

Online optimisation and active control of the cure process of thick composite laminates

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Abstract

This paper addresses the development of an active control tool for the in-situ optimisation of the cure process of thick composite parts. The methodology integrates a cure process model with real time monitoring data exploring potential temperature dwells that accelerate the curing while avoiding undesirable thermal gradients. The cure process simulation is based on a Finite Element (FE) model solution validated in the curing of a thick composite flat panel with an average absolute error of about 1.8°C. The active control tool interacts PID controller of an oven setting a new cure temperature periodically. The implementation of active control tool during the curing of a thick carbon fibre/epoxy cable has the capability to determine in real time optimal solutions minimising process duration whilst also satisfying constraints in temperature overshoot. A process duration reduction of about 70% can be achieved compared to a nominal cure cycle with a maximum temperature overshoot lower than 9°C. The active control tool can replace off-line optimisation tools exploiting in situ with real time monitoring to drive the process and minimise the effects of uncertainty.

Keywords

Composites; Process Monitoring; Cure; Automation; Process Optimisation

1. Introduction

The utilisation of continuous fibre composites has grown and expanded in different applications in the last decades due to their high specific stiffness and strength. Thermosetting unidirectional carbon fibre cables are widely used in various industry sectors such as in sail yacht rigging [1], crane pedants, and bridge hangers [2]. These applications require high cable diameters in the range of 10-100 mm to meet stiffness and strength requirements.

Conservative cure processes associated with long thermal profiles are selected in practice to prevent large thermal gradients and exothermic effects, resulting in increased manufacturing costs. In the case of serial production, the curing stage becomes crucial for process duration, manufacturing costs and production rates. Multi-objective

optimisation methods have been developed to address conservative approaches for minimising cost and the likelihood of occurrence of process failures. These are based on optimisation schemes, such as Genetic Algorithms [3] or fuzzy logic controllers [4] investigating optimal solutions predictively resulting in minimisation of both process duration and potential defects [3,5,6]. Multi-objective optimisation schemes make use of numerical models such as cure simulation [7] or data assimilation combining observation values and simulation [8]. The benefits offered by the exploration of the design space by numerical optimisation can be accompanied by relative instability of some of the solutions with respect to perturbations of nominal process parameters leading to potential risks. Curing involves different sources of uncertainty such as tool/air temperature, surface heat transfer coefficient and cure kinetics behaviour [7,9,10]. Stochastic simulation, performed prior to the process, provides predictions of process variability considering the full input process parameters. Consideration of boundary conditions and cure kinetics variations indicates significant variability in cure time reaching coefficients of variation of approximately 22% [10]. The magnitude of uncertainty also affects the outcome of process optimisation. Higher levels of uncertainty results in greater optimal cure times to counteract variability [11]. The confidence intervals of process outcomes estimation are wide, leading to more conservative process cycles in order to prevent extreme events predicted by stochastic simulation. Stochastic optimisation schemes enable the consideration of inherent input uncertainties to minimise process outcomes variability providing more stable solutions [7].

Current optimisation schemes are restricted to off-line use only. Process monitoring techniques have been developed to provide information during the composites manufacturing process identifying potential defects and monitoring the progress of each stage [12–16]. The production of high-quality parts with zero defects requires comprehensive control of the manufacturing process. The utilisation of optimisation schemes and stochastic models prior to the process does not include the interaction with monitoring data to enhance model prediction capabilities and optimisation schemes efficiency. Off line optimisation cannot deal with instabilities in the presence of process parameter variations during the process. Alternative curing processes such as layer by layer curing [17] or layered self-resistance electric heating (L-SRE) [18] control the exothermic effects minimising degree of cure inhomogeneities, although their maturity level in terms of industrialisation is low. Inverse schemes have been developed integrating process models with monitoring data for off-line characterisation of material properties such as preform permeability [19,20] and also real time estimation of process outcomes such as duration and defect generation [21,22]. The incorporation of inversion schemes in the manufacturing processes provides critical information about process conditions, although action needs to be taken in cases in which undesirable phenomena occur during the process. Such schemes have been utilised for material properties characterisation and estimation of cure process outcomes without taking any control action during the process. Limited studies have

focused on the integration of control systems into the filling stage of composites manufacture. In the filling stage of Liquid Composite Moulding (LCM), the flow front can be actively controlled by locally heating resin reducing its viscosity [23] or by varying injection pressure [24] accelerating filling while eliminating voids formation and dry spots. Local pressure sensors strategically placed on the tool cavity can interact with flow models enabling the automated control of flow process by triggering inlet gates [25] or adapting injection flow rate [26,27] accounting for process variations to minimise the formation of voids.

The present study focuses on the development of an active control scheme integrating a cure process model with real time monitoring data for the in-situ minimisation of cure process duration with respect to exothermic effects. Constitutive models are developed, based on experimental data representing material properties, and utilised in a cure process model. A manufacturing trial is performed to evaluate the accuracy of the cure model. The active control scheme interacts with a cure simulation interface suggesting potential temperature dwells accompanied by real time surface temperature and material state data. The cure simulation interface evaluates the suggested temperature against applied conditional limitations and accepts or rejects the proposed temperature. The active control scheme is applied to the cure of a thick round carbon fibre/epoxy cable and its performance is compared with that of off-line multi-objective optimisation of the cure process.

