Hot Drape Forming Of Thermoset Matrix Composites – Characterisation and Simulation

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Abstract

Hot drape forming of continuous fibre reinforced thermosetting composites is a process that is currently under development in the aerospace industry. Previous research work in continuous fibre reinforced sheet forming has focussed on the use of thermoplastic matrix composites, for which specialised finite element analysis codes and material characterisation experiments have been developed. This paper applies these characterisation techniques and numerical simulation methods for the first time to thermoset matrix composites. A picture-frame shearing test is employed to characterise the intraply shearing viscosity of a 2x2 twill carbon fibre reinforced epoxy prepreg. A transversely isotropic power-law material model is used to characterise the material, with an Arrhenius law to represent the viscosity variation with temperature. Finally, the intraply shearing viscosity law is incorporated, along with other material parameters, in a commercial finite element simulation of the hot drape forming process. A Linear Variable Differential Transformer is used to measure the displacement of a point in a structure during the forming process, and the result is compared to the output of the finite element code.

1. Introduction

Sheet-forming processes offer cost-effective production methods for fabricating high strength, lightweight structural component, of use to the aerospace, automotive and industrial sectors. Much work has been carried out on the characterisation and simulation of thermoplastic composite forming processes [1,2,3]. The finite element sheet-forming simulation development [4] has followed that of the metal stamping industry, where simulations are run to determine the optimum tool and blank shapes for the required part and whether that particular shape can be formed from a flat sheet of material.

Thermoset-matrix composite materials are much more widely used in the aerospace industry than thermoplastics, and recently, attention has focussed on the possibility of automatically sheet-forming uncured prepreg stacks over complex shapes, a process which is known as hot-drape forming [5].

It is widely accepted that four different modes of deformation exist for sheet-forming of molten continuous fibre reinforced thermoplastic composites. These are (Figure 1) interply shear, intraply shear, resin percolation and squeezing flow. It is likely that the same mechanisms are present in the forming of continuous fibre reinforced thermosetting materials.

The mechanism of interply shear is used when the material follows a single-curvature in at least one fibre direction, and has been characterised by the use of ply pullout tests [6]. The modes of resin percolation and transverse squeezing flows are encountered when the composite flows in response to pressure gradients in the material, such as might be encountered at corners or abrupt changes in mould geometry.

This paper will concentrate on the intraply shear deformation mechanism for thermoset composite materials. With this mode of deformation the fibres slide past each other in the plane of the material, while maintaining their original length. Intraply shearing is necessary for the composite to accommodate itself to a double-curvature mould shape. For unidirectional material there appears to be no limit to the amount of intraply shear that can be accommodated but for fabrics this is not the case. With fabrics a definite fibre locking angle restricts the amount of shearing possible, and buckling becomes likely (for fabrics intraply shear is often termed as trellising).

