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Process Simulations for Manufacturing Thick-Section Parts with Low-Cost Fibre Reinforced Polymers

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Abstract

A resin flow model for vacuum-bag-only prepregs is coupled with heat transfer in a commercially-available finite element software. The coupled model simulates the processing of composites manufactured from glass-fibre/epoxy-powders, where the powders have been calendared onto the fabric. For these materials, resin flow occurs in the through-thickness direction, which leads to a reduction in laminate thickness (up to 40%). The resin flow model is implemented in the finite element software using user subroutines. The results show good agreement with both experimental test data and simulations from other software. Finally, a 3D simulation is developed for processing thick-section composite parts.

1. Introduction

Advanced composite materials continue to break into new applications as a lightweight, high strength solution for large primary structures. While fibre-reinforced polymers have long been the first choice for turbine blades in the wind energy industry, blades continue to increase in size and new materials are introduced, such as carbon-fibre for turbine spar caps. At the same time, the development of marine renewable energy has created new possibilities for the application of composite materials. Marine renewable energy converters, such as tidal turbine blades, must withstand immense loading conditions in an aggressive sea water environment for up to 20 years. Although blades are typically less than 10 m in length, to withstand the bending moment on the blade, the thickness of composite laminates must transition from thin at the blade tip (2-5 mm) to very thick at the root (c. 100 mm).

A challenging aspect of manufacturing thick-section composite parts is that they are inherently difficult to process due to the thermal properties of the constituent materials; the reinforcing fabrics have poor transverse conductivity (< 0.3 W/m.K, [1]) and the resin systems (also poor conductors) often generate an exothermic heat flow. This combination of properties can often lead to a build-up of heat within the laminate that can decompose the resin system, or create a sufficiently large thermal gradient that the final part is warped due to residual stresses or cure state [2].

Characterisation of epoxy powders has shown that they are a suitable alternative to conventional vacuum-bag-only (VBO) prepreg resins for thick-sections because they can achieve sufficiently low viscosities for full laminate consolidation (minimum viscosity of 1 Pa.s), while producing an exothermic heat flow (approx. 180 J/g) that is less than half of what is reported for conventional epoxy systems designed for infusion [3]. Commonly used in the powder coating industry, these epoxy powders are a one-component system, which means that the resin, hardener and a heat-activated curing agent are already present in the powder mix. They can be used to create VBO prepregs by calendaring a layer of powder onto one side of the reinforcing fabric. This means that the polymer flow path for impregnation is reduced by placement of powder upon reinforcing fabric surfaces. By applying heat and vacuum pressure the resin melts and flows into the fabric. Increasing the temperature further activates the curing agent and the epoxy chemically crosslinks. The use of a heat-activated curing agent means that the epoxy has exceptional chemical stability at ambient temperatures. This is advantageous for storage, but it also means that individual parts can be consolidated and partially cured at high temperatures, brought back to ambient conditions to be assembled together, and then re-heated for co-curing. This ability has already been demonstrated for 12.6 m wind turbine blades [4], as shown in Figure 1.

Figure 1: Integrally-heated ceramic moulds for manufacturing 12.6 m wind turbine blades (left), and the finished turbine blades made from glass-fibre/epoxy-powder (right).

Although the epoxy powders possess many attributes that make them suitable for the manufacture of larger, thicker turbine blades, there are also challenges with the technology. Due the fact that curing can only occur at elevated temperatures, specialised heated tooling is required. Furthermore, despite producing a relatively small exotherm, epoxy powders have poor thermal conductivity, and they add increased bulk to the initial preform; making heat transfer difficult. Without careful control of the heating cycle, it is possible that large temperature gradients will still occur and ‘locked-in’ thermal residual stresses will affect thick-section parts. By simulating the heat transfer within the laminate during processing, it is possible to optimise the heating cycle so that any thermal gradients are reduced. Previous work has been carried out to model heat transfer coupled with resin flow for a one-dimensional case; it was shown that for thick-section composites, the thickness change due to resin flow is significant, and consequently affects the heat transfer within the laminate [5]. While the one-dimensional (1D) case (through-the-thickness) is sufficient for large laminates of uniform thickness, in many applications the composite geometry is complex and the heat transfer is three-dimensional (3D) due to geometric discontinuities such as ply-drop offs and other edge effects. This is especially prominent in tidal turbine blades where the blade profile must rapidly transition from thick to thin, as previously mentioned. With these considerations in mind, the aim of the current work was to develop a suitable 3D model for coupled heat transfer and resin flow in epoxy powder-based VBO prepregs.

