Some Proposed Experimental Tests for use in Finite Element Simulation of Composite Forming

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SUMMARY: Successful numerical simulations in the automotive industry have resulted in new concepts for design and manufacture. One of the new concepts is to have a ‘virtual-manufacturing-facility’ through numerical simulation. Simulations for the processing of metals have been successful due to the accepted methods for measuring material properties, and for the laws and models to describe their deformation. The measuring techniques and models for the deformation of composites have not enjoyed the same acceptance. Consequently the success of numerical simulation for the composites industry will depend on simple methods for determining material characteristics, and demonstration of accurate simulation results. This paper presents a three-test method for determining the material characteristics which dominate the forming process for multi-ply composite forming, and then uses simulations of the same tests to verify the accuracy of the numerical simulation process. Finally, a simulation of a composite forming process is presented to demonstrate the application of the material tests.

KEYWORDS: thermoforming, diaphragm forming, fabric, forming, numerical simulation, prepreg

1 INTRODUCTION

The use of high strength fibre reinforced polymer composites in the aerospace industry is increasing due to the weight and stiffness benefits they offer. However they are generally considered to be expensive components, with a trade-off between cost and benefit having to be continually justified in the competitive market place. As metals and their processing methods are improved to meet these demands, so must the composite components.

Numerical process simulation is a computer based means to potentially optimise a manufacturing process, reduce lead time, and thus reduce manufacturing cost. It offers the ability to apply ‘virtual’ changes to a process, in a more cost-effective manner than real process trials might be. This ‘virtual-try-out-space’ is already deemed an essential technology to ensure competitiveness in the automotive industry. However, for aerospace composites applications, the uptake of this technology has been slow.
2 THERMO-FORMING OF COMPOSITES

Press- and diaphragm-thermo-forming are composite material forming processes that are receiving increased attention in aerospace industries. These two processes are similar to metal stamping, in that flat sheets of material are forced over, or into, a mould by an external force to form a part.

In thermo-forming of composite materials the ‘press’ action is applied by either a rubber block driven by a ram, or by flexible membranes and a pressure difference. Rubber-block-press-forming can achieve much higher forming forces than the flexible membrane ‘diaphragm-forming’ process.

A variation of the diaphragm-forming process is to envelop the sheet composite material between two diaphragms with a vacuum holding the two diaphragms together. When the external pressure is applied, the double-diaphragm assembly behaves as one, but provides a compacting restraint to the sheet composite material, which delays the onset of wrinkling.

The composite materials used in aerospace manufacture are usually ‘prepreg’ materials, (fibres in a fabric or uni-directional sheet form, pre-impregnated with a matrix) and require elevated temperatures to soften the matrix material sufficient to form the material. Hence these processes are ‘thermo-forming’ processes, and may be applied to either thermoplastic or thermoset matrix systems. Thermoplastic matrix systems require higher temperatures (180 – 280 °C depending on thermoplastic) than do epoxy thermoset matrix systems (40 – 80 °C) to achieve a suitable resin viscosity for forming.

Numerous publications describe the shape correlation achieved with numerical simulation of composite thermoforming [1,2], however there is rarely an indication of force correlation and/or an indication of how the material properties used to produce the results were derived.

To enable numerical process simulation to be used universally for composites manufacture optimisation, there must be a series of simple tests to characterise the prepreg materials. This paper presents three tests which we believe provides adequate material characterisation to derive the software input values for numerical process simulation using the PAM-FORM software.

3 PAM-FORM SOFTWARE

The code used to simulate the laminate forming process is PAM-FORM, an emanation of the explicit finite element code PAM-STAMP. PAM-STAMP is a well-established code in the metal industry for sheet metal forming. It allows for a true virtual manufacturing that encompasses the possibility to test several materials and several processes. Matched metal tools, rubber pad forming, membrane forming, hydro-forming and blow forming are some of the processes modelled by the software. By simulating a process, PAM-STAMP enables to define appropriate blankholder conditions, drawbead locations and characteristics, locator pins, draw slits etc. The basic idea that precedes the development of PAM-FORM, a specific adaption for composites forming, was to take advantage of the most advanced and validated numerical technology and apply it to composite forming. Specific developments were necessary to model a number of critical features of composite forming, including the composite ply materials, inter-ply sliding, ply to tool sliding, and thermal behaviour.