2. Methodology

2.1. Cure simulation

The simulation of cure was performed using the Finite Element Analysis (FEA) code FLEXPDE 7 [28]. FLEXPDE 7 constitutes a general partial differential equation solver that uses FEA for numerical solution of one-, two- and three-dimensional time-dependent boundary value problems. The code allows the utilisation of non-linear constitutive models representing material behaviour and properties including cure kinetics, specific heat capacity and thermal conductivity. The cure process can be expressed by the following governing energy balance for the one-dimensional heat transfer problem in cartesian and cylindrical coordinates respectively:

$$\frac{\partial}{\partial z} \left(K \frac{\partial T}{\partial z} \right) = \rho c_p \frac{\partial T}{\partial t} - (1 - v_f) \rho_r H_{tot} \frac{d\alpha}{dt}, \quad z \in [0, t_{part}] \quad (1)$$

$$\frac{1}{r} \frac{\partial}{\partial r} \left(K \frac{\partial T}{\partial r} \right) = \rho c_p \frac{\partial T}{\partial t} - (1 - v_f) \rho_r H_{tot} \frac{d\alpha}{dt}, \quad r \in [0, R_{cable}] \quad (2)$$

Here ρ is the density of the composite, c_p is its specific heat capacity, T the temperature, α the degree of cure, K the thermal conductivity, v_f the fibre volume fraction, ρ_r the resin density, H_{tot} the total heat of the curing reaction,

and t_{part} , R_{cable} the thickness and the radius of a flat plate and round cable respectively. The left-hand side of Eqs. 1, 2 represents heat conduction. The first term of the right-hand side of Eqs. 1, 2 expresses the rate of change of volumetric enthalpy, whilst the second term the heat generated due to the exothermic resin reaction.

Two models were developed to simulate the cure of a flat panel and a round cable. The material is unidirectional (UD) carbon fibres prepreg with 12K tows and areal density of 200 g/m² with an epoxy resin mixed with hardener and accelerator (System A). The cured ply thickness (t) of the prepreg is 0.18 mm. Assuming uniform heating across the tool cavity and around the cable, the heat transfer problem becomes one-dimensional -in the through the thickness and the radial directions respectively - requiring the use of only one element in the other dimensions. Figure 1a illustrates a schematic representation of the flat panel model geometry used for the cure model validation. The composite comprises [228]₀ UD prepreg plies resulting in a fibre volume fraction of 60% at a thickness of 41 mm. The model is built using 57 elements across the thickness, each representing four UD plies with 0.72 mm nominal thickness. The prescribed thermal profile, assigned to the surface nodes of the lower and upper elements of the model, coincides with the monitored cure temperature profile applied on the composite panel during the cure process including two dwells at 80 and 150°C for 1 h each. A perfect insulation boundary condition is implied at the sides of each element to represent the symmetry of the geometry. The initial degree of cure and temperature considered in the model are 2% and 25°C respectively.

Figure 1b shows a schematic representation of the cure process of a carbon fibre/epoxy round cable used for the evaluation of the active control tool. The heat transfer problem was solved using cylindrical coordinates and is one-dimensional in the radial direction from cable centre to the outer surface. A perfect insulation boundary condition is implied at the cable centre to represent the symmetry of the problem, whilst forced air convection was applied on the top surface. The cure model consisted of [112]₀ UD prepreg plies with a volume fraction of 60% and diameter of 40.1 mm. The cure model is represented by 16 elements to enable the execution to be carried out in a very short time for active control. A sensitivity analysis of the dependence of cure model results on number of nodes highlighted the use of 16 elements results in sufficient accuracy, with an error of less than 0.5°C in maximum temperature compared to the results obtained with a finer discretisation using 60 elements

The main outputs of interest of the cure simulation are the total cure duration (t_{cure}), the maximum temperature overshoot (ΔT_{max}) and the time at which this occurs after the initiation of the cure process (t_{over}). Cure time is defined as the time at which the minimum degree of cure of the part is greater than 95%, which is the degree of cure that the resin reaches in a cure at the nominal cure temperature of 140°C as determined by Differential Scanning Calorimetry (DSC). When the degree of cure reaches this threshold, the simulation ends. The maximum

temperature overshoot is defined as the maximum difference between the prescribed temperature imposed by the external thermal profile on the part surface and the temperature in the composite over the whole duration of the process.

