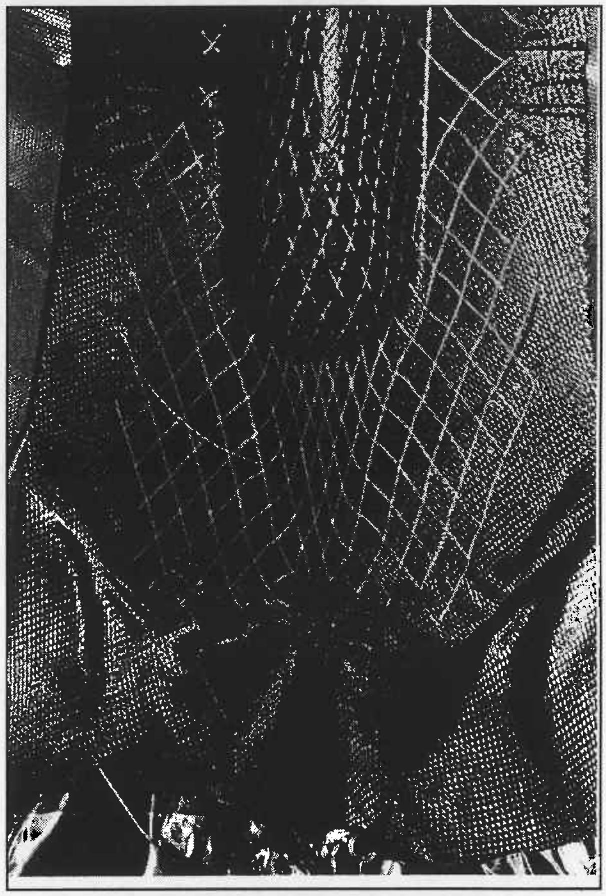

Figure 23: Top view of the [(+45°,-45°)]$_8$ PEI-CETEX part.

Some initial simulations (not shown here) did not show the characteristic behaviour found in Figure 23. A correct numerical simulation (Figures 24 through 26) were only obtained once the springs that hold the composite during the pre-heating phase and during the transfer from the oven to the press were included in the compute model. In this case the necking, stretching and the wrinkles are all obtained in the calculation.

The reason of the wrinkling is that the composite, because of the necking, starts to slide below the blankholder during the forming. Consequently the tension forces decrease and become insufficient to prevent the appearance of the wrinkles. Figure 26 is an exploded view of pressure distribution in plies 1 (bottom), 4 and 8 (top) at the final deformation state. From this it may be seen that the contact pressure is low on the flat area in the 90° direction and therefore unable to generate the necessary tension forces (the dark areas of the figure 26 correspond to low pressure areas). Also superimposed on the figure are the final isolines of the fibre directions. The locking in the rounded part is clear and can be compared to the experiment results (Figure 26): it has been shown that the numerical results agree to within 5% of test results [14]. The numerical simulation also predicts the thickening due to the necking in the central zone. The thickness increases from 2.8 mm to over 4.0 mm.

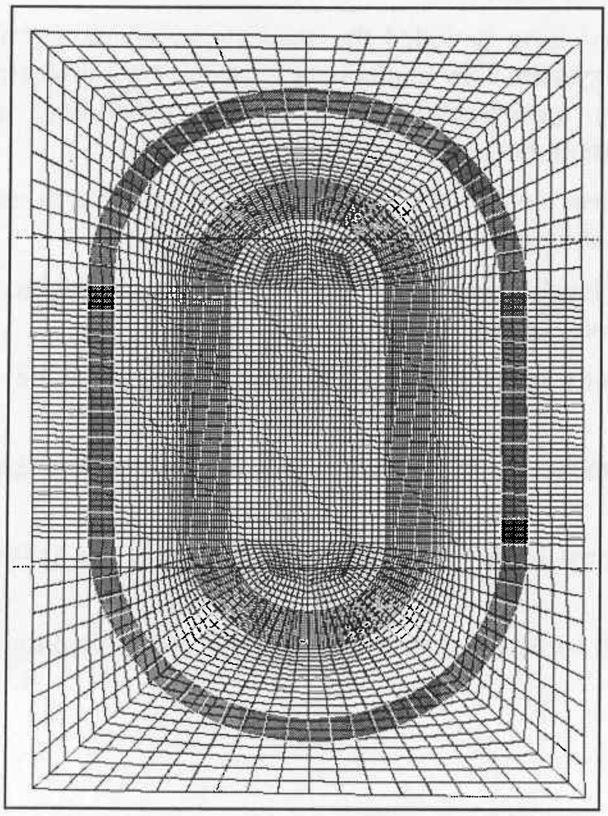

Figure 24: Initial configuration of the $[(+45°,-45°)]_8$ PEI-CETEX part with blankholder.

