A STUDY INTO THE FORMING OF ADVANCED THERMOPLASTIC COMPOSITE LAMINATES IN DIAPHRAGM FORMING

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ABSTRACT

Diaphragm forming offers several advantages over other forming techniques in the manufacture of advanced thermoplastic composites. The technique can be used in the forming of complex curvature parts. It produces parts with excellent surface finish and can provide an isothermal environment during forming. This work investigates the effect of buckling in both a single and double curvature moulds using APC-2 as the working material. A control system was set up to provide linear displacement of parts during forming and was found to be accurate within the range of 1-100mm/min. In the double curvature elliptical dish mould buckling was established for both cross ply and quasi isotropic layups. Forming rate experiments were also carried out on a single curvature 90° mould, however no buckling occurred. An estimation was made on what rates are likely to induce buckling, using tensile test data which was carried out on Upilex RV at 390°C and ply pullout tests on APC-2 which were carried out at the same temperature. An investigation was also made into the effect of spring forward on 90° parts from both a male and female tool for both APC-2 and CF-PEI. The parts made from the male tool in each case had larger spring forward. It is felt that this is due to the different cooling characteristics of the parts. The effect of consolidation pressure was also investigated for $[0/90]_{2S}$ APC-2 layups in the male 90° mould. It was found that a consolidation pressure in excess of 200kPa was required to fully consolidate these parts. The time held at consolidation was also investigated, with the dwell being varied from 15 to 45 minutes. This was found to have little effect on the quality of the part.

1. INTRODUCTION

The introduction of thermoplastic composites has given the composite industry increased scope in the design of components. The main advantages of thermoplastic composites compared to thermosets are superior damage tolerance, good hot/wet performance, unlimited shelf life and shorter processing cycles. The ability to reuse and reprocess the thermoplastic material a number of times without significant loss of properties can also reduce costs significantly.

In order to facilitate the introduction of thermoplastic composites into industry, it is necessary to be able to understand and predict forming phenomena which may occur. A major problem in the forming of thermoplastic composite laminates is the occurrence of fibre buckling in the laminate, and this clearly could effect the in-service performance of a finished component. Previous work in the area of buckling of thermoplastic composite laminates has shown buckling to be dependant on three parameters: original preform dimensions[1], forming rate[2] and the stiffness of the diaphragms[2]. This work looks at the buckling phenomenon for both a double and single curvature mould. All parts were formed using APC-2 material.

Another phenomemon which occurs is that of spring forward. When a fibre reinforced laminate is formed into a mould at the processing temperature of the laminate, and is then cooled and removed from the mould there will be a decrease in the formed angle of the part. Therefore it is necessary to quantify this effect for accurate mould design. This work looks at the effect of forming 90° composite parts from both a male and female mould. The semi-crystalline APC-2 and the amorphous CF-PEI thermoplastic composites were both used to investigate this effect. Amorphous polymers compared to semi-crystalline polymers tend to give a more attractive glossy surface finish, however they tend to be more susceptible to creep and fatigue[3]. Composites manufactured from the amorphous range of thermoplastics can meet the most stringent flammability requirements, and thus could be used in aircraft interiors[4]. APC-2 has not only good temperature resistance but high toughness, and so offers the possibility of being suitable for primary aircraft structures[4].

Optimisation of the pressure consolidation cycle is also another important factor which requires investigation during forming of thermoplastic composite laminates. Thus the diaphragm forming technique provides an ideal environment to carry out this experimental work under isothermal conditions. A male 90° mould was used to analyse this effect with a $[0/90]_{2S}$ APC-2 layup being used in each test.

2. EXPERIMENTAL:

The diaphragm forming techniquehas been derived from vacuum forming of a thermoplastic sheet. In diaphragm forming the laminate is placed over the mould between two plastically deformable diaphragms. These diaphragms exert a biaxial tension on the laminate during forming and can help to prevent such effects as wrinkling and buckling.A vacuum ring between the diaphragms helps to extract air or any generated gases from the laminate as the thermoplastic matrix is brought to its processing temperature. References[1,5] offer a detailed description of the diaphragm forming process.

Three mould geometries were used in the analysis,a male elliptical dish mould and a male and female 90° moulds. These moulds are shown in Figures 1 and 2 respectively.

Buckling of thermoplastic composite laminates was investigated by use of a male elliptical dish mould and a female 90° mould. The 90° moulds were used to measure the spring forward phenomemon. The variation of consolidation pressure and the time spent at consolidation was analysed using the male 90° mould.

To analyse the effect of buckling it was necessary to be able to monitor and control the forming rate of the composite into the mould. This was achieved through the use of a high temperature Linear Variable Differential Transformer (LVDT), model number LIN 256, with a linear range of ±25mm. The central core of the LVDT was placed directly over the undeformed pre-preg layup and allowed to follow the displacement of the part during the forming sequence as shown in Figure 3.

The AC output from the LVDT is first rectified using a signal conditioning unit, and it is this signal which is used to control the pressurisation rate of the autoclave, to obtain the desired forming rate. A data acquisition system was also installed to facilitate the recording of the parameters, pressure, displacement and temperature. The output signals from the respective transducers and thermocouples are then sent back to a PC via an EXP-16 multiplexer board and a DAS-8PGA analogue to digital card.