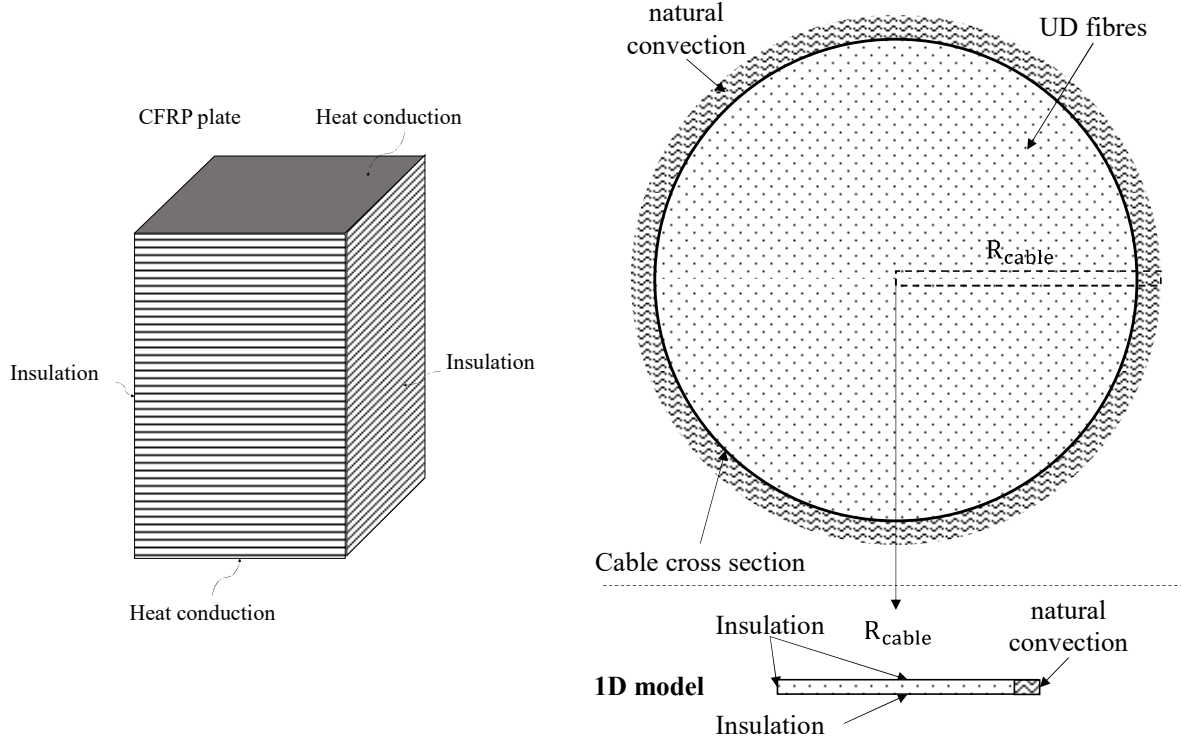


Figure 1 Cure process simulation models: a) Composite flat panel b) Composite round cable.

2.2. Constitutive models and characterisation

A Mettler Toledo DSC 1 Differential Scanning Calorimeter (DSC) was used for the characterisation of System A cure kinetics. Four isothermal tests at 80, 100, 130, and 140°C and one dynamic test from -25°C to 220°C at 1°C/min were performed. In all experiments, the weight of the sample did not exceed 10 mg to minimise thermal gradients. The total normalised reaction enthalpy (H_{tot}) was measured during the dynamic run to be 362 J/g. The DSC results were integrated to calculate the degree of cure using a sigmoidal and horizontal baseline for dynamic and isothermal experiments respectively. The cure kinetics model used for the fitting of the experimental data is a combination of an n^{th} order term and an term controlling diffusion [29]:

$$\frac{d\alpha}{dt} = k_1(1 - \alpha)^{n_1} + k_2(1 - \alpha)^{n_2}\alpha^m \quad (3)$$

where m, n_1, n_2 are the reaction orders and k_1 and k_2 the rate constants defined as follows:

$$k_i = \frac{A_i e^{\left(-\frac{E_i}{RT}\right)}}{1 + e^{C(\alpha - \alpha_T(T-273.15) - \alpha_c)}}, \quad i = 1, 2 \quad (4)$$

where A_i is pre-exponential factors, E_i the activation energy for the chemical reactions and R the universal gas constant. The denominator in Eq. 4 accounts for diffusion limitations to the cure kinetics as the glass transition temperature during the process approaches the curing temperature. This is implemented through a critical value of the degree of cure expressed as a function of temperature, where α_T , α_c are phenomenological parameters controlling the value of critical degree of cure as a function of temperature, whilst C is the breadth of the transition to diffusion-controlled reaction.

The evolution of the glass transition temperature T_g of the resin system of this study with degree of cure was quantified in a series of DSC dynamic experiments with a heating rate of 10°C/min. In each of the DSC runs, the resin sample was partially cured and the degree of cure was calculated as the ratio of measured to total enthalpy. Subsequently, a second dynamic run was performed to measure the glass transition temperature corresponding to the measured degree of cure of the first run and the glass transition was determined according to the ASTM E1356 standard. The glass transition temperature dependence on degree of cure can be expressed by the Di Benedetto equation [30] as follows:

$$T_g = T_{g0} + \frac{(T_{g\infty} - T_{g0})\lambda\alpha}{1 - (1 - \lambda)\alpha} \quad (5)$$

where $T_{g\infty}$ and T_{g0} are the glass transition temperature of the fully cured and uncured material respectively and λ is a parameter controlling the convexity of the dependence.