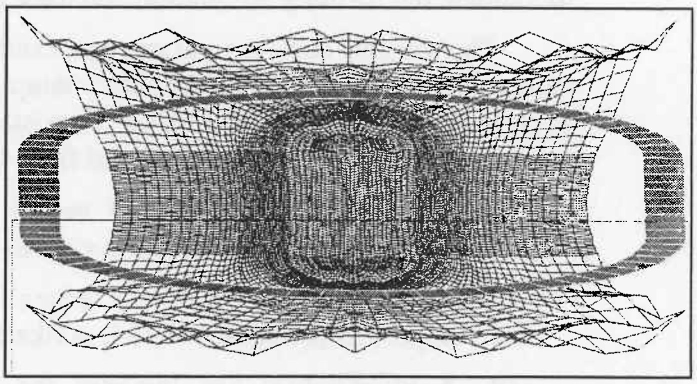

Figure 25: $[(+45°,-45°)]_8$ PEI-CETEX part and blankholder. After pre-heating, before forming.

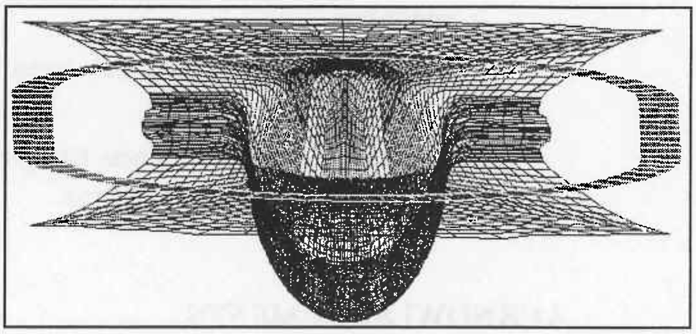

Figure 26: End of forming the $[(+45°,- 45°)]_8$ PEI-CETEX part with blankholder.

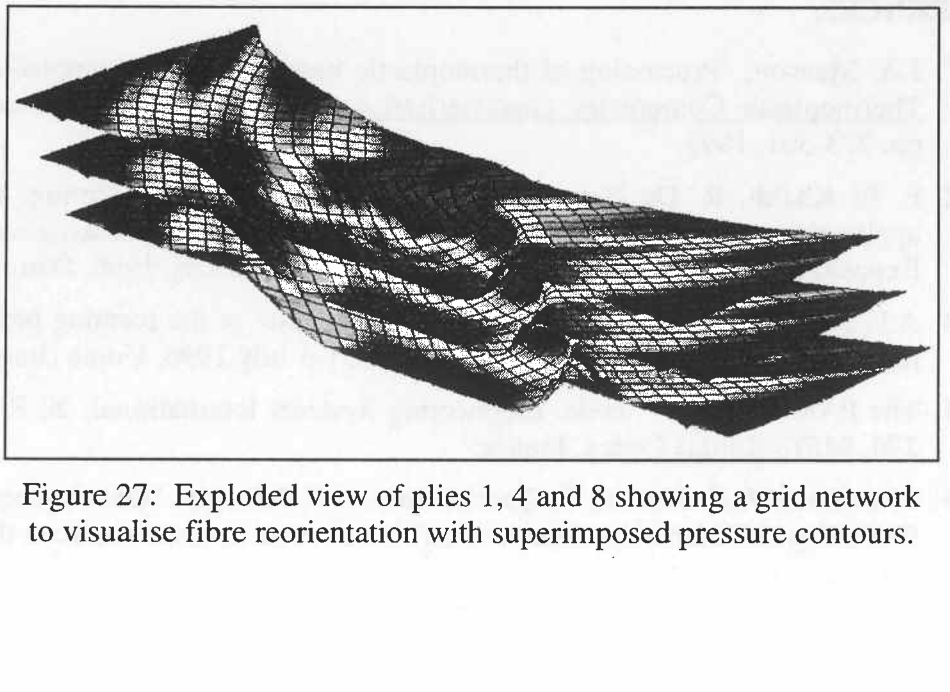

Figure 27: Exploded view of plies 1, 4 and 8 showing a grid network to visualise fibre reorientation with superimposed pressure contours.

6- CONCLUSION.

This paper has presented a comprehensive study of the forming of a sikkens component using two carbon fibre reinforced thermoplastic materials; namely, APC2-AS4 and PEI-CETEX. Both experimental and simulation techniques have been used to understand the formability of the two materials under different processing conditions. Furthermore the opportunity has been taken to validate the forming simulation software against experimental tests.

The various forming parameters examined have included the stacking sequence, forming velocity and the use of a blankholder clamping system. The results have proven very satisfactory. In particular the simulation has consistently agreed with test results in predicting such phenomena such as ply wrinkling and fibre reorientation.

Experimental and simulation results have identified the following effects which most influence material formability in the various cases studied here:

i) A low punch velocity will reduce the level of intra- and inter-ply viscous forces giving improved formability and less likelihood of ply wrinkling.

ii) A blankholder can increase the zones of tensile loading and thereby reduce ply wrinkling.

iii) The influence of the clamping system has been demonstrated on a specific stacking sequence.

iv) The stacking sequence has been shown to have a strong influence on the material formability.

Generally the numerical code has proven to be a valuable tool for the understanding and prediction of the press forming process.

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