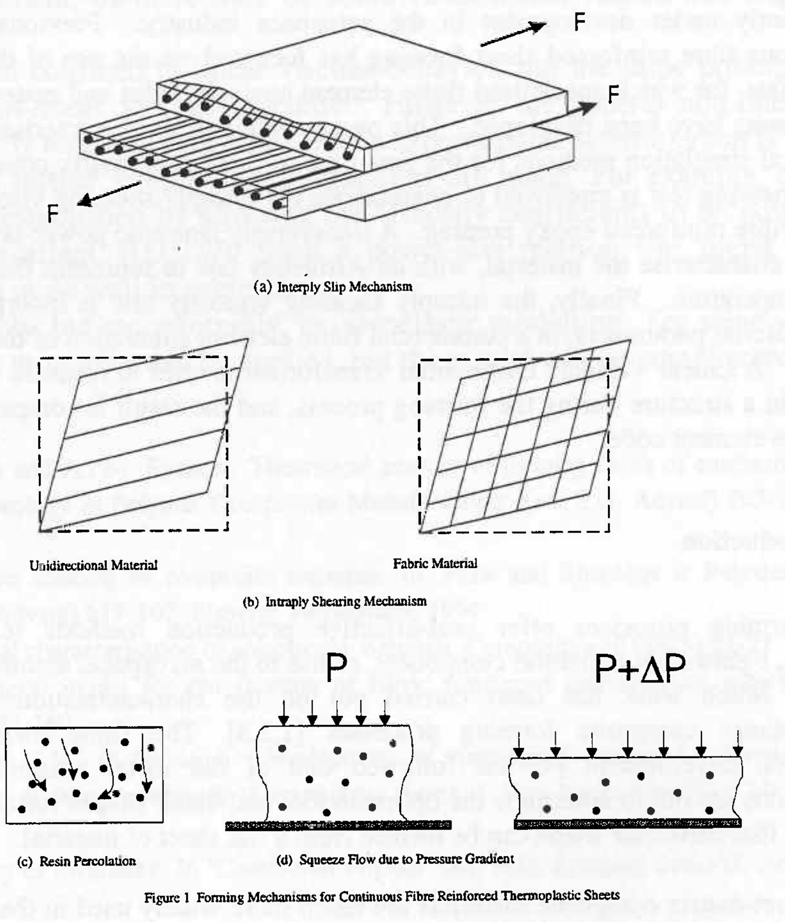

Figure 1 Forming Mechanisms for Continuous, Aligned Fibre Reinforced Materials

Torsional rheometry was traditionally used to determine the in-plane shear behaviour of molten fluids. This approach was proposed for determining the flow behaviour of fibre reinforced composite melts, but serious reservations as to the validity of this method were encountered. The method could not measure directly the reaction of the composite melt and the assumption that the deformation was uniform was not valid [7]. These reservations meant that a new method of rheologically measuring the in-plane deformation for composite melts had to be found. Some work has been carried out on tensile testing of +/-45 degree specimens [8], but the deformation was, of necessity, unhomogenous.

The authors have previously developed a method of characterising the intraply behaviour of unidirectional and fabric-reinforced thermoplastics, known at the picture-frame shear test [8,9,10]. This test enables the shearing viscosities of the material to be deduced from the force-deflection response of the picture-frame experiment.

In this paper, the picture-frame shear test will be employed to characterise a thermoset-composite material, namely a 2x2 twill carbon-fibre reinforced epoxy prepreg. The material is investigated at temperatures between 60 and 100 degrees centigrade, at times over which no chemical curing is encountered. This would represent a typical hot-draping process temperature, after which the formed component would be autoclave cured at a higher temperature and for longer times.

2 Intraply shear tests

The picture frame test is used to impart a homogeneous deformation to a composite melt and therefore, by use of a continuum model, the output from the test is used to determine the viscosities which are used to predict the intraply shear behaviour of a composite material [8,9,10].

2.1 Test description

The test equipment consists of a four bar linkage in an environmental chamber positioned on a tensile test rig. A schematic of the operation of the test can be seen in figure 2 below. The actuator imparts a constant displacement and a load cell reads the force imparted by the actuator.

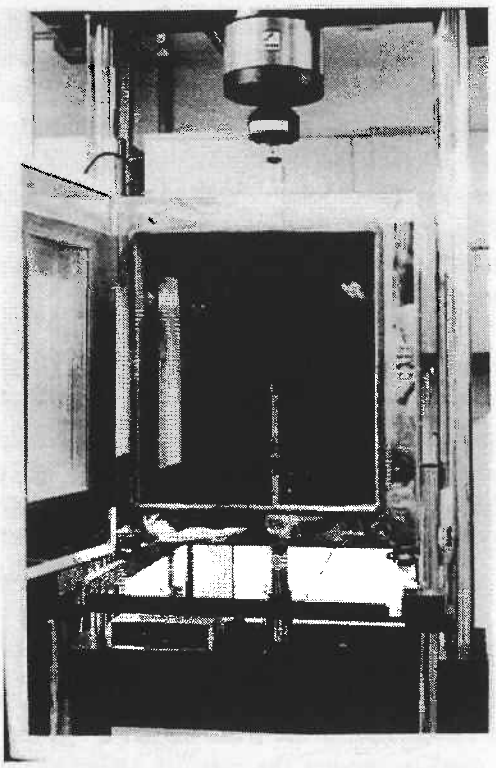

Figure 2 Picture frame in oven

It was determined that 5 rates of actuator displacement would be carried out for each test case to allow good definition of the behaviour of the material. Three temperatures were chosen that encompassed the proposed forming temperatures most accurately. Previously, it was discovered that with a glass fibre 1/7 satin weave reinforced PA-12 material a considerable difference in material behaviour between the positive and negative occurred [9,10]. This was taken into account in the test matrix here and both directions of shear were investigated.

Due to the low load levels encountered during tests, friction on the picture frame had to be measured and subtracted from the experimental result, in order to increase the accuracy of the experiment [10].

