PART FORM PREDICTION METHODS FOR CARBON FIBRE REINFORCED THERMOPLASTIC COMPOSITE MATERIALS

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Keywords: *composite part form prediction, digital manufacturing, simulation*

1 Abstract

This paper introduces predictive technologies for carbon fibre reinforced plastics which can be integrated with assembly simulations for the purpose of understanding the applicability of thermoplastic based systems for use in sustainable transport systems. The process-induced deformation during thermoforming could affect the final shape and dimensions of a composite part and this is a significant factor when using clash detection during the build validation stage of an assembly simulation. In this work formula calculation and simulation strategy are presented for the study of the deformation behaviour of a 90°, V-shaped angle manufactured using carbon fibre reinforced polyphenylene sulphide (PPS). The experiment processing conditions were re-created in a virtual environment and analysed using the finite element method. The simulation can predict more accurate result than simplified equation but is still about 15% lower than the corresponding experimental data. The error induced in the simulation result is caused by the material property which is modelled by combining carbon fibre and PPS test data rather than woven lamina. Simulated 'as manufactured' part forms have been successfully transferred to a digital manufacturing environment where they can be used for more realistic build validations.

2 Introduction

Digital manufacturing methods use flawless, nominally sized CAD components for production planning and product knowledge acquisition during product development. Digital manufacturing techniques can simulate assembly sequences using 'as designed' forms but the reality of using composite components is that part variability can cause problems during assembly as the 'as manufactured' form may not match the geometry used for any simulated build validation, see Fig. 1. This work seeks to cover this technology gap by developing simulation methods backed up by theoretical and practical validation, to establish carbon fibre reinforced thermoplastic materials as a realistic alternative to thermoset based material systems, for structural applications in more sustainable transport systems of the future. Methods for the prediction of simple composite part forms are presented. The FE based method is integrated within a digital manufacturing framework covering the current gap between part design and final assembly simulation for composite components.

3 Method

3.1 Thermoforming of Carbon Fibre Reinforced Polyphenylene Sulphide Composite

Experimental samples were manufactured from continuous carbon fibre (5H-satin) reinforced PPS pre-consolidated laminates supplied by TenCate Advanced Composites. The laminates consisted of 8 plies with 50% fibre volume fraction. Two different layup configurations, $[[(0,90)/(\pm 45)]_2]_S$ and $[[(\pm 45)/(0,90)]_2]_S$, were investigated. Samples used for the experiment cut from the laminate measured 150mm long and 120mm wide by 2.48mm thick. The experiment set up used in this work is shown in Fig. 2. The manufacturing cell consists of a heating station, a forming station and a matched mould tooling rig. The matched mould tooling was designed with an open V angle of 92°, this decision was based on previous literature where it was shown that a mould angle of 92° can produce a finished internal angle of 90°[1].

Sample was heated in the infrared oven until reaching the forming temperature (320°C) then transferred and indexed into the mould. The mould was subsequently closed causing the pliable sample to take up the ‘V-shape’. The formed part was held in the mould for 180 seconds and then removed to cool to ambient room temperature. Fig. 3 shows the temperature profile of a sample thermoformed with 170°C mould. Different mould temperatures were employed to investigate the effect of mould temperature on the deformation of the V-shape part. Six different mould temperatures including 80°C, 110°C, 140°C, 170°C, 200°C and 230°C were investigated. This ensured that the subsequent prediction work could echo the test conditions and their resulting affect on the final shape of the test sample. For sample with $[[(\pm45)/(0,90)]_2]_S$ layup configuration, only 170°C mould condition was tested to study the stacking sequence effect on part deformation.

Inspection of the final V-shape geometries was carried out using a coordinate measuring machine (CMM) with 0.5μm accuracy. Both the inner surface and outer surface angles were measured for each sample. For each side, the angle was calculated using two planes which were defined using 20 sampling points on each surface.

3.2 Simplified Calculation for Predicting Spring-in of Angled Composite Part

As one of the most important factors of residual stresses and shape distortion is the thermal contraction occurs during cooling from forming temperature to room temperature[2], a one-dimensional equation has been proposed to predict the warp angle in curved laminates based on composite material anisotropy[3, 4]. Modification is made due to no chemical reaction in thermoplastic composite during thermoforming.

$$\Delta\theta = (\theta - 180)\frac{(\alpha_l - \alpha_t)\Delta T}{1 + \alpha_t \Delta T} \quad (1)$$

where: $\Delta\theta$ is the spring-in angle; θ is the mould angle; α_l is the longitudinal coefficient of thermal expansion (CTE); α_t is the through-thickness coefficient of thermal expansion; ΔT is the change in temperature.