The numerical method used is finite elements with explicit time integrations. Large displacements, large rotations and large strains are modelled. Nonlinear material behaviours
and nonlinear sliding laws can be taken into account. Due to the explicit nature of the method, very large problems (several hundred thousands of elements for several dozen plies) can be treated.

The mathematical material model is based on a Maxwell model in parallel with two independent elastic fibre directions with the possibility to superimpose an elastic parent sheet. A locking angle can be defined with appropriate post-locking shear modulus definition. The viscosity in the Maxwell model may be constant or follow a Cross equation or a power law. Advanced friction laws with temperature effects may be used. Heat conduction through shell elements and heat transfer through mechanical contact (such as inter-ply contact or ply to tool contact) are modelled.

Numerous references describe the application of PAM-STAMP to the process of metal stamping [2,3,4]. The success of these numerical simulations in industry is largely due to the universal acceptance of testing procedures for measuring material properties, and laws which describe deformation of the material – ie stress/strain relationships, and failure modes.

This paper demonstrates that simple experiments can be conducted to derive the material properties to be used in the numerical simulation of the process.

## 4 THEORY

Most composite components are made from several layers of a base ‘ply’ material. A ply may be a fabric or unidirectional material. Aerospace applications commonly use a ply which has the resin (thermoset epoxy or thermoplastic) pre-impregnated to ensure correct resin content.

In conventional manufacture, the assembly of the plies into the mould is a manual process. This requires the operator to handle each ply, and manually encourage the ply to conform to the contours of the mould. The result is an inevitable variation in ply orientation between operators and parts, resulting in a variation in the properties of the cured parts.

Thermo-forming process allows the plies to be assembled flat with greater accuracy, or even by automation, to be later formed into the complex mould shape by a repeatable process.

The assembly of pre-cut plies is termed a ‘stack’ or ‘preform’ of plies. For thermo-forming, the preform is usually consolidated by vacuum to minimise air voids trapped between plies, as voids in a cured part can significantly reduce mechanical properties. After consolidation, the preform is formed into the desired shape by a thermo-forming operation.

In thermo-forming of composites, three dominant deformation modes exist in transforming the flat preform into a complex curved part:
- intra-ply shear (shear within one ply of material),
- inter-ply shear (between adjacent plies, or a ply and a mould) and
- out-of-plane bending.

To characterise each deformation mode independently, three tests have been used. A bias-extension test for the intra-ply characteristics, a ply pull-out test for the inter-ply characteristics, and a self-weight-single-ply cantilever test for the out-of-plane bending characteristics. A sketch of the three tests is shown in Figure 1.
Figure 1. Three experimental tests are used to characterise the dominant deformation modes of fabrics in the thermoforming process.

In addition to these three tests, fibre direction moduli are calculated from known fibre content and rule of mixtures. A knock-down factor can be used to account for the fibre waviness due to crimp in fabrics.

4.1 Bias-Extension Test

In the bias-extension test, the prepreg specimen is oriented with the fibres at ±45° to the specimen axis, and loaded in tension with a constant cross-head velocity. This test is used to measure the locking angle, the in-plane shear modulus and the sheet viscosity.

The locking-angle of a fabric is the fibre angle at which the out-of-plane buckling initiates. It is measured by identifying the first out-of-plane displacements during the bias-extension test. At axial strain beyond this point, the axial force will increase. The locking-angle was found by Johnson and Costalas [5] to be a function of fabric architecture and is independent of strain rate and viscous effects (within the useful range of forming temperature/viscosity).

The shear modulus can be derived by consecutive points on the force/extension curve before and after the fibre-lock. A typical curve (Figure 2) indicates the force is not linear, suggesting a shear modulus which is a complex function of axial strain or fibre angle. PAM-FORM allows a pre- and post- locking-angle shear modulus to be defined. Hence two shear modulus figures are derived from the force/extension data.

In deriving the shear modulus, the fibre deformation has been found to follow trellis behaviour in the central uniform shear region up to the fibre locking-angle. This allows the width contraction to be calculated based on trellis geometry changes, thus giving the true longitudinal and transverse strains. Allowing for the ±45° fibre directions, the shear modulus may be calculated.
Beyond the fibre lock-angle, extensive fibre straightening, fibre slippage and out-of-plane buckling occur, making shear modulus calculations difficult. In practical terms, fibre deformation beyond the lock-angle generally produces wrinkles, which are undesirable in structural components. Hence, accurate modelling beyond this point is of little practical value. An approximation to the shear modulus beyond the locking-angle can be made by measuring the increase in the axial load with increase in axial strain, and assuming that no further trellis width reduction occurs beyond the locking-angle. This approximation is justified as the visible change in width beyond the fibre lock-angle is primarily due to out of plane movement of the fabric, and fibre slippage from the free edges of the specimen.