3 Material Characterisation

Interpretation of the results of the picture-frame shear test has employed the notion of an *Ideal Fibre Reinforced Fluid* [11,12], which considers the material to be an incompressible continuum of appropriate anisotropic symmetry, reinforced with one or two families of fibre direction that are inextensible. Various elastic and simple linear and power-law viscous relationships have been employed to interpret the results of the picture-frame experiment, which usually result in a straight-line plot with viscosity functions as the slope and intercept of the line [8,10]

From the displacement and load outputs from the experiment it is possible to plot a function that has viscosity as the slope. The average friction force, at any particular displacement of the actuator, (calculated over the tests at that rate and temperature) is subtracted from the experimental force response. Shear angle and shear rate are computed from the displacement and rate of displacement given by the experiment. Typical force-deflection responses for the 2x2 twill material at different actuator displacement rates are shown in Figure 3 below:

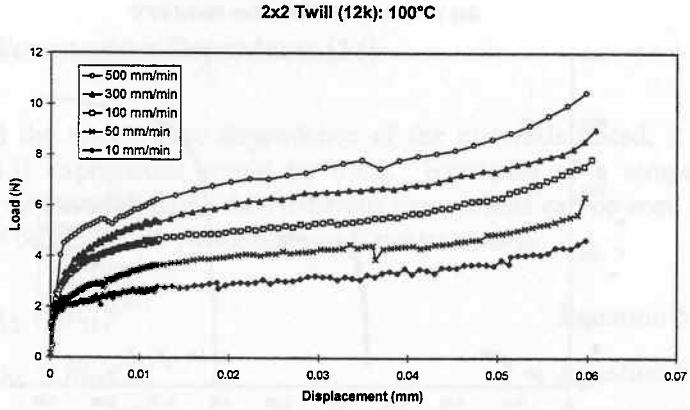

Figure 3 Force-displacement response of 2x2 twill at 100 degrees C.

The analysis of the results for the 2x2 twill material in this paper is conducted using the simplest models first and progressing to more complex models, only if the simpler models fail. The simplest model to implement for a fabric is the isotropic Newtonian model, in which the material is characterised by a single rate-independent viscosity.

The results derived for the picture frame can be seen below in Equation 1 [10]:

$$\frac{F\dot{d}}{L^2 t} = \eta\left(\dot{\gamma}\sqrt{\frac{1+3\sin^2\lambda}{\cos^2\gamma}}\right)^2 \qquad \text{Equation 1}$$

In order to plot this equation the axes variables X and Y are used (Equations 2 & 3).

$$X = \left(\dot{\gamma}\sqrt{\frac{1+3\sin^2\lambda}{\cos^2\gamma}}\right)^{1+n} \qquad \text{Equation 2}$$

$$Y = \frac{F\dot{d}}{L^2 t} \qquad \text{Equation 3}$$

From this model it is a simple matter to develop more complex models with variable viscosities such as power law and Carreau models. An example of the best fit for an isotropic power-law model for the 2x2 twill is shown in Figure 4. The data should all fall on a straight line if the model represented the material behaviour well. As can be seen this model is not a very good fit.

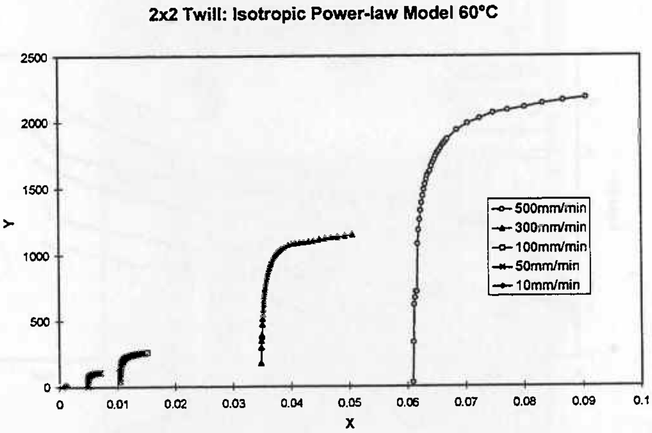

Figure 4 2x2 Twill isotropic power law at 60C

This gives rise to the need for more complex models. The models now considered are anisotropic models [10]. The first and simplest model considered is the transversely isotropic Newtonian model. The interpretation of the picture frame test for this model results [10] in the following equation:

$$\left(\frac{Fd}{\dot{\gamma}L^2 t}\right)\left(\frac{\cos^2\gamma}{1+\sin^2\gamma}\right) = \eta_{12} + \eta_{33}\left(\frac{2\sin^2\gamma}{1+\sin^2\gamma}\right) \qquad \text{Equation 4}$$

If the material appears not to behave in a Newtonian manner then a power-law model, Carreau model or combinations of these can be used to try to obtain a fit. Figure 5 shows a plot of a power law model against the data at 100 degrees. Again, the data should collapse onto a straight line if the model represents the material well, and viscosity coefficients m_{12} and m_{33} may be found from the graph as described elsewhere [10]. Clearly, the fit achieved is much better than for the simpler isotropic case.