3. RESULTS AND DISCUSSION:

Buckling was first established on the elliptical dish mould using $[0/90]_{2S}$ and $[0/\pm45/90]_{S}$ layups. Forming rate experiments for the $[0/90]_{2S}$ layup were carried out at 6, 15, 25mm/min, with buckling established at 25mm/min for this layup. The parts formed at 15, 25mm/min are shown in Figure 4. It can be seen from Figure 4 that out of plane buckling is just beginning to occur in positions marked *A* and *B*, with identical buckles occurring on the other side of the part. As the forming of a quasi-isotropic would clearly develop much higher shearing stresses, forming was carried out at much lower rates. The onset of buckling being established at 3mm/min. Indeed it was necessary to form at 1mm/min to obtain a quasi-isotropic part without out of plane buckling.The forming time alone for this part was forty six minutes. The parts which were formed at 1 and 3mm/min are shown in Figure 5. The stiffness of the quasi isotropic layup was greater than that of the $[0/90]_{2S}$ layup, with the pressure reguired to form the former 175kPa and the latter 150kPa.Clearly the analysation of the forming mechanisms within an elliptical dish part is non trivial and first reguires a full understanding of the forming of single curvature parts such as 90° L-section parts.

Forming rate experiments were carried out using both 90° moulds at various rates. The maximum rate at which parts can be accurately formed was 100mm/min, above this rate the intake of pressure into the autoclave was not sufficient to accurately follow the autoclave controller to give a linear displacement.Plots of the forming characteristics for the part formed at 100mm/min are shown in Figure 6-7. Figure 6 illustrates the linearity of the part displacement during forming. The pressure rise however is non-linear and rises exponentially as the part forms. This is clearly shown in Figure 7. The maximum forming rate using pressure control was 400kPa. It took twice as much pressure to form parts in the female mould as it did in the male mould.Typical forming pressures for 8 ply laminates in the male mould was 50 kPa, whereas it required pressures of 100kPa to form similar laminates in the female mould. Fibre spreading in the region of the bend was much more significant in parts made in the female mould, and necessitated the use of slip plies(see Figure 8). This concurs with the work of Mallon[6].Thus for parts formed in the female mould at the pressurisation rate of 400kPa, the forming time was 15 seconds.These forming speeds did not induce buckling.It was clear that the shearing force transmitted by the Upilex-RV diaphragms onto the laminate during forming was adequate to ensure that sufficient interply slip occurred to prevent buckling.

Muzzy[7] highlighted the ease in which fibres can buckle in the forming of a 90° part in the absense of a tensile force being applied on the laminate. He compared the start of forming of a 90° bend to three point bending. Therefore as fibres will be both in tension and compression during forming, both the tensile and compressive stresses can be approximated by

$$\sigma_{1T} = V_f E_f \varepsilon_{1T} \qquad (1)$$

$$\sigma_{1C} = \frac{G_m}{1-V_f} \qquad (2)$$

By assuming that the modulus in tension is equal to the modulus in compression, the equation can be combined to obtain the critical buckling strain for APC-2, and is

$$\varepsilon_{1CB} = \frac{G_m}{V_f E_f (1-V_f)} = \frac{10\ \text{MPa}}{0.61(220\text{GPa})(0.39)} = 1.9\% \qquad (3)$$

This underlines the importance of the diaphragms in maintaining a biaxial tension on the laminate during forming, as buckling can occur at very low compressive strains.

This shear force exerted by the diaphragms must be able to overcome both the yield force of the PEEK, and the induced shear forces between the individual plies due to the applied forming rate to prevent out of plane buckling occuring. When the Upilex-RV diaphragms has formed fully into the female mould, the Upilex is strained by 21%. Work carried out by Bradaigh[8] suggests that there is a high degree of coupling between the diaphragms and laminate during forming. Thus the corresponding stress resulting from the strained diaphragms should be transmitted to the laminate. Uniaxial tensile tests have been carried out by Monaghan[9] on Upilex-RV at 390°C (the processing temperature of APC-2). Therefore from this work a value of 21% engineering strain on the Upilex RV corresponded to an engineering stress value of 3MPa. The resulting force on the Upilex when the laminate is fully formed can be obtained by dividing the stress by the cross sectional area of Upilex in contact with the laminate, and is 28.1N.

Murtagh[10] has carried out work investigating the interply slip process of APC-2. This was done using a specially designed rig which can provide a normal force for consolidation and a shearing apparatus which provides the pulling out force to a central ply of a chosen layup combination. This work is explained in greater detail elsewhere[10]. He found that by increasing the shearing rate during a pullout tests resulted in higher values of shear stress. By analogy it should be possible to use these results to predict the shear stresses developedwithin the laminate during forming of a 90° part by determination of the shear rate. The shear rate can be determined by the equation

$$\text{Shear Rate, } \gamma = \frac{v}{nh_i} \qquad (4)$$

where v is the shear velocity, n is the number of sheared layers and h_i is the resin layer thickness.

Thus a forming rate of 100mm/min into the female tooling corresponds to a shear rate of 0.75(1/s). Murtagh observed from his work that the effect of layup had little effect on the shear stress/shear rate results on all but the unidirectional layup, where much higher shear stresses were recorded. This may be explained by the processing cycle used,where laminates were first consolidated at 1MPa for 5 minutes. The pressure then being reduced to 100kPa to facilitate shear pullout. The consolidation pressure allowed fibres which were parallel to intermingle with fibres from other plies in the unidirectional layup. This had the effect of reducing the resin rich layer between plies, thereby causing higher shear stresses to be developed when ply pullout was initiated. Clearly little fibre interaction occurred between different plies in angled layups, though the obtained shear stresses may still be higher than those that would arise in diaphragm forming of a pre-preg layup due to the consolation pressure which was applied. Using these results a shear rate of 0.75(1/s) corresponded to a shear stress of 1.5kPa for a cross ply layup[refxx]. The corresponding sheared area on one side of a 90° part is, A= (60x75x2)mm^2· This corresponds to a shear force between plies of 13.5N. Therefore the forming rate would have to more than double before the tension which the diaphragms exert could be exceeded. Although using pressure control obtained much faster forming times the shear rate does not remain constant during forming, decreasing dramatically as the part reaches its fully formed position. Thus the shear stress levels are unknown for this forming case. As previously stated the shear stresses obtained by Murtagh are likely to be much higher than those to be expected in diaphragm forming. It is likely therefore that forming can be carried out at rates exceeding 200mm/min when using Upilex RV as a diaphragm material, while at the same time preventing buckling.