The sheet viscosity is derived from the work of Johnson and Costalas [5], where a prepreg rheology model for the bias-extension test has been developed which assumes a single sheet viscosity. (Previous rheology models have required up to three viscosity parameters to describe the viscous nature of the prepreg behaviour. The use of a single viscosity will be attractive to industry users.)

Johnson and Costalas [5] demonstrate that in the initial stages of the bias-extension test, the highly non-linear theoretical strain function tends to a value of 4 as the strain approaches zero. This leads to the following condition:

\[ \sigma_{11} \to 4 \lambda \eta_1 \quad (1) \]

where \( \sigma_{11} \) is the axial stress, \( \lambda \) the strain rate, and \( \eta_1 \) the sheet viscosity. From (1) the single sheet viscosity can be derived.

Figure 2. The bias extension results in uniform shear in the central region of the specimen only. Extrapolation of the curve to meet the vertical axis allows the sheet viscosity to be derived. The peak in the PAM Output Force curve was due to inertia effects from a steep start-up curve.
4.2 Ply-Pull-Out Test

This test involved measuring the force to pull one ply from between two other restrained plies. The test fixture allowed a predetermined clamping force to act over the area of the ply to be pulled out. The results are temperature dependent, so were conducted at controlled temperatures. A plot of force versus extension allowed the friction behaviour to be studied.

A similar procedure was used by Murtagh and Mallon [6] in their investigation of thermoplastic matrix fabrics. Murtagh and Mallon noticed that a degree of fibre straightening occurs before uniform tension loads result for inter-ply slip of fabrics. Although this is an accurate representation of the effect, it complicates the friction behaviour immensely. As a simplification, a Coulomb law using a single coefficient of friction was assumed based on the steady state pull-out force measured, i.e. after any fibre straightening has occurred.

Figure 3 shows the comparison between the measured friction force, and the assumption of a Coulomb friction law. All three plies were oriented in the 0/90 direction. It can be stated that over the pressures where most of the forming occurs, the Coulomb friction gives reasonable results.

![Figure 3. The assumption of Coulomb friction simplifies the friction law considerably, but with a slight penalty to the accuracy.](image)

4.3 Self-Weight Bend Test

Based on ASTM 1388 [7] this test measures the flexural rigidity of a strip of fabric material as it bends due to its own weight when a length is suspended over a free edge.

The application of this test for dry carbon and glass fabric materials was conducted previously by Wang et al [8], however the derived rigidity was used only as a comparative measure of drapability. It was applied in the present work to provide a quantitative measure of the bending stiffness of a complex fibre geometry, such as that in a fabric.

The aim is to derive a calibration factor (Bending Factor) for the software prediction of out-of-plane bending stiffness of a single ply. The need for this calibration is that the software assumes uniform properties through the thickness of each ply, based on fibre direction modulus and ply thickness, i.e. the software assumes the modulus of the ply is constant through the ply thickness, as shown in Figure 5. In reality the fibres of a fabric are clustered
into bundles (tows) which are woven to make the fabric. The effect of weaving results in a single bundle of fibres undulating through the thickness as it progresses down a length of fabric. Where the bundle crosses the centreline of the ply, it will have minimal contribution to the ply bending stiffness. Where the bundle is at the extremity of the ply thickness it will contribute significantly to the ply stiffness. Consequently, the out-of-plane bending stiffness of a single ply varies within one weave period of the fabric, and is much less than if uniformly distributed fibres were present. The bending stiffness is a function of fabric architecture and fibre properties. Figure 5 indicates the effect described.

In conducting the ASTM 1388 test on prepreg materials, the viscous effect of the resin introduces a time dependency on the deflection. The deflection increases rapidly and then slowly asymptotes towards the constant value. The constant value can be assumed to be the effective deflection required for the test. (The rate of change of deflection is perhaps another measure of the viscous parameter.)