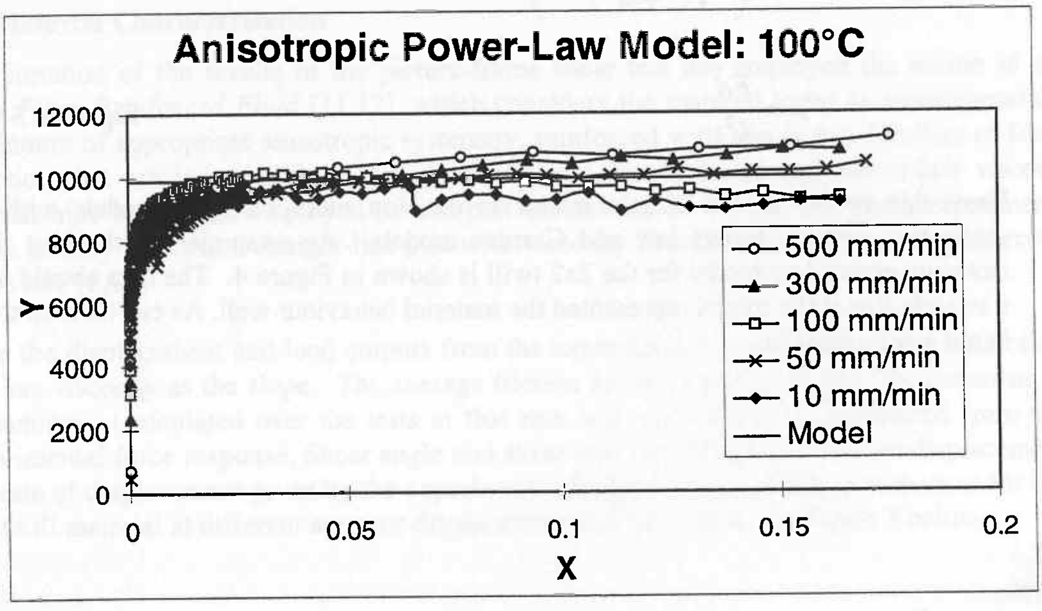

Figure 5 Anisotropic power law response of 2x2 Twill material at 100°C

4 Rheological Temperature Dependence [14]

In order to model the temperature dependence of the materials tested, it was decided that Arrhenius-type [13] expressions would be used. Examples of a temperature dependent anisotropic power-law model, using the Arrhenius expressions can be seen in Equations 5 to 9. This could also be applied to Newtonian, or Carreau models.

$$\eta_{12} = m_{12}\dot{\gamma}^{n-1} \quad \text{Equation 5}$$

$$m_{12} = \overline{m}_{12} e^{\xi_{12}(T_0 - T)/T} \quad \text{Equation 6}$$

$$\eta_{33} = m_{33}\dot{\gamma}^{n-1} \quad \text{Equation 7}$$

$$m_{33} = \overline{m}_{33} e^{\xi_{33}(T_0 - T)/T} \quad \text{Equation 8}$$

$$n = \overline{n} e^{\xi_n(T_0 - T)/T} \quad \text{Equation 9}$$

The parameters used, T_0, $\overline{m}_{12}$, $\overline{m}_{33}$, $\overline{n}$, ξ_{12}, ξ_{33} & ξ_n, are determined from the lowest and highest temperatures used. T_0 is the lowest temperature used. $\overline{m}_{12}$ is the in-plane viscosity parameter at that temperature, $\overline{m}_{33}$ is the out-of-plane viscosity parameter at that temperature and $\overline{n}$ is the power law index at that temperature. The values for ξ_{12}, ξ_{33} & ξ_n are determined using equations 10, 11 & 12, for this case T, m_{12}, m_{33} & n are the values at the maximum temperature.

$$\xi_{12} = \frac{T}{T_o - T}\ln\left(\frac{m_{12}}{\overline{m}_{12}}\right) \quad \text{Equation 10}$$

$$\xi_{33} = \frac{T}{T_o - T}\ln\left(\frac{m_{33}}{\overline{m}_{33}}\right) \quad \text{Equation 11}$$

$$\xi_{3n} = \frac{T}{T_o - T}\ln\left(\frac{n}{\overline{n}}\right) \quad \text{Equation 12}$$

This gives the complete anisotropic power-law model. This can be easily adapted for other material models by introducing the appropriate Arrhenius expression for each of the material parameters. Figures 6 & 7 show how close the temperature dependent model is to the models which have been created independently of temperature.