The application of above equation requires effective CTE of laminate property which can be approximately derived using micromechanics of composite theory. The parameters to carry out this formula calculation are shown in Table 1. As ΔT changes with mould temperature applications, different results can be obtained corresponding to experimental condition.

3.3 Finite Element Analysis for Thermoforming Process of Thermoplastic Composite

The Abaqus/Standard program was used to perform the finite element analysis. The thermoforming process of V-shape composite part was modelled using solid element with refiner mesh at the corner region, as shown in Fig. 4. The forming aluminium mould was modelled as 3D rigid surface. And the woven fabric layer was represented as two layers of unidirectional material with different in-plane orientation and half thickness[5].

As thermoplastic composites exhibit significantly inelastic and rate-dependent behaviour in thermoforming stages, a proper constitutive model which can characterize these material properties is needed for this simulation. Based on the assumption that fibres have a linearly elastic behaviour and the matrix responds viscoplastic with temperature[6], uniaxial tension tests were performed to characterize the PPS behaviour at elevated temperature and different strain rate. The injection moulded PPS samples were tested under different conditions with temperature from 20°C to 200°C and strain rate from 0.01/min to 10/min. Part of the test data is shown in Fig. 5 and Fig. 6. Using micromechanics theory, the temperature-dependent orthotropic elastic and both temperature and strain rate dependent plastic behaviour of the composite material can be obtained by integrating the PPS and carbon fibre properties.

The simulation procedure contains contact, press, clamp, and demoulding stages, as shown in Fig. 7. Temperature condition was created according to experiment record. The bottom mould was fixed during the whole simulation while the up mould could only move along vertical direction. The sample was constrained without rotation around length and thickness direction.

3.4 Integration of FEA Simulation Data with Digital Manufacturing Environment

The geometry of the tool and part required in finite element analysis can be imported from designer using CATIA CAD software, as shown in Fig. 8. Then the thermoforming simulation was implemented based on the design information. The deformed part shape predicted using the

SIMULIA/Abaqus was transferred to the assembly simulation environment DELMIA which is seamlessly integrated with CATIA as well. This shows how simulated part forms could be transferred to the digital environment for the purpose of assembly validation in digital manufacturing techniques.

4 Results

The experiment thermoformed final sample angles are shown in Fig. 9. Significant spring-in deformation occurs in thermoforming process ranging from 2.0865° to 3.4310° comparing to original mould angle. In most cases, the parts formed by higher temperature mould get larger deformation. But the mould with low temperatures 80°C and 110°C produce similar results, 2.1193° and 2.0865° respectively. The results for two different layup laminates formed with 170°C mould find the average final angles are 89.4957° for $[[(0,90)/(\pm 45)]_2]_S$ samples and 89.4089° for $[[(\pm 45)/(0,90)]_2]_S$ samples. It illustrates that for symmetrical laminates stacking sequence has little effect on spring-in deformation. Similar conclusion is also reported in other references[7, 8]. But another experiment in previous work[9] found the layup configuration of symmetric laminates could affect final deformation when the sample is made with large length/width ratio.

The simplified equation predicted spring-in angles are compared with the experimental measured values as shown in Fig. 10. The results agreed in trend of mould temperature effect as higher mould temperature will cause larger deformation. However, the calculated deformation is far lower than the test data.

The simulated spring-in phenomenon is shown in Fig. 11. The results of the simulations for 170°C and 230°C mould conditions carried out are 89.126° and 88.594° respectively. Inconsistency is found in these simulation results as part with 170°C mould deformed 15.14% more and part with 230°C mould deformed 2.54% less when compared to their experiment counterparts. The FE simulations re-create virtually, the test conditions for the sample forming processes and produce closer results comparing to experiment data than equation calculations. These results again demonstrate that deformations will arise for the composite angles as they are formed and that the shape variation is dependent on processing conditions.

5 Discussion

The experimental results arising from this work demonstrate that, even for a simple thermoplastic composite structure, there is a significant process induced deformation ranging from 2.1193° to 3.4310° in a designed 92° sample. This behaviour is difficult to predict using theoretical calculations.