2. Methodology

2.1. Materials

An epoxy powder (GRN 918) supplied by ÉireComposites Teo. [6], reinforced with a stitched uni-directional glass fibre fabric was the basis for all simulations presented. While some material properties for the epoxy powder have been characterised and fitted to semi-empirical models (e.g. cure kinetics and viscosity) [3], any parameters taken from literature are tabulated and referenced in section 3.

2.2. Heat transfer modelling

Heat transfer was modelled in the commercial finite element analysis code Abaqus® FEA using UMATHT, a subroutine for user-defined thermal material behaviour. By defining a thermal constitutive model in the subroutine, UMATHT approximates a solution to the model iteratively, at each time increment, using Newton’s method. As in the 1D case [5], the basic heat equation with internal energy, conduction and heat generation terms was used to describe the thermal behaviour of the composite material,

$$\rho c_p \frac{\partial T}{\partial t} = \kappa \left(\frac{\partial^2 T}{\partial z^2} \right) + (1 - V_f)\rho_r H_T \frac{d\alpha}{dt} \tag{1}$$

Where ρ is the density of the impregnated ply (kg/m^3), c_p is the specific heat capacity of the composite (J/kg.K), κ is the thermal conductivity of the composite (W/m.K), V_f is the fibre volume fraction, ρ_r is the resin density (kg/m^3), H_T is the total enthalpy of reaction (J/kg), and $d\alpha/dt$ is the temperature-dependent rate of cure (s^{-1}) which is determined using a cure kinetics model.
To simulate 3D heat transfer for the UD material, an orthogonal thermal conductivity matrix (κ_{ij}) was used when implementing Equation 1 in the UMATHT subroutine. UMATHT allows for solution-dependent state variables to be created at the beginning of the analysis, which are then updated at the end of each time increment. This means that it was possible to update any temperature-dependent properties such as thermal conductivity and specific heat capacity at the end of each time increment. UMATHT also reads in the temperature at the beginning of each time increment and the value of the temperature increment. Using this information, a solution for the epoxy powder's cure kinetics model was approximated at each time increment by implementing the Runge-Kutta method [7] within the UMATHT code, i.e. the temperature prediction was used to update the degree of cure (DOC), and the DOC informed the heat generation term in Equation 1.

2.3. Resin flow modelling

Resin flow modelling has been a topic of interest for most composite manufacturing processes over the last few decades. Even in the case of autoclave prepregs, which are already fully impregnated, squeeze flow models have been developed which predict compaction due to excess resin flowing out of the composite both in-plane and through the thickness [8]. More recently, research has been carried out to model flow within VBO prepregs which are only partially impregnated with resin, using the classical Darcy's Law for flow through a porous media [9], [10]. In cases where resin must flow both around the fibre tows (inter-tow) and within them (intra-tow), the process is considered to be dual-scale in nature. Given that these two flow regions have permeabilities that can differ by four orders of magnitude, Cender et al [10] analytically modelled resin flow a VBO prepreg ply as being flow through two porous media in series. An illustration of this concept is shown in Figure 2.

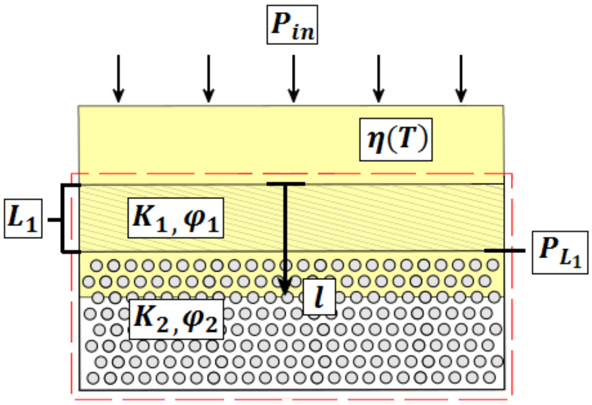

Figure 2: Illustration of resin flow in a VBO prepreg when the fibre bed is modelled as two porous media in series.