The Bending Factor used as input for the software is between 0 and 1. It was found that inputting a value equal to the ASTM 1388 measured flexural rigidity divided by the stiffness based on fibre direction modulus and ply thickness gave accurate results in ASTM 1388 simulations. This produced a Bend Factor between 0.02 and 0.007 for a typical aerospace plain weave carbon fibre epoxy prepreg material.

Figure 5. The software assumes uniform distribution of fibres through the thickness of a ply. This will over-estimate the out-of-plane bending stiffness of a fabric. The ‘Bending Factor’ in the software input can compensate for this.

5 Results

The simulation of industrial applications by the authors was in the area of diaphragm forming of aerospace thermoset epoxy-carbon prepreg fabrics. As the time taken for the deformation is in the order of minutes, an isothermal process was assumed. Consequently, results are presented for one temperature only, although similar relationships exist at other temperatures.

Figure 6 shows the shape correlation between the experimental and test results for the bias-extension test on a commercial aerospace carbon-epoxy fabric prepreg at an optimum forming temperature. Notice the low force magnitudes which were shown in Figure 2. (The peak in the simulation force prediction at small displacements is due to inertia effects and can be removed by filtering or use of a smoother cross-head acceleration.)
Figure 6. Shape correlation between PAM-FORM output and bias-extension test. Pictures of specimens courtesy of DLR, Stuttgart.

Figure 7 shows the ASTM 1388 test simulation. The strip of material was modelled to fall under its own weight. The length was adjusted until the tip deflected to meet the reference plane. As observed in the experiment, the simulation required about 0.75 second for the strip to settle at a constant deflection. The transient period is due to viscous effects of the resin.

Figure 7. Simulation of a strip of composite material deflecting under its own weight, as per the ASTM 1388 test procedure. This test is a calibration of the bending stiffness.

Figure 8 displays the effect of a ply material that is too stiff. In this case, the two plies are being forced over a radius of a tool by a diaphragm. The plies on the right are too stiff, lifting the diaphragm off the upper face of the tool as the diaphragm forces the plies against the vertical tool surface.
Figure 8. Effect of bending factor on ability of plies to conform to a radius on a tool. The plies on the right are too stiff, lifting the plies and diaphragm off the upper face of the tool.

A similar process for material characterisation is required for each of the materials used in a process simulation – i.e. diaphragm materials, and release plies in the stack. Having demonstrated good individual material behaviour through simulations, and the appropriate material interface/friction behaviour, the complete process can be simulated.

As an example of the full process simulation, we present the forming of a flat dish with a vertical flange. In this case the dish was based on the critical geometry for a part we wished to diaphragm form. Figure 9 shows the quarter model of the dish (inverted), the vacuum box and the double diaphragm arrangement.

Figure 9. The original and partially formed circular dish with vertical sides.
The software allowed a comparison between the single- and double-diaphragm-forming process for this geometry and materials. Figure 10 is a view looking under the plies as they are formed. The part consists of 9 plies of woven carbon fibre/epoxy prepreg material, of layup sequence [0,45,45,0,45,0,45,45,0]. The double diaphragm process delays the onset of wrinkles and produces better quality parts.

![Figure 10. Single-diaphragm-forming (left) and double-diaphragm-forming (right).](image)

In this example, the plies exhibit a variation in shear behaviour due to the variations in fibre orientations. For this example, the 0° orientation was along one edge of the quarter model, the 90° orientation along the other free edge. Fibres of the 0/90 plies are oriented parallel to these directions and no shear extension occurred along these edges, whereas the ±45° plies do exhibit shear along these free edges. The variation in length of the plies shown in Figure 11 agrees with this observation, and correlates with the ply stacking sequence.

![Figure 11. At the edge of the dish forming simulation, the different shear behaviour between 0/90 and ±45 plies is evident. This is typical of the real process.](image)
6 CONCLUSION

This paper has shown that the dominant material deformations of a prepreg fabric can be characterised by three simple tests. These tests allow the input for a finite element program to be derived. The finite element program has been shown to accurately simulate the three simple tests. This allows confidence in the more complex process simulations of an aerospace composite component formed by the double-diaphragm-thermoforming process.

As material suppliers release new products, there is a need to have available quick, easy, well defined tests procedures to characterise these new materials for use in numerical simulation.

Further, it is proposed that these three tests may form the basis for simple composite material characterisation tests to allow the aerospace industry to gain confidence in the acceptance of the use of numerical simulation as a virtual-prototyping tool.

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