The composites' anisotropy in shrinkage behaviour, originating from the difference in thermal expansion behaviour of the fibres and the matrix, during thermal processing cycle is the fundamental reason for the part deformation[10-12]. The influence of mould temperature on the deformation is more dependent on the composite's thermal properties. After demoulding, the part will deform because of the thermal shrinkage during the cooling from mould temperature to room temperature. The samples formed using the 230°C mould temperature will generate largest the shrinkage when cooling down to room temperature. Therefore for the same ply orientation, the final bend angles decrease with increasing mould temperature. However, there is still some deformation which occurs due to crystallization behaviour and tool-part interaction and the full principle for the composite part shape variation is sophisticated. Although the final part dimension can be controlled by using different mould temperature, all the temperature range cannot produced the intended 90° part in current thermoforming rig. Therefore, change the material system or redesign the mould (increase mould angle) is possible solution to achieve a final 90° V-shape part.

If no allowance is made for this shape variation during assembly through the use of fixturing or shims for example, then there will be problems in achieving design tolerances. The finite element analysis based prediction method presented here would enable the designer to tailor the material system or processing conditions to control the angle to within the required tolerance. But this prediction method still needs improvement to more accurately reflect the experiment results. Error could be induced when combining separate PPS and carbon fibre properties to represent the composite material model. The property of PPS tested in the lab is not exactly the same as the matrix in the laminates from supplier, especially the parameters used in injection moulding for the test specimen. Using simplified unidirectional layers to stand for 5H-satin woven fabric laminates may also induce error.

The work shows how manufacturing simulation techniques, which have been used mainly for metallic based component assembly, can be extended to composite applications facilitating the use of realistic part form predictions for build validation simulations. Simulation method has been established to predict the deformation behaviour of thermoplastic laminate composite as it is thermoformed. By transferring simulated 'as manufactured' part forms to a digital manufacturing environment, this method can deliver 'as manufactured' part shape to digital manufacturing system for more realistic assembly validation.

6 Acknowledgments

The authors would like to thank the Department for Education and Learning (DEL) for funding the All Island Project as well as the China Scholarship Council for its financial support.

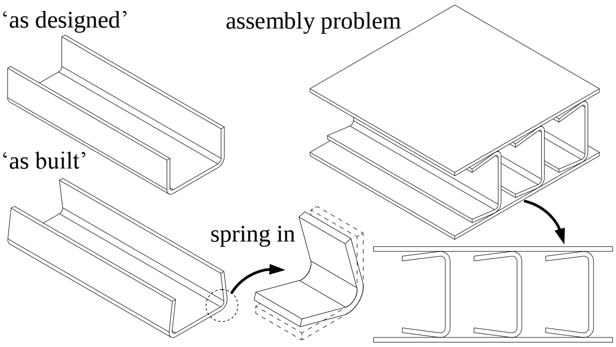

Fig.1. Composite Part Deformation Caused Problems in Assembly Simulation

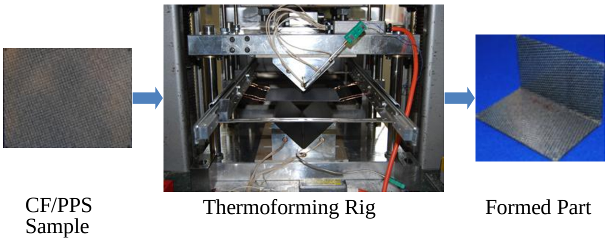

Fig.2. Thermoforming of 90° Composite V Part

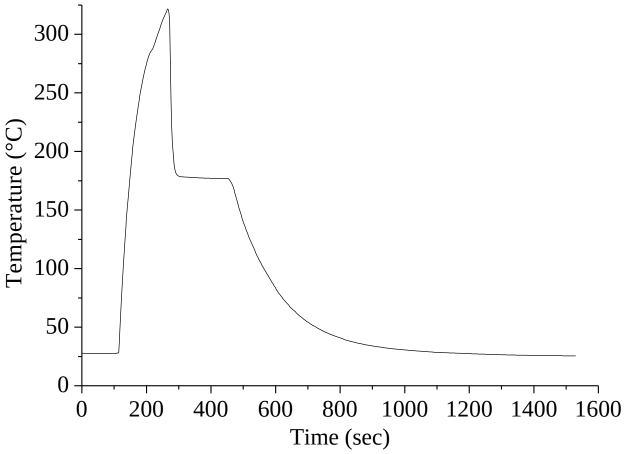

Fig.3. Temperature Profile Measured for a Sample during Thermoforming Experiment

Table 1. Parameters for Spring-in Calculation

	CTE (E-6/°C)				
θ (measured)	CF (long.)	CF (trans.)	PPS	α_l	α_t
91.9379°	-0.41	4.99	52.2	0.441	37.8