Written in numerical form, Equations 2 and 3 can be used to predict inter-tow resin flow and intra-tow resin flow, respectively, in a VBO prepreg ply for non-isothermal conditions,

$$\frac{dl}{dt} = \frac{K_1}{\varphi_1 \eta} \cdot \frac{P_{in}}{l} \quad , \quad l < L_1 \tag{2}$$

$$\frac{dl}{dt} = \frac{K_2}{\varphi_2 \eta} \cdot \frac{K_1 P_{in}}{K_2 L_1 + K_1 (l - L_1)} \quad , \quad l \geq L_1 \tag{3}$$

Where K_i is the permeability (m^2), φ_i is the porosity, η is the viscosity, P_{in} is the pressure applied by the vacuum bagging (Pa), l is the resin flow front position within the fibre layer (m), and L_1 is the flow length representing the inter-tow region. The subscripts 1 and 2 denote the inter-tow and intra-tow parameters, respectively.

The resin flow equations, along with a chemorheological model for the epoxy powder [3], were implemented in UMATHT and solved using the Runge-Kutta algorithm. With only one atmosphere of pressure being applied to VBO prepregs, it was assumed that the "squeeze out" of excess resin is negligible and that the resin-rich layer predominantly flows into the dry adjacent fibre layers. The net result of this is a significant thickness change for the laminate; for epoxy powder laminates, this can be as much as 40%. Naturally, heat transfer within the laminate is affected by this compaction. To address this coupling of heat transfer and resin flow, the resin flow calculations were used to determine the thickness change of each ply and a state variable was created for the resulting data. This state variable was then called into another user subroutine for thermal expansion, UEXPAN. By representing the thickness change as a uni-directional thermal contraction, it was possible to inform Abaqus of the compaction and update the thermal gradients appropriately for each time increment.

3. Results and Discussion

It should be noted that for all Abaqus simulations 8-noded trilinear displacement and temperature elements (C3D8T) were used. Table 1 presents the material properties that were used for the Abaqus simulations; while some of the properties have been measured experimentally, the remaining properties have been taken from literature. Note that h is the thickness of an individual glass-fibre ply. Details of the cure kinetics and chemorheological models are the topic of another publication [3].

Table 1: Material properties for processing simulations

Parameter	Value	Units	Reference
ρ	1800	kg/m^3	-
c_p	3.1667(T) – 44.5	J/kg.K	[11]
κ	4.38 E-4(T) + 3.0 E-1	W/m.K	[12]
V_f	0.5	-	-
ρ_r	1220	kg/m^3	-
H_T	184,000	J/kg	[3]
K_1	1.0 E-09	m^2	[13]
K_2	2.5 E-14	m^2	[13]
φ_1	1	-	-
φ_2	0.33	-	[14]
P_{in}	101,350	Pa	-
h	0.001	m	-

3.1. Resin flow model verification

To verify that the resin flow calculations were being performed properly within UMATHT, a simple unit cell model (1 element) was created in Abaqus. This unit cell was placed under isothermal conditions (120°C) so that the results of the flow model could be directly compared against the analytical solution of Equations 2 and 3, as derived by Cender et al [10]. It was found that the numerical model results agreed with the analytical solution. Furthermore, the Runge-Kutta algorithm was tested for a range of time increments (7, 15, 30, 60, and 120 secs) and it was found that there was negligible variation in the accuracy of the solution. This flexibility with time increment size is important for very large simulations where a huge number of calculations must be performed.

3.2. Heat transfer model verification

Verification of an Abaqus 1D heat transfer model was carried out by comparison with a commercial composites processing software, RAVEN [15], and a MATLAB-based model previously developed by Maguire et al [5]. In all cases, the simulation consisted of 1D heat transfer through a 96 ply, uni-directional glass-fibre/epoxy-powder laminate, with a 1.5 mm layer of bagging material and a 10 mm steel tool on the upper and lower boundaries, respectively. A surface film condition interaction with a heat transfer coefficient (HTC) of 40 W/m^{2}K was used to model forced convection for the upper and lower boundary conditions.

With RAVEN, it was possible to input the material parameters and run a 1D heat transfer analysis on a thick-section composite part; however, it was not possible to modify the software's in-built cure kinetics models to match the model developed for the epoxy powder. As such, the heat transfer model omitted the effects of cure. In the case of the MATLAB model, cure was included, but the resin flow model was omitted so that 1D heat transfer could be verified in isolation from the coupling effects of thickness change. The Abaqus model consisted of 96 stacked elements, with insulated sides so that heat transfer could only occur through the thickness i.e. 1D heat tranfer.

As shown in Figure 3, the Abaqus model achieved good agreement with both the RAVEN and MATLAB simulations. At higher temperatures, RAVEN predicts slightly faster heat transfer through the thickness of the laminate; however, it was unclear whether this was a result of some small difference in the numerical methods used, or some variation with the input parameters.