The specific heat capacity of the composite is computed making use of the rule of mixtures as follows:

$$c_p = w_f c_{pf} + (1 - w_f) c_{pr} \quad (6)$$

where w_f is the fibre weight fraction, c_{pf} the fibre specific heat capacity and c_{pr} the specific heat capacity of the resin. The specific heat capacity of the fibre is computed using [3]:

$$c_{pf} = A_{fc_p} T + B_{fc_p} \quad (7)$$

where A_{fc_p} and B_{fc_p} control the linear dependence of fibre specific heat capacity on temperature. The specific heat capacity of the resin system was measured using a modulated mode of the DSC instrument. Three isothermal tests were carried out at 100, 120, and 130°C. The amplitude and the period of the modulation was 1°C and 1 min

respectively, whilst the heating rate to reach the isothermal temperature was 20°C/min. The specific heat capacity of the resin was approximated using a modified logistic equation:

$$C_{pr} = B_{rcp} + \frac{\Delta_{rcp}}{1 + e^{C_{cp}(\alpha - \alpha_{Scp}T - \alpha_{Tcp})}} + T \left(A_{rcp} + \frac{\Gamma_{rcp}}{1 + e^{C_{cp}(\alpha - \alpha_{Scp}T - \alpha_{Tcp})}} \right) \quad (8)$$

where A_{rcp} , B_{rcp} are the slope and the intercept of the linear dependence of the specific heat capacity of the uncured resin on temperature, Γ_{rcp} , Δ_{rcp} denote the strength of the step reduction in specific heat capacity at the vitrification point and its temperature dependence respectively, whilst C_{cp} , α_{Scp} , α_{Tcp} are the breadth and the phenomenological parameters controlling the degree of cure at which the transition occurs.

The thermal conductivity of the anisotropic composite material in the transverse direction is calculated as follows [31]:

$$K_{33} = v_f K_r \left(\frac{K_{tf}}{K_r} - 1 \right) + K_r \left(\frac{1}{2} - \frac{K_{tf}}{2K_r} \right) K_r \left(\frac{K_{tf}}{K_r} + 1 \right) + \sqrt{v_f^2 - v_f + \frac{\left(\frac{K_{tf}}{K_r} + 1 \right)^2}{\left(\frac{2K_{tf}}{K_r} - 2 \right)^2}} \quad (9)$$

where K_{tf} is the thermal conductivity of the fibre in the transverse direction expressed as follows:

$$K_{tf} = B_{tf} \quad (10)$$

where B_{tf} is a constant. The resin thermal conductivity model for the resin system can be expressed by the following equation [32]:

$$K_r = \frac{1 + \theta\alpha}{\beta + \gamma T} \quad (11)$$

where θ , γ are fitting parameters controlling the linear dependence on the degree of cure and temperature respectively, whilst β the contribution of structure scattering and of vacant-site scattering to thermal resistance.

2.3. Optimisation and active control scheme

An active control scheme was developed integrating the cure simulation model with monitoring data for the real time optimisation of curing. A schematic representation of the active control is shown in Figure 2. The aim of the active control tool is to find, in real time, dwell temperatures (T_{i+1}) that do not produce problematic temperature overshoots in the composite part, while minimising the duration of the process. The control scheme acts in real time considering the cure model predictions based on the available monitoring data. More specifically, the active

control tool interacts with the cure simulation interface suggesting a cure temperature (T_{sug}) higher than the current value (T_i) - measured by the control thermocouple placed on the outer surface of the composite part - by a constant temperature step increase (T_{step}). The cure model interface accepts or rejects the suggested temperature based on a series of conditions. The active control sets the new allowable temperature (T_{i+1}) - as provided by the cure model interface - to the oven PID controller and thus to the composite part. This way, there is real time control and at the same time estimation of potential temperature dwells which drive the process to faster cycles with respect to the applied process constraints and design parameters. The active control is triggered when the temperature reaches 60°C at which the material is still in an inert state.

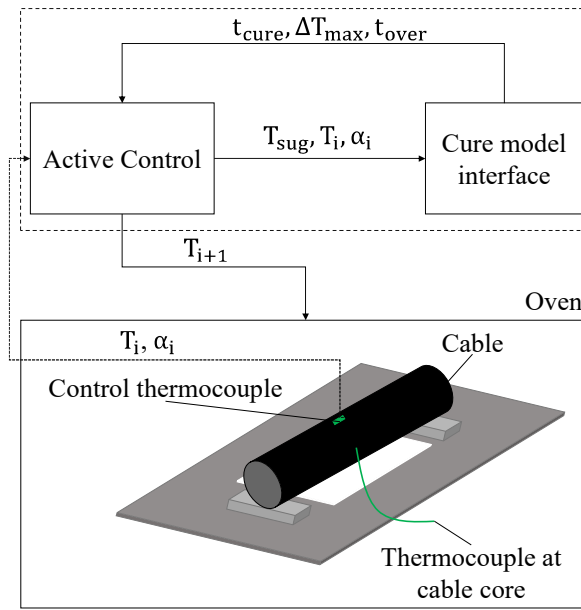


Figure 2 Schematic representation of active control tool.