A spring forward analysis was carried out on both the male and female 90° moulds. Tests were carried out on both semi-crystalline and amorphous thermoplastic composites, APC-2 and CF-PEI respectively. The layups which were used as well the results which were obtained are shown in Table 1. The male mould produced parts which had an inside radius of 4mm and the female mould produced parts of inside radius 10mm. Spring forward has been proven to be independant of the radius of curvature of the mould[11] and so should not be a factor in this analysis. All angles were measured using a shadow graph. The processing conditions were kept constant in each case, with cooling being initiated two minutes after the consolidation pressure was reached, which in each case was 400kPa. At the end of the 15 minute consolidation dwell the APC-2 part temperature was approximately 230°C, and the parts were removed from the mould at this stage. The CF-PEI parts which had a processing temperature of 310°C were removed at approximately 145°C. Spring Forward is a thermally induced phenomenon which occurs as a laminate cools in its mould as a result of the anisotropy of the laminate[11], and is observed as a decrease in the enclosed angle of a part. The high temperature at which thermoplastic composites must be processed highlights the significance of these thermally induced stresses which result mainly from the large difference between the in plane and out of plane coefficients of thermal expansion[12]. As can be seen from the results presented in Table 1, the spring forward obtained from the male tooling is larger than that from the female in each case. It is felt that this is due to the positioning of the part during cooling. In the male tooling the enclosed angle of the part is effectively in contact with the tool as the part cools, thus slowing down the rate at which the bend cools. The oppisate then occurs in the female tool with the bend region being open to the air, which cools faster than the mould due to its larger thermal mass. A type K thermocouple was used to measure the temperature between the mould surface and the bottem diaphragm. It was found that once cooling was initated there existed a temperature difference of 30°C between the air temperature of the autoclave and the mould surface. This therefore would allow the female parts to cool quicker and may explain the difference in spring forward between the two moulds. $[90°]_8$ parts were also made in both tools under the same conditions, however the sides of the produced parts were curved which made the measurement of the enclosed angle very inaccurate. The experiment was repeated in the female mould, this time using a consolidation time of 75 minutes. The pressure was taken off and the part removed at approximately 100°C. This time the sides were perfectly straight and the spring forward was measured to be 0.3°. The spring forward in the carbon fibre PEI parts was smaller than that obtained from the APC-2 parts. This can be explained by the fact that the volume change of the amorphous composite compared to its semi-crystalline counterpart is lower as it solidifies from melt conditions[13].Thus the amorphous composite is less susceptible to distortions during cooling.

Consolidation experiments were also carried out on the male 90° mould using $[0/90]_{2S}$ layups in each case. Once again the forming conditions were identical to those which were used in the spring forward analysis. As previously stated the forming pressure required for this particular layup was 50kPa. During these experiments the vacuum pressure was also varied so that consolidation pressures varying from 100-600kPa could be examined,ie 60kPa autoclave pressure plus 40kPa vacuum pressure is equivalent to 100kPa consolidation pressure. The quality of the formed parts was assessed by ultrasonically C-Scanning the flat sides of each part. The scanning was carried out using the Pulse Echo Technique with Double Through Transmission. This system is not as yet calibrated to estimate the void content within the laminate, it can nevertheless provide a qualitative assessement of the consolidation quality. These scans of the parts at the various consolidation pressures are shown in Figures 10 - 16. It can be seen from Figure 12 that 200kPa consolidation pressure is the threshold pressure with all parts above this consolidation pressure perfectly well consolidated. All parts consolidated at lower pressures showed evidence of voids. It is interesting to note that the part consolidated at 100 kPa appears better consolidated than the part at 160kPa. This may be due to the fact that the latter had full vacuum pressure, which caused the diaphragms to be slightly stiffer. This may have prevented the part from being fully pressed against the mould. The consolidation time was varied from 15 minutes to 45 minutes on a part with a consolidation pressure of 160kPa, to ascertain did time held at pressure have any effect on a parts quality. As can be seen from Figure 17 the quality of the part having the dwell of 45 minutes is almost identical to that of the part with the dwell of 15 minutes.

4. CONCLUSIONS

A displacement forming rate control system was successfully designed and installed, which allowed forming rates between 1-100mm/min to be accurately obtained.
The onset of buckling was established for both a $[0/90]_{2S}$ and $[0/\pm45/90]_{2S}$ layup in an elliptical dish mould. The rates being 25mm/min and 3mm/min respectively.
Forming rates of up to 100mm/min and 400kPa/min were used on the female 90° mould, but buckling did not occur.
It was estimated that forming rates exceeding 200mm/min are required before buckling would occur in the 90° mould using Upilex RV diaphragms.
A spring forward analysis was carried out using both male and female 90° moulds. It was found that the spring forward was consistently bigger on the parts made from the male mould. It is felt that the positioning of the enclosed angle on the mould has a significant effect, whether it is in contact with the mould or open to the autoclave surroundings.
An examination was also carried out on the effect of consolidation pressure on $[0/90]_{2S}$ layups which were made in the male 90° mould. It was found 200kPa was the threshold consolidation pressure. Parts consolidated above this pressure appeared to be well consolidated, while parts below it appeared to be badly consolidated. The effect of time held at consolidation pressure was also investigated and was shown to little effect on the quality of the formed part once the part temperature had fallen below 230°C.

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6. REFERENCES

1. **Mallon, P. J.**, C. M. O'Bradaigh and R. B. Pipes. 1989. "Polymeric Diaphragm Forming of Complex-Curvature Thermoplastic Composite Parts", *Composites*, 20(1):45-56.