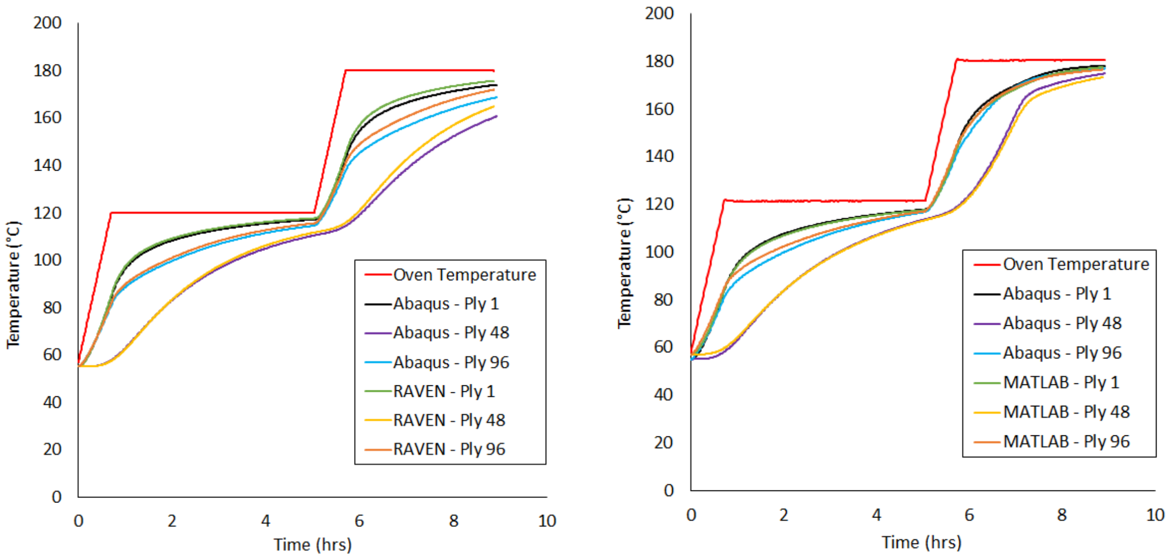

Figure 3: Comparison of RAVEN and Abaqus simulations with curing effects omitted (left), and MATLAB and Abaqus simulations with cure included (right).

3.3. Simulation vs experimental

While experimental validation of the coupled resin flow and heat transfer models is ongoing, some preliminary thermocouple data was available for a 96 ply uni-directional glass-fibre/epoxy-powder laminate processed on flat 10mm steel tool in an oven. The laminate had in-plane dimensions of 400 x 400 mm, with thermocouples distributed at the centre of the laminate. The laminate was debulked and consolidated every 24 plies meaning that the thickness change was small in comparison to a 96 ply laminate consolidated in one cycle. Similarly, repeated cycling reduced the exothermic heat flow of the epoxy powder, with the result that the material temperature did not overshoot the oven temperature. Only thermocouple data for the final cycle was provided.

Taking the experimental conditions into account, and using the same boundary conditions as the previous section, the Abaqus simulation was able to produce a relatively accurate prediction for the temperature distribution in the laminate, as shown in Figure 4. The general thermal behaviour of the material was captured, and with better characterisation of the material parameters, a more accurate prediction should be possible.