The cure simulation runs a one-dwell thermal profile with duration 30 min using as inputs the current cure oven temperature T_i , the degree of cure α_i , and the suggested temperature T_{sug} , whilst it outputs ΔT_{max} , and t_{over} . The computational time of the cure simulation is about 12 s allowing the possibility to provide real-time feedback to the active control. The aim of the cure simulation is to calculate the maximum temperature overshoot and the time at which it happens within a window of 30 min. The limitations applied to the active control related to selection of temperature dwells are illustrated in Figure 3. The cure model interface executes the cure model if the suggested temperature (T_{sug}) does not exceed the maximum allowable temperature (T_{max}). T_{sug} is accepted if the maximum temperature overshoot (ΔT_{max}) is not higher than the maximum allowable temperature overshoot (ΔT_{lim}) or if the time difference (Δt_{exo}) between the time of the maximum overshoot occurs (t_{over}) and the time needed for the part to cool down (t_{rampc}) to avoid exceeding ΔT_{lim} is higher than a safety factor time (Δt_{sf}). Δt_{sf} is a safety margin

to the time difference Δt_{exo} to avoid exothermic effects corresponding to potential process variability arising from the inherent time constant of the manufacturing setup.

$$\Delta t_{\text{exo}} = t_{\text{over}} - t_{\text{rampc}} \quad (12)$$

$$t_{\text{rampc}} = \frac{(\Delta T_{\text{max}} - \Delta T_{\text{lim}})}{r_{\text{cool}}} \quad (13)$$

If one of the conditions is not fulfilled a second simulation run is performed using T_i as the instantaneous cure temperature. The same constraints are applied to the second run and if the overshoot is lower than the limit, T_i is selected as the next temperature dwell for the active control. Otherwise, the temperature setting T_{i+1} is calculated as follows:

$$T_{i+1} = T_i - (\Delta T_{\text{max}} - \Delta T_{\text{lim}}) \quad (14)$$

Table 1 reports the parameter values used in the current study. The active control tool and a cure model interface allowing automated execution of the FLEXPDE 7 solver were implemented in Python 3.9.

Table 1 Active control parameters.

Active control parameters	Values
ΔT_{lim}	10 °C
T_{max}	160 °C
T_{step}	5 °C
Δt_{sf}	5 min
r_{cool}	1.5 °C/min

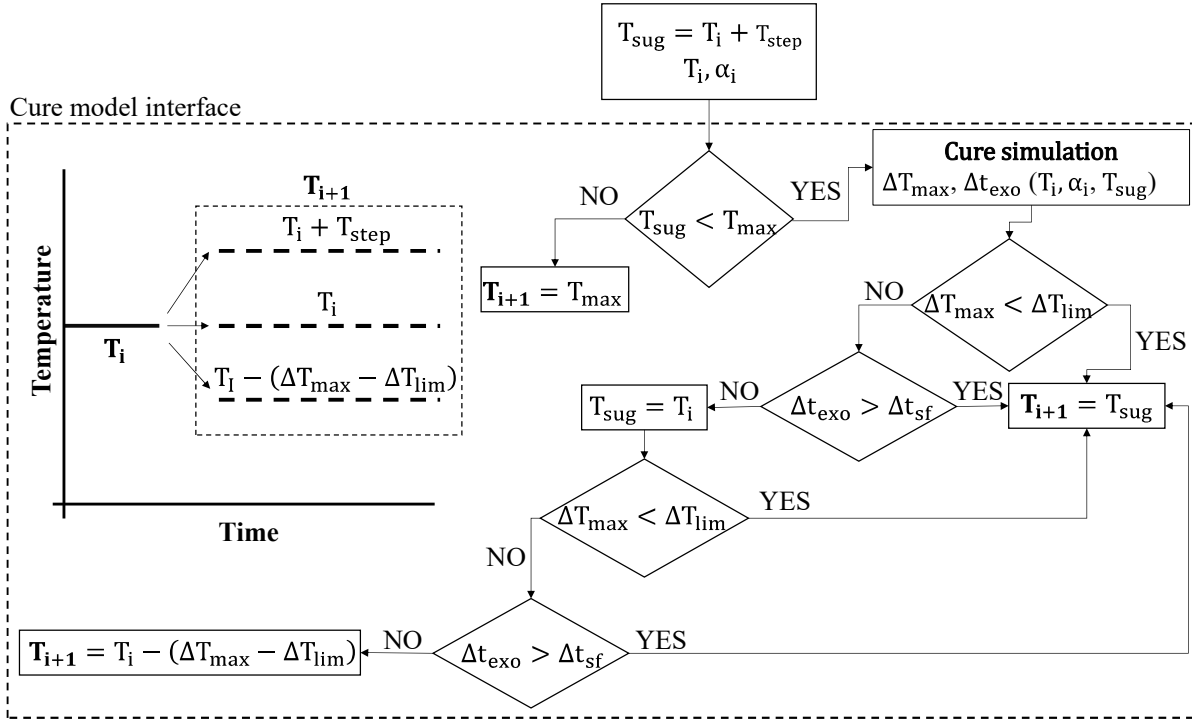


Figure 3 Cure model interface of the active control tool.

2.4. Manufacturing trials

The cure simulation model was validated in the curing of a thick UD carbon/epoxy composite panel. The composite part consisted of 228 UD prepreg plies with dimensions 100 mm × 100 mm resulting in a thickness of 41 mm. Aluminium plates were placed on top and bottom of the panel, whilst pieces of foam were attached on the sides for insulation. Figure 4a shows the curing setup. The whole assembly was placed on a hydraulic press heated at 80°C for 1 h to ensure equilibration of temperature in the thickness direction, followed by a second dwell at 150°C for another 1 h. Five k-type thermocouples were inserted evenly through the thickness as illustrated in Figure 4b to monitor the evolution of the through thickness part temperature. This setup achieves close control of boundary temperatures; therefore, allowing validation of the simulation operation within the body of the curing component. A TM500 12-Channel Datalogging Thermometer was utilised to acquire the temperature data.