2. **Monaghan, M. R.** , C. M. O'Bradaigh, P. J. Mallon and R. B. Pipes. "The effect of Diaphragm Stiffness on the Quality of Diaphragm Formed Thermoplastic Composite Components", *SAMPE Quarterly*, 21(4):48-55, July 1990.

3. **Cogswell, F. N.** , "Thermoplastic Aromatic Polymer Composites", Butterworth-Heinemann Ltd., Oxford, England, 1992.

4. **Heym, M.** , E. D. Western, M. Winkler. "New Material Forms for Manufacture of Thermoplastic Composites",

5. **Mallon, P. J.** , and C. M. O'Bradaigh, "Development of a Pilot Autoclave for Polymeric Diaphragm Forming of Continuous Fibre-Reinforced Thermoplastics", *Composites*, 19(1):37-47.

6. **Mallon, P. J.** , C. M. O'Bradaigh, M. R. Monaghan and R. B. Pipes, "Admissable Deformations in Diaphragm Forming of Continuous Fibre Reinforced Thermoplastics". In *Proceedings of IUTAM Symposium on Inelastic Deformations in Composites*, May 1990. Rennssalaer, New York.

7. **Muzzy, J. D.** , X. Wu and J. S. Colton, "Thermoforming of High Performance Thermoplastic Composites". In *Proceedings of SPE Conference*, Antec 1989.

8. **O'Bradaigh, C. M.** , "Analysis and Experiments in Diaphragm Forming of Continuous Fibre Reinforced Thermoplastics", PhD thesis,pp. 61-63, Dept. of Mechanical Engineering, University of Delaware, December 1990.

9. **Monaghan, M. R.** , "Mechanical Characterisation of Polymeric Diaphragm Films", PhD Thesis,pp. 39-41, Dept. of Mechanical Engineering, UC Galway, June 1993.

10. **Murtagh, A. M.** , M. R. Monaghan and P. J. Mallon, "Investigation of the Interply Slip Process in Continuous Fibre Thermoplastic Composites". In *Proceedings of ICCM-9 Conference*, Madrid, June 1993.

11. **O'Neill, J. M.** , T. G. Rogers and A. J. M. Spencer, "Thermally Induced Distortions in the Moulding of Laminate Channel Sections", *Math. Engng Ind.,* Vol 2, No 1, pp. 65 - 72.

12. **Mulhern, M. B.**, "Design of Moulds for Thermoplastic Composite Components using a CAD Package". In *Proceedings of ICCM-9 Conference*, Madrid, June 1993.

13. **Cogswell, F. N.** , "The Experience of Thermoplastic Structural Composites during Processing", *Composites Manufacturing*, 2(3/4):208-216, 1991.

Figure 1. Elliptical Dish Mould used in the Buckling Analysis.

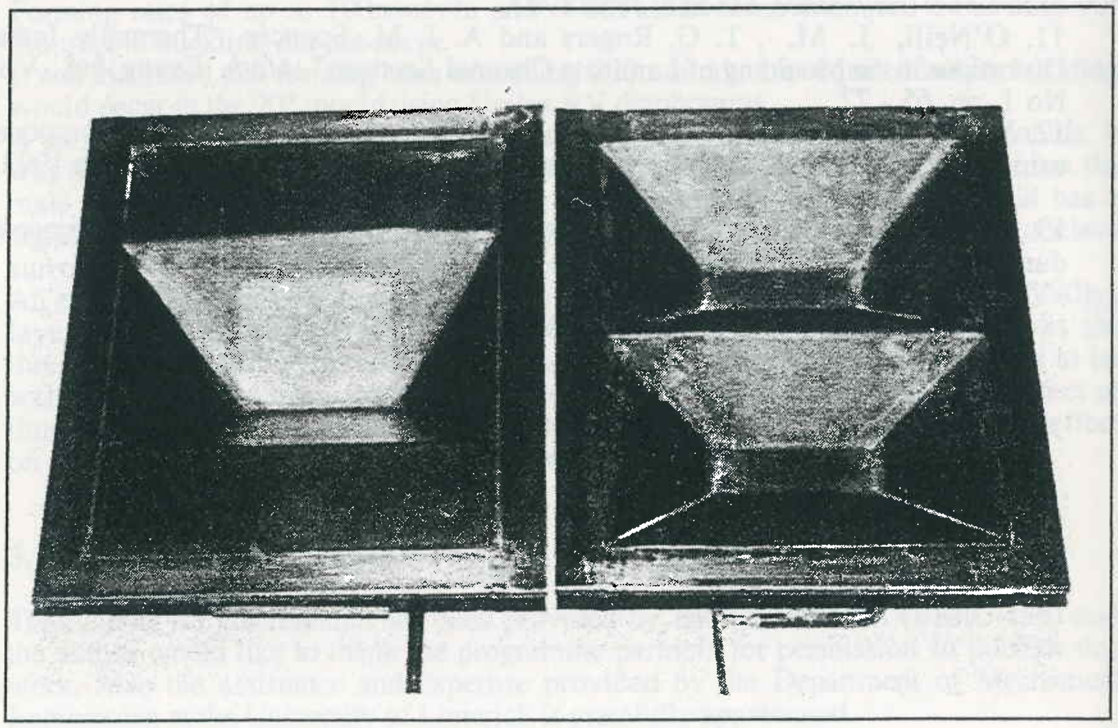

Figure 2. The 90° Moulds which were used in Buckling, Spring Forward and Consolidation Analysis.