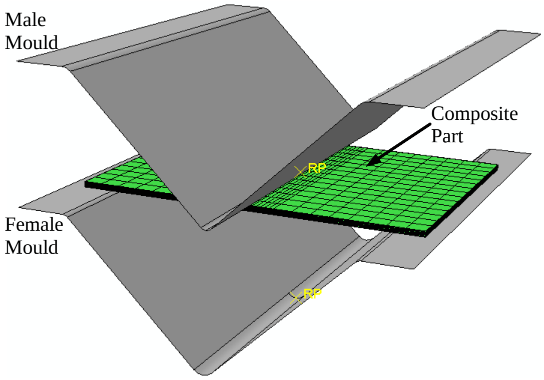

Fig.4. FE Model for Thermoforming Analysis

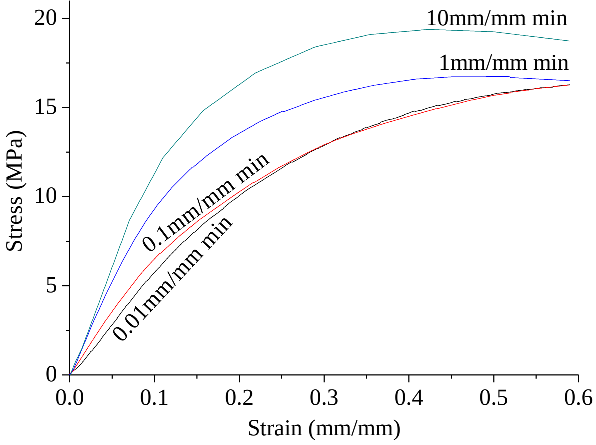

Fig.5. The σ-ε Relationship of Pure PPS Tested at 120°C with Different Strain Rate Conditions