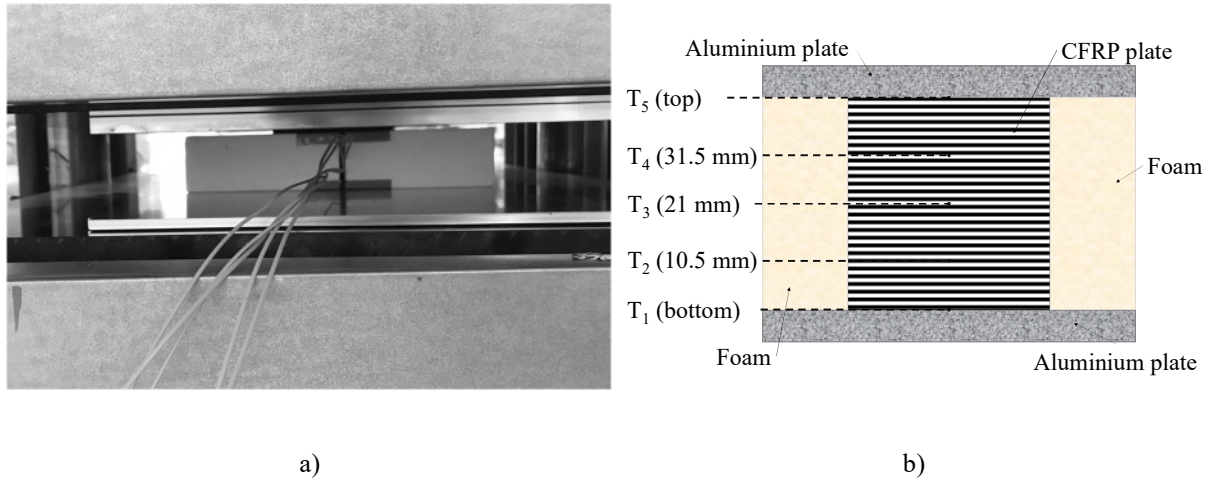


Figure 4 a) Curing stage of flat composite panel b) schematic representation of K-type thermocouples mounting within the composite panel.

The validation of the active control tool was performed during the cure of a round cable in an industrial oven. The experimental set-up is depicted in Figure 5. The round cable consisted of wound UD prepreg plies, equivalent to 112 layers from centre to the surface consolidated by release film resulting in a diameter of 40.1 mm for the whole assembly. Two k-type thermocouples were placed on the outer surface and in the centre of the cable. The thermocouple on the outer surface was used as a control thermocouple for the PID controller, whilst the thermocouple in the centre to monitor exothermic effects only for validation purposes. In order to evaluate the material state of the cable after the completion of the cure process, a dynamic DSC run was performed with a heating rate of 10°C/min.

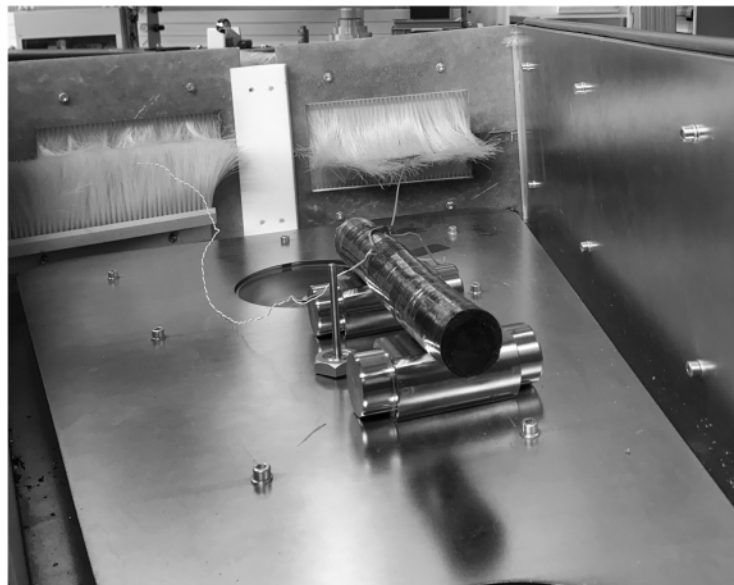


Figure 5 Active control tool validation experimental set-up

3. Results and Discussion

3.1. Constitutive models

A fitting was performed on the experimental data as acquired by the DSC and MDSC runs to estimate constitutive model parameters for System A cure kinetics, glass transition temperature and specific heat capacity. The fitting was performed using the hybrid Genetic Algorithm implemented in the Solver of Microsoft Excel [33]. Figure 6 illustrates the performed fitting of the cure kinetics model, presented in Eqs. 3-4, on the experimental data with an average absolute error of about 0.01. Figure 7a shows the experimental data of glass transition temperature and the fitting performed following the Di Benedetto model as described in Eq. 5. The resin specific heat capacity model fitting is depicted in Figure 7b alongside the modulated DSC (MDSC) results, whilst the average absolute error is equal to 0.01 J/g/°C. The model constants of Eqs. 3-8 obtained by the fitting are reported in Table 2.