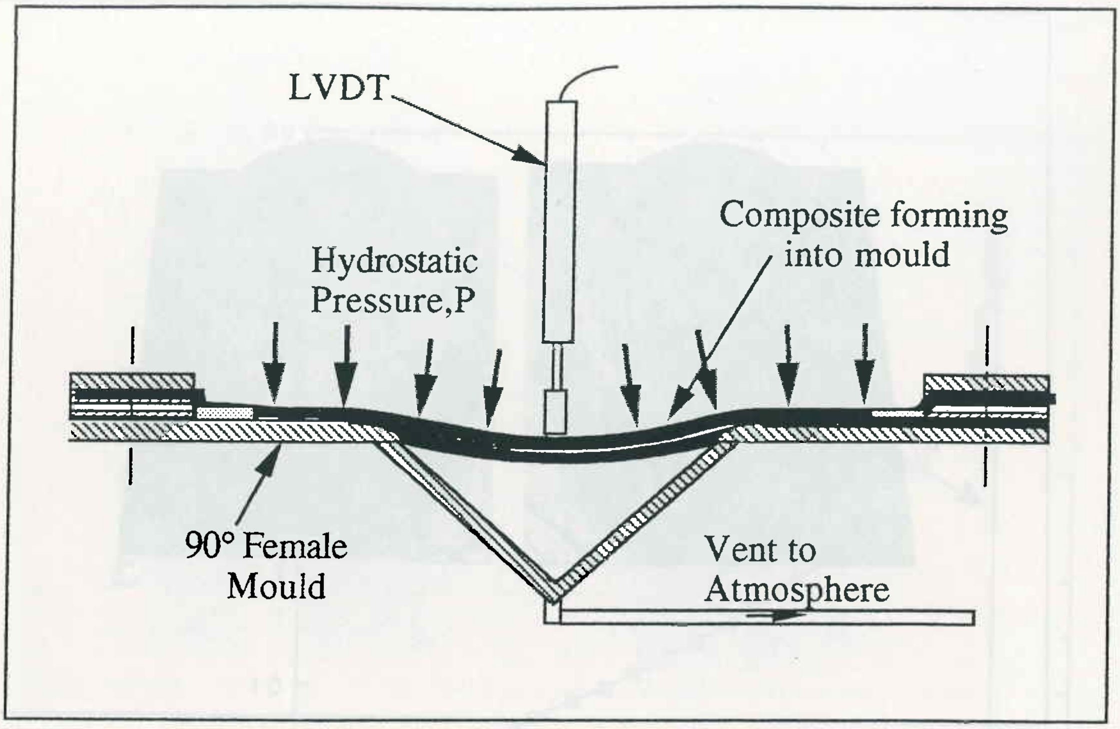

Figure 3. LVDT Arrangement over the Female Mould.

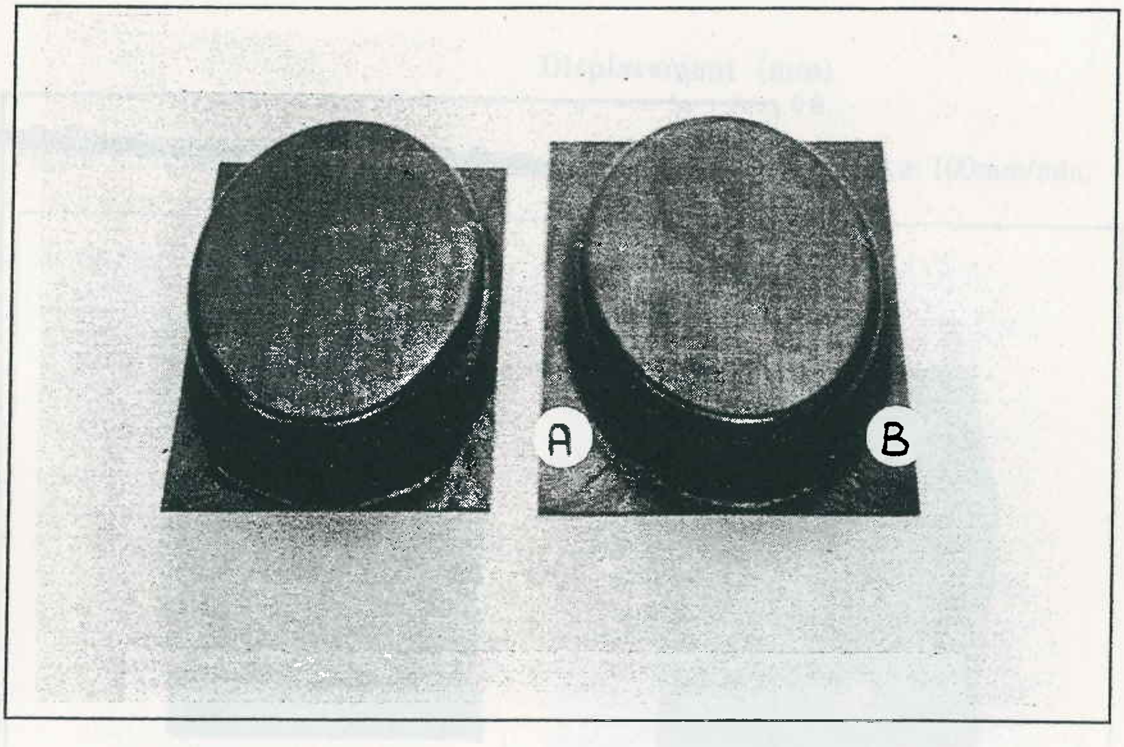

Figure 4. $[0/90]_{2S}$ parts formed at 15,25mm/min respectively.