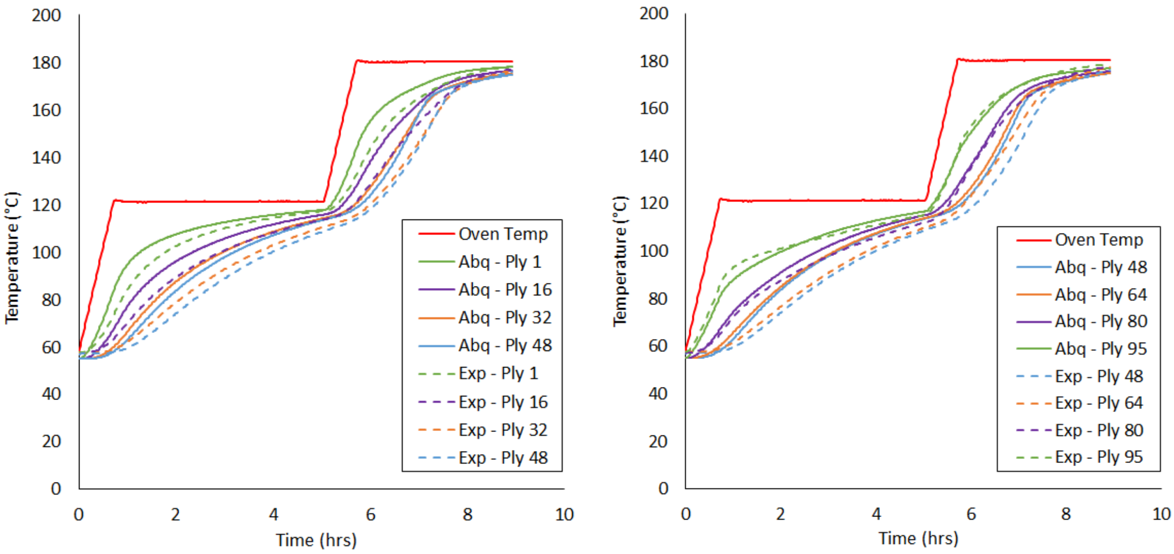

Figure 4: Comparison of Abaqus predictions and thermocouple data for the lower half of the 96 ply laminate (left) and for the upper half (right).

3.4. Coupled 3D model

A 3D model of the 400 x 400 mm, 96 ply uni-directional glass-fibre/epoxy-powder laminate was created in Abaqus. A uniform forced convection HTC of 40 W/m^{2}K was applied to all the outer surfaces of the bagging and steel tool; characterisation of the actual HTC over all the surfaces is outside the scope of this work. The symmetry of the laminate was used to model one quarter of the laminate, thus reducing the number of elements required. A mesh bias was used to concentrate nodes towards the edges of the laminate where it was expected that in-plane heat transfer would be more prominent. Each ply was made one element thick, and a minimum time increment of 120 seconds was used. A detailed convergence study on mesh size and time increment size will be the subject of future work.

Figure 5 shows the simulation results for temperature and degree of cure (DOC) 100 mins and 195 mins into the process cycle, representing the material behaviour during consolidation and curing, respectively. The results show that there were both in-plane and out-of-plane gradients within the laminate for temperature and DOC. As expected, the in-plane temperature gradient was more prominent at the edges of the laminate, resulting in non-uniform thickness change i.e. the edges consolidated/compacted faster than the centre of the laminate. During consolidation the epoxy maintained a low DOC, and it was not until the laminate reached sufficiently high temperatures that the curing agent activated and the catalysed reaction could take place. Interestingly, the laminate finished curing at the outer edges before curing fully at the centre of the laminate. This is not often the case with thermosetting materials where heat can build up too rapidly at the centre of the laminate and result in considerable overshoot from the programmed oven temperature. For this reason, the lower enthalpy of reaction for the epoxy powder should be considered a significant advantage of the material. Despite this advantage, there is still a potential issue with the size of the cure gradient which could result a shrinkage differential. Optimisation of the process cycle may help to reduce this gradient; however, characterisation of the cure shrinkage for the epoxy powder should also be carried out to determine what effects it may have.