The thermal conductivities parameters values presented in Eq. 11 were derived from a similar epoxy resin system (Huntsman XU3508/ XB3473 [34]) and presented in Table 3. The densities of the epoxy resin (ρ_r), and carbon fibre (ρ_{cf}) used in manufacturing trials and process simulation are also reported in Table 3.

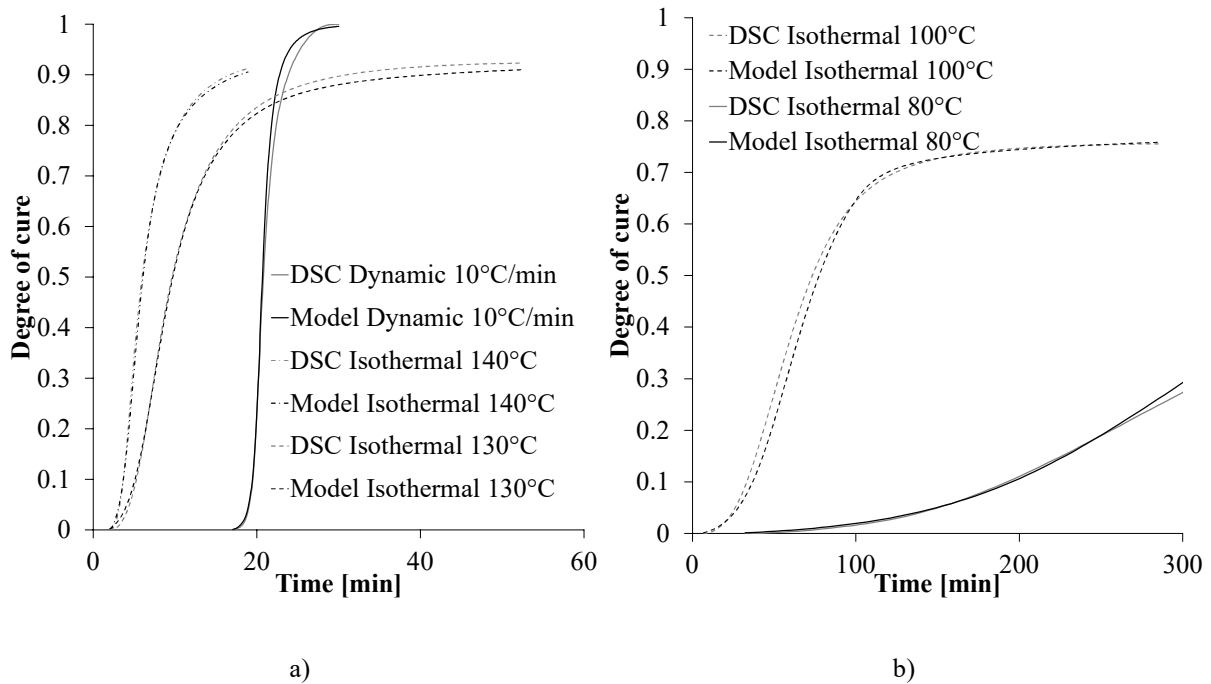


Figure 6 Cure kinetics model fitting a) Isothermal 130, 140°C and dynamic 10°C/min b) Isothermal 80, 100°C.