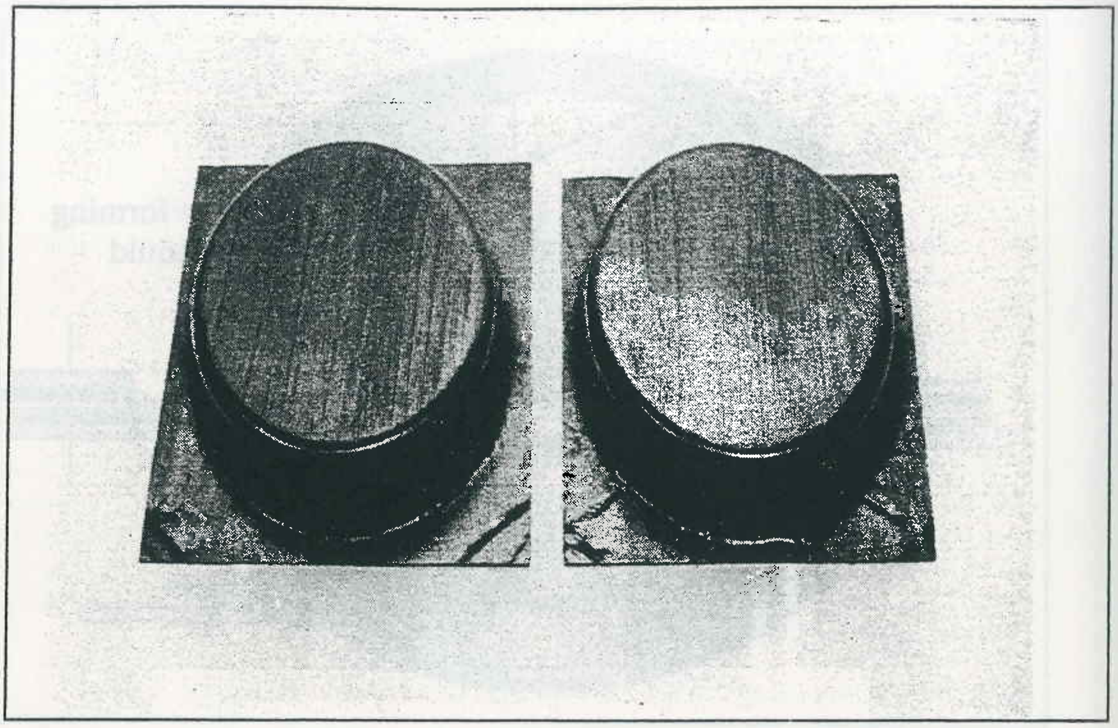

Figure 5. [0/±45/90]S parts formed at 1,3mm/min respectively.

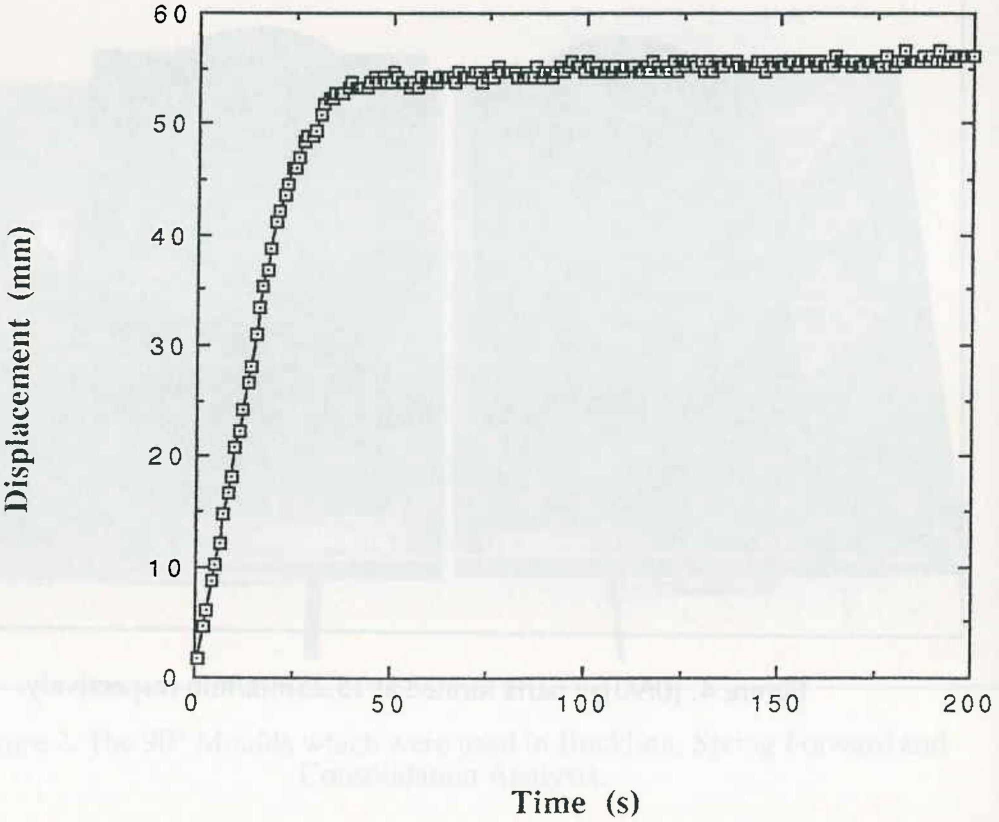

Figure 6. Controlled Displacement of 90° $[0/90]_{2S}$ Part Formed at 100mm/min.