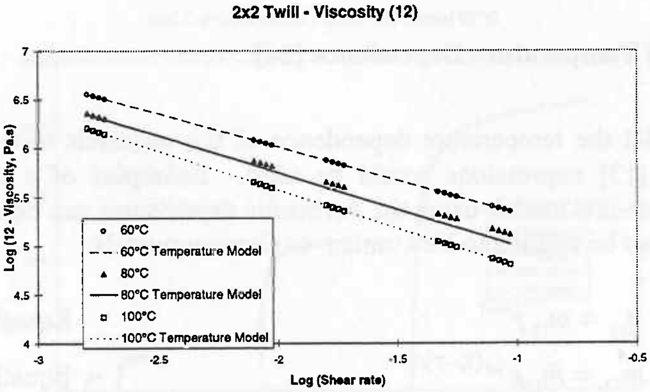

Figure 6 2x2 twill temperature dependent model of viscosity-12

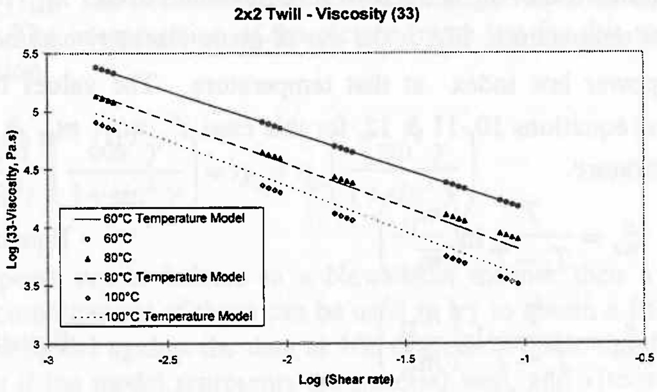

Figure 7 2x2 twill temperature dependent model of viscosity-33

These models can be then compared with the original force deflection data to determine how closely they fit, as shown in Figure 8

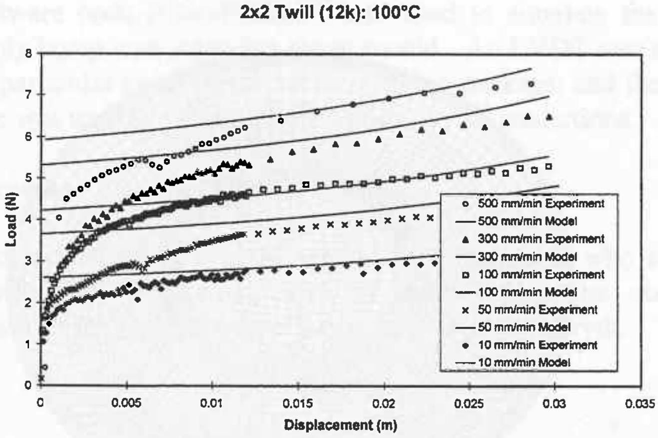

Figure 8 2x2 Twill model/ experiment comparisons at 100°C

This plot shows gives a good indication as to the accuracy of the intraply shear model used.

5. Force/Deflection Validation using PAM-FORM™

The information from the material models can be used in the commercial finite element code PAM-FORM™ [14]. A number of experiments were carried out to validate the PAM-FORM™ results, using the models developed in section 4. These were conducted by double-diaphragm forming a two-ply 2x2 twill layup over a top-hat shaped tool. The diaphragms used were a Nylon bagging film, and the entire assembly was formed in an autoclave at 100 degrees C.

A Linear Variable Displacement Transducer (LVDT) was used in conjunction with the autoclave to monitor the deflection of a particular point on the top diaphragm during the forming trials. The position of the LVDT in the experiment is shown in Figure 9.