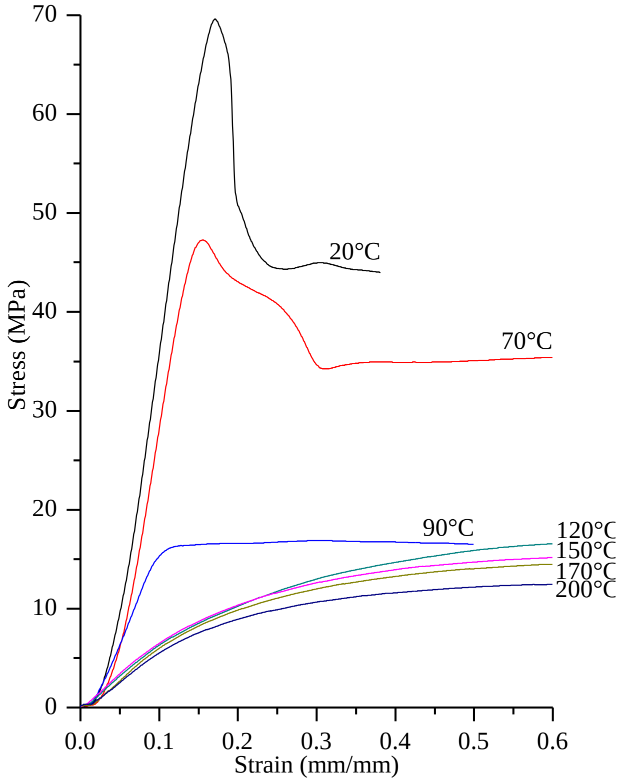

Fig.6. The σ-ε Relationship of Pure PPS Tested at Strain Rate of 0.1mm/mm min

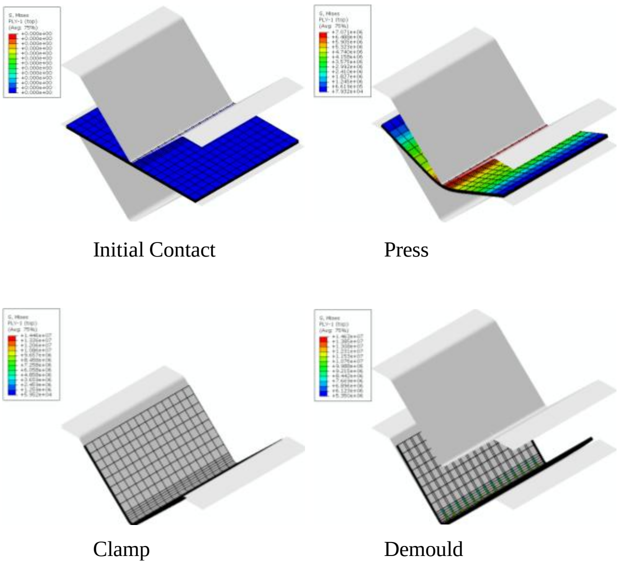

Fig. 7. Thermoforming Process Modelled in Abaqus

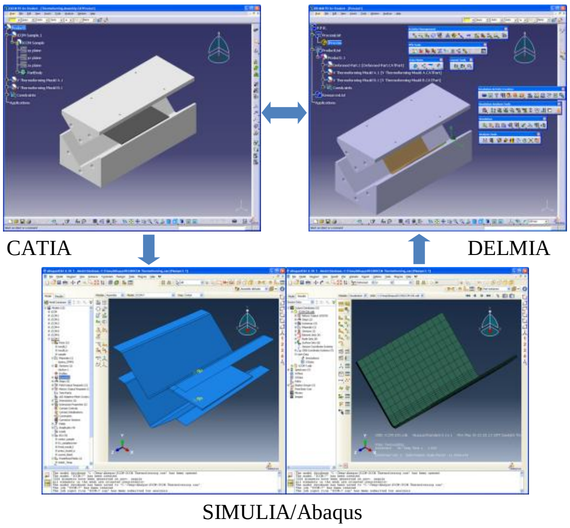

Fig. 8. Data Transfer in CAD, FEA, and Assembly Simulation Environment

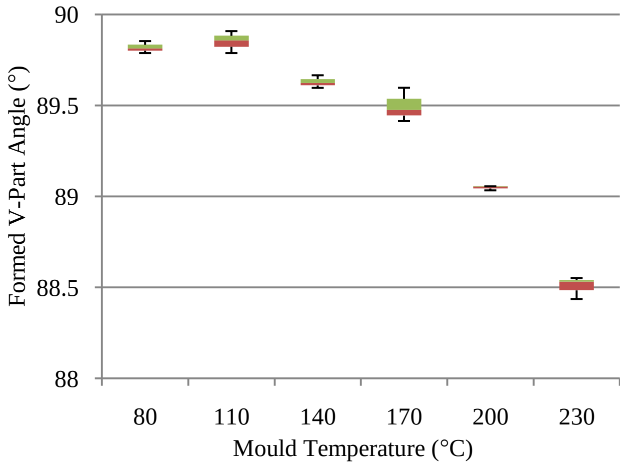

Fig.9. Measured V-shape Angle for Six Mould Temperatures

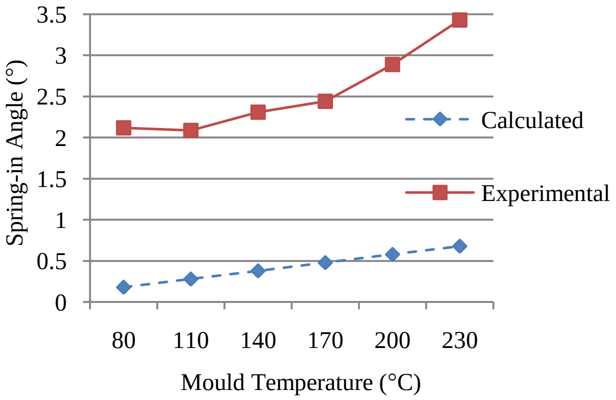

Fig.10. Comparison of the Experimental and Calculated Deformation Results

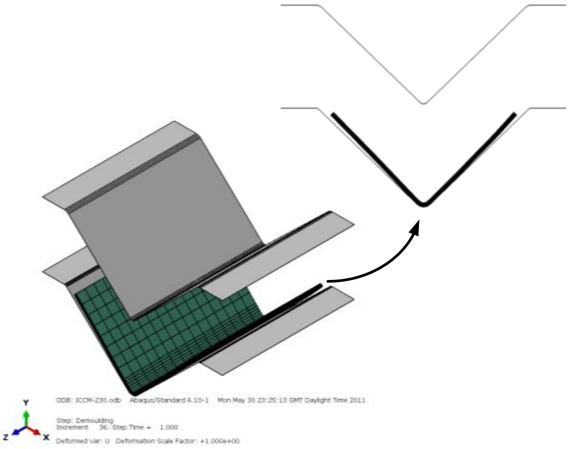

Fig. 11. Simulated Spring-in after Demoulding

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