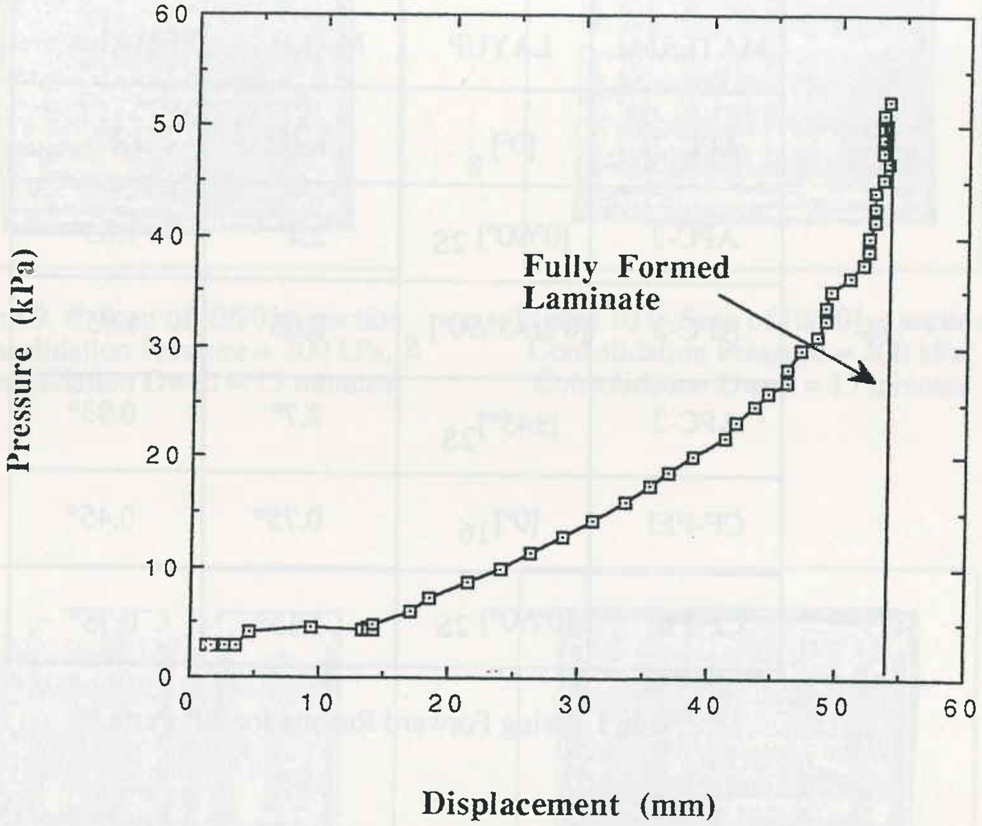

Figure 7. Pressure-Displacement Curve for 90° $[0/90]_{2S}$ Part Formed at 100mm/min.

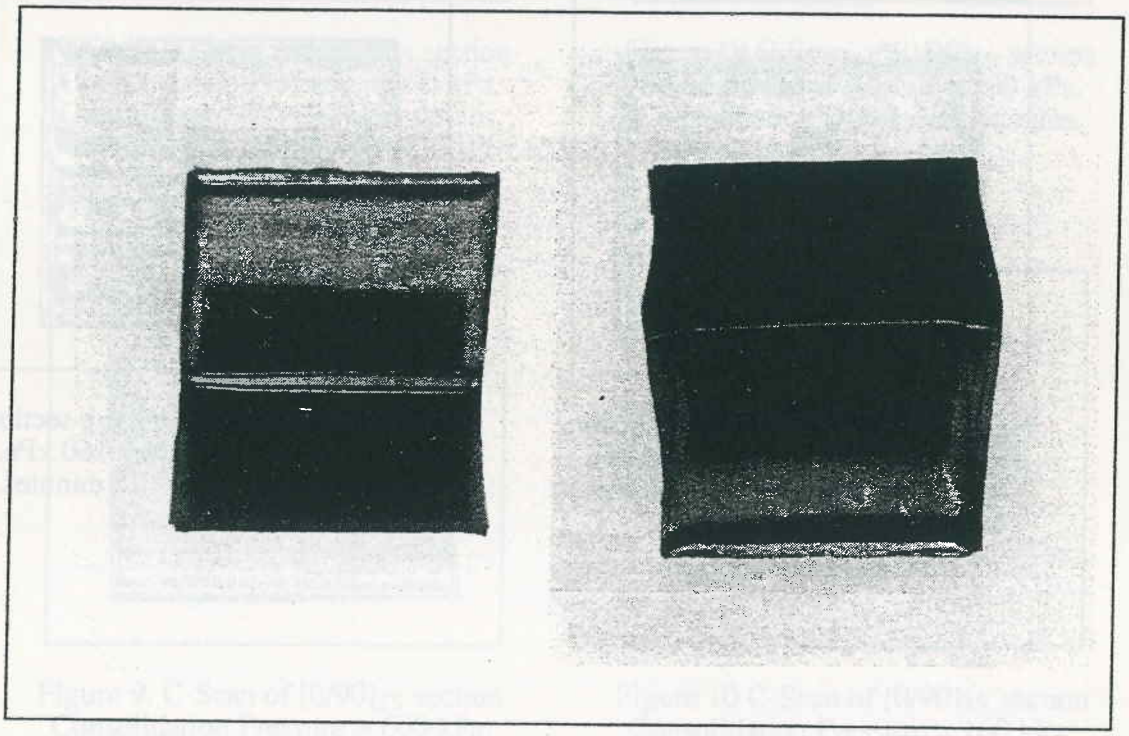

Figure 8. 90° Parts Formed in the Female Mould with and without Slip Plies.

MATERIAL	LAYUP	MALE	FEMALE
APC-2	$[0°]_8$	1.75°	1.5°
APC-2	$[0°/90°]_{2S}$	2.4°	1.85°
APC-2	$[0°/\pm45°/90°]_S$	2.6°	1.95°
APC-2	$[\pm45°]_{2S}$	2.7°	0.93°
CF-PEI	$[0°]_{16}$	0.75°	0.45°
CF-PEI	$[0°/90°]_{2S}$	1.15°	0.75°

Table 1.Spring Forward Results for 90° Parts.

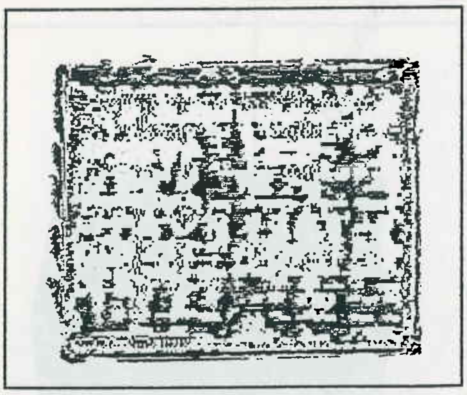

Figure 9. C-Scan of $[0/90]_{2S}$ section
Consolidation Pressure = 100 kPa.
Consolidation Dwell = 15 minutes.