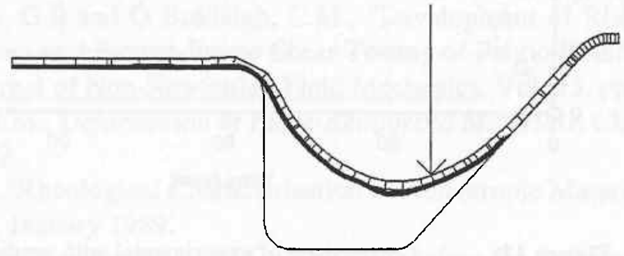

Figure 9 Position of LVDT during the forming experiments

The LVDT took readings of the vertical displacement of the diaphragm and composite sheet and these were later compared to the Z-displacement results in the PAM-FORM™ simulation. The X and Y displacements of the node were minimal and so were disregarded for the purpose of the comparison. These trials were also modelled on the PAM-STAMP finite element code. The deformation predicted by the simulation after 90 seconds of forming is shown in Figure 10.

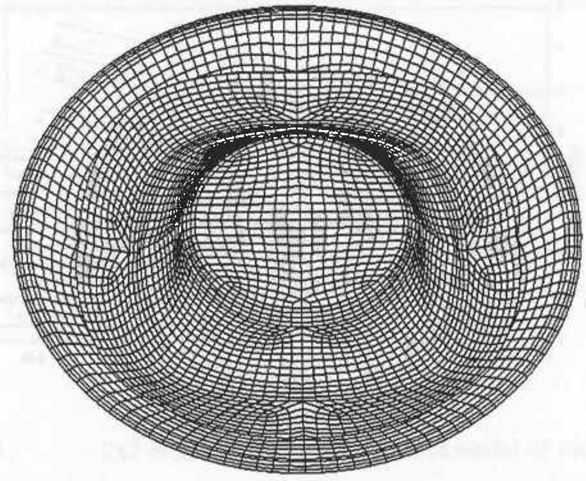

Figure 10 Predicted deformation after 90 seconds of forming

Figure 11 shows the displacement Vs time recorded for the test and the displacement predicted by PAM-FORM™. It is clear from the graph that the experimental results correlate well with the finite element model predictions. The part formed was also similar in deformed shape to that simulated by PAM-FORM™. It was generally seen that the program had simulated quite well the results obtained from the experiments.

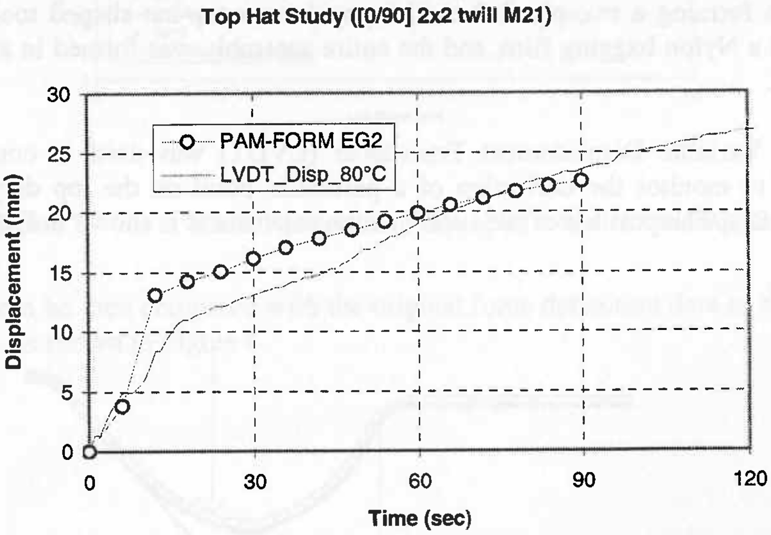

Figure 11 Comparison of experimental with predicted data

Obviously, the simulation provides an extremely powerful tool for analysing and predictng the effects of various parameters such as relative material properties of the diaphragm and the composite, effect of diaphragm and ply thicknesses, temperature etc.

6. Conclusions

The picture-frame shear test, previously developed for characterisation of thermoplastic composites in intraply shear, has been successfully applied to a 2x2 twill fabric reinforced thermoset prepreg with a power-law anisotropic and Arrhenius model being employed to fit the data between 60 and 100 degrees centigrade. The material data was incorporated in the finite element software code PAM-FORM™ and used to simulate the double diaphragm forming of a two-ply layup over a top-hat shape mould. An LVDT was used to measure the displacement of a particular point on top of the forming package, and the resulting pressure-displacement curve was used to validate the PAM-FORM™ predictions.

7. Acknowledgements

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