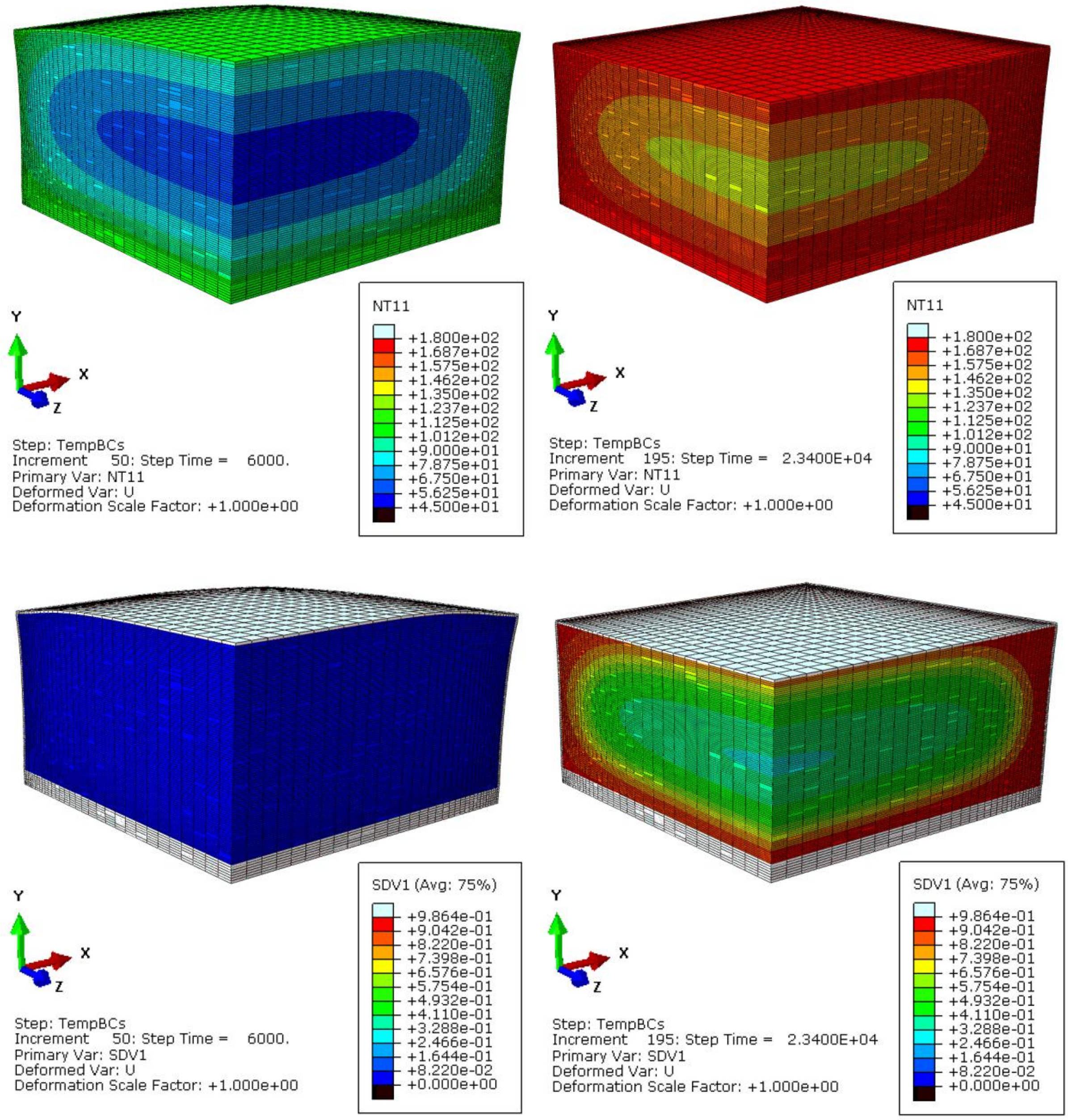

Figure 5: 3D simulation, in Abaqus, for the processing of a 96 ply thick laminate made from glass-fibre/epoxy-powder; temperature within the laminate after 100 mins (top left) and 390 mins (top right), and degree of cure (DOC) in the laminate after 100 mins (bottom left) and 390 mins (bottom right).

4. Conclusions

The work presented outlines the development of numerical simulations for processing thick-section composite parts. These thick-section parts are manufactured using an epoxy powder based vacuum bag only (VBO) prepreg technology. The epoxy powder offers a number of advantages for processing thick-section parts including excellent storage stability, low viscosity, and fast curing with a low exothermic enthalpy of reaction. The technology has been used to develop 12.6 m wind turbine blades, and the aim of developing numerical simulations was to aid in upscaling the technology for larger, thicker blades in a cost-effective manner.

An existing coupled resin flow and heat transfer model, as well as cure kinetics and chemorheological models, were implemented in UMATHT, a subroutine for user-defined thermal material behaviour. A Runge-Kutta algorithm was used within UMATHT to approximate the resin flow and curing at each time increment. Another user subroutine, UEXPAN, was used to convert the resin flow within each ply into a corresponding thickness change, thereby coupling the heat transfer and resin flow.

Implementation of the resin flow model within UMATHT was verified against an analytical solution under isothermal conditions. The accuracy of a 1D heat transfer simulation in Abaqus was assessed by comparison with an equivalent simulation in a commercial composites processing software, RAVEN, and with the model developed in MATLAB. All three simulations showed good agreement. The Abaqus simulation was also compared with preliminary experimental thermocouple data, again showing good relatively agreement; however, more robust experimental validation is ongoing.
Finally, a 3D simulation of the processing of a 400 x 400 mm, 96 ply thick glass-fibre/epoxy-powder laminate was performed. The simulation showed that the edges of the laminate experienced both in-plane and out-of-plane temperature and cure gradients, resulting in faster consolidation at the edges of the laminate. Furthermore, cure within the laminate did not result in a build-up of exothermic heat, as is common for thermosetting resins and can cause damage to the final part. Further optimisation of the process cycle through use of advanced 3D simulations should assist in increasing the speed of processing while reducing cure gradients which could otherwise lead to warpage of parts.

5. Acknowledgements

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