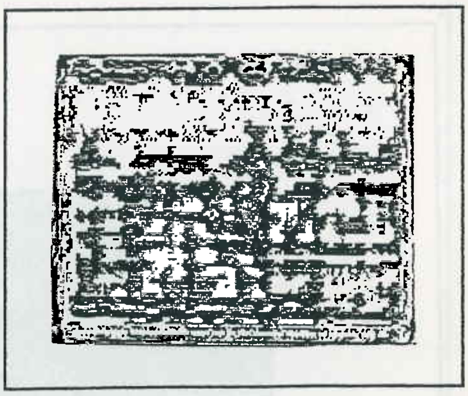

Figure 10 C-Scan of $[0/90]_{2S}$ section
Consolidation Pressure = 160 kPa.
Consolidation Dwell = 15 minutes.

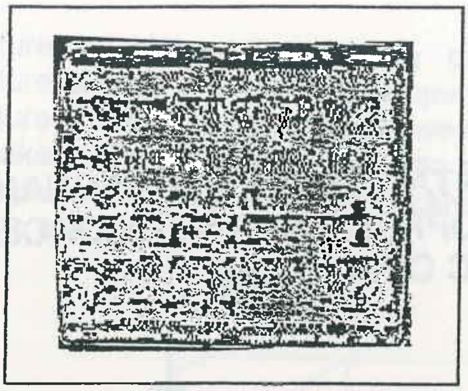

Figure 9. C-Scan of $[0/90]_{2S}$ section
Consolidation Pressure = 200 kPa.
Consolidation Dwell = 15 minutes.

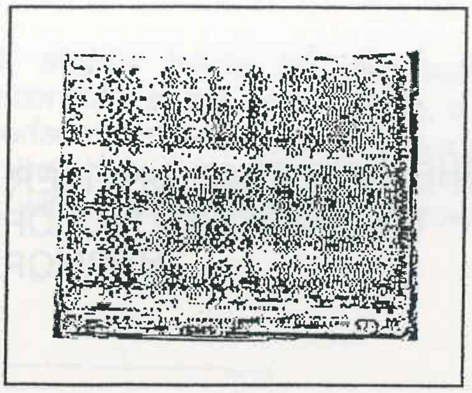

Figure 10 C-Scan of $[0/90]_{2S}$ section
Consolidation Pressure = 300 kPa.
Consolidation Dwell = 15 minutes

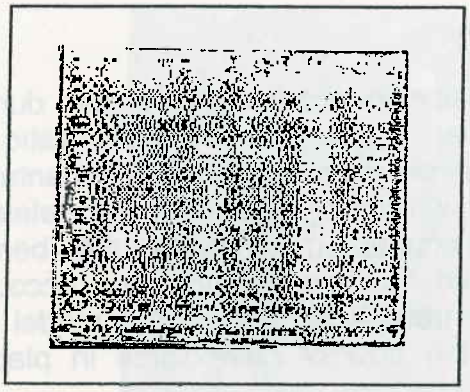

Figure 9. C-Scan of $[0/90]_{2S}$ section
Consolidation Pressure = 400 kPa.
Consolidation Dwell = 15 minutes.

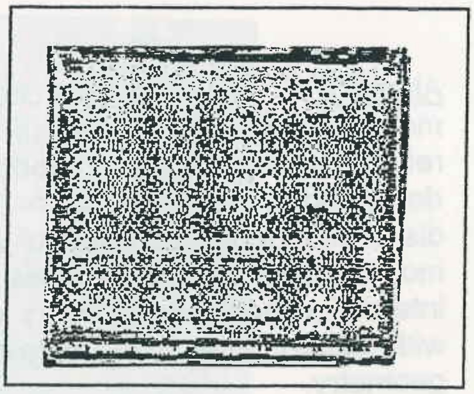

Figure 10 C-Scan of $[0/90]_{2S}$ section
Consolidation Pressure = 500 kPa.
Consolidation Dwell = 15 minutes.

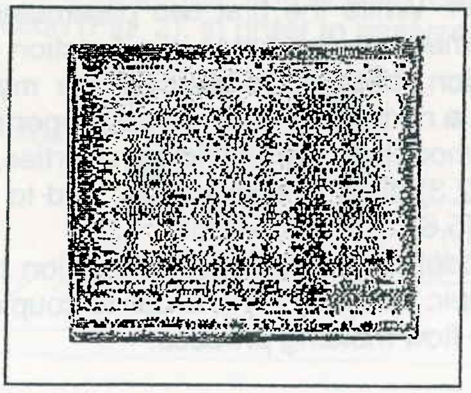

Figure 9. C-Scan of $[0/90]_{2S}$ section
Consolidation Pressure = 600 kPa.
Consolidation Dwell = 15 minutes.

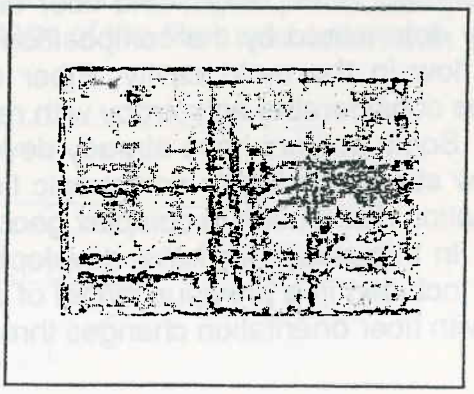

Figure 10 C-Scan of $[0/90]_{2S}$ section
Consolidation Pressure = 160 kPa.
Consolidation Dwell = 45 minutes.