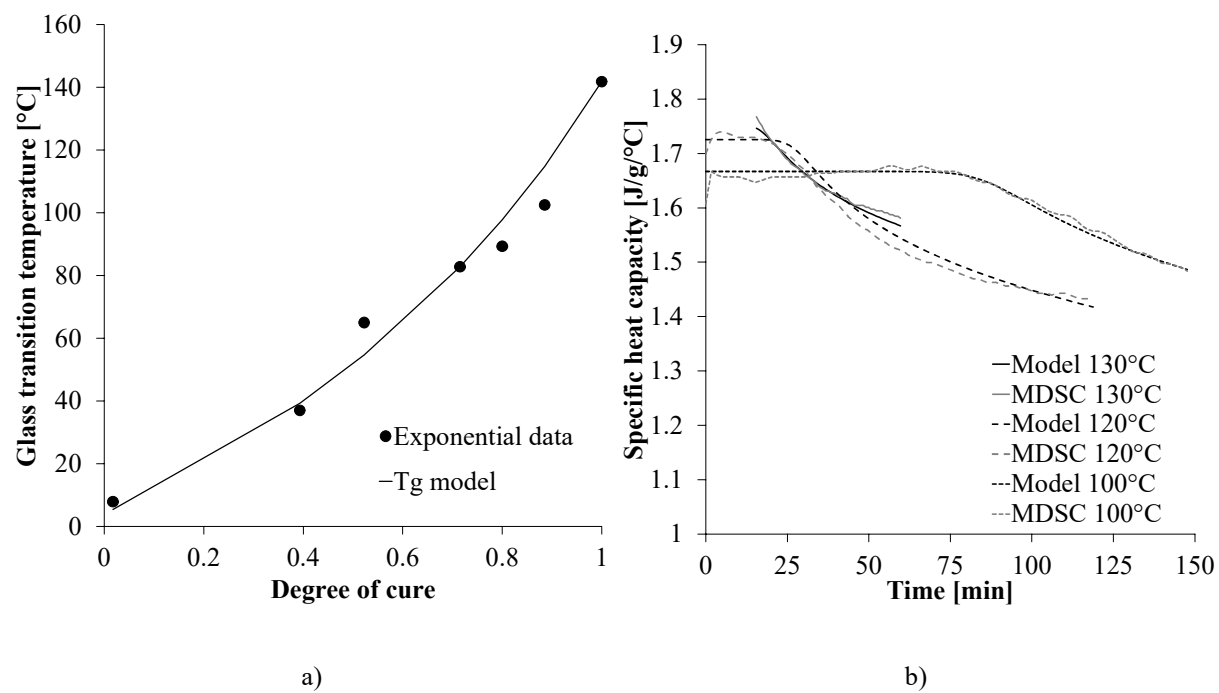


Figure 7 a) Di Benedetto equation fitting b) Specific heat capacity model fitting.

Table 2 Cure kinetics, Glass transition temperature and fibre [3] and resin specific heat capacity models constants.

Parameter	Values	Units
A_1	4.67E + 09	s^{-1}
A_2	5.84E + 09	s^{-1}
E_1	103,631.31	$Jmol^{-1}$
E_2	90,435.52	$Jmol^{-1}$
m	0.94	-
n_1	5.93	-
n_2	2.24	-
α_C	0.0064	-
α_T	-1.71	K^{-1}
C	44.4	
H_{tot}	362	Jg^{-1}
T_{g0}	277.26	K
$T_{g\infty}$	414.96	K
λ	0.53	$Jg^{-1}K^{-2}$
A_{fcp}	0.0023	$Jg^{-1}^{\circ}C^{-2}$
B_{fcp}	0.765	$Jg^{-1}^{\circ}C^{-2}$
Δ_{rcp}	1.073	$Jg^{-1}^{\circ}C^{-2}$
B_{rcp}	0.301	$Jg^{-1}^{\circ}C^{-2}$
Γ_{rcp}	0.00269	$Jg^{-1}^{\circ}C^{-2}$
A_{rcp}	0.00021	$Jg^{-1}^{\circ}C^{-2}$
C_{cp}	29.4	$^{\circ}C^{-1}$
α_{scp}	0.0061	-
α_{tcp}	0.184	$^{\circ}C^{-1}$

Table 3 Thermal conductivity model constants [32], resin and fibre densities.

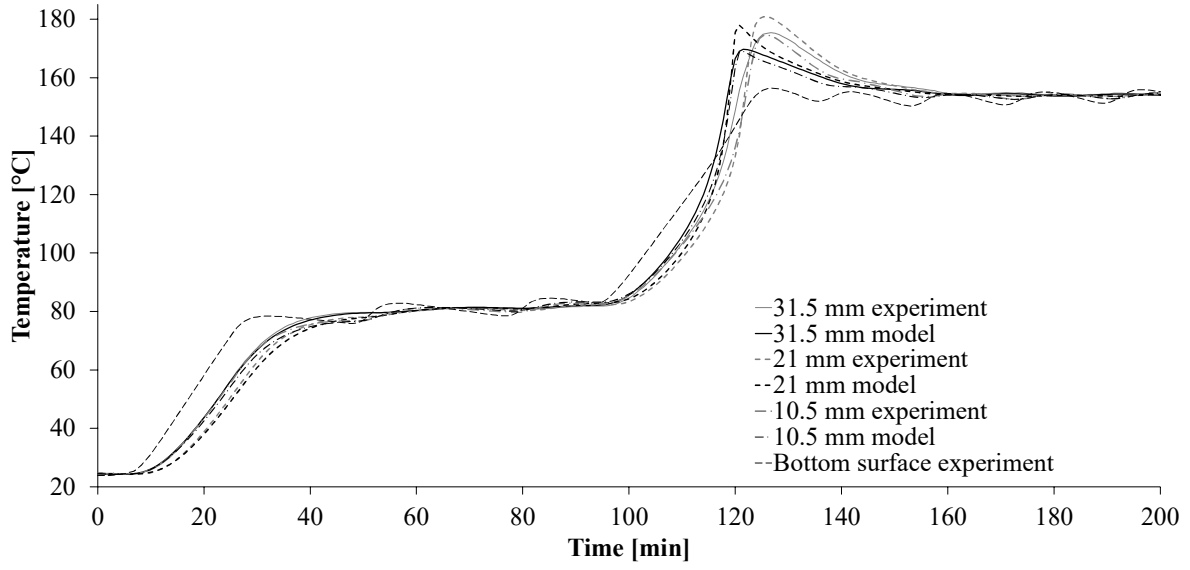
Parameter	Values	Units
B_{tf}	0.765	$Jg^{-1}^{\circ}C^{-2}$
θ	0.44	$Wm^{-1}K^{-1}$
β	-12.1	$W^{-1}mK$
γ	0.061	mW^{-1}
ρ_r	1.16	gml^{-1}
ρ_{cf}	1.78	gml^{-1}

3.2. Cure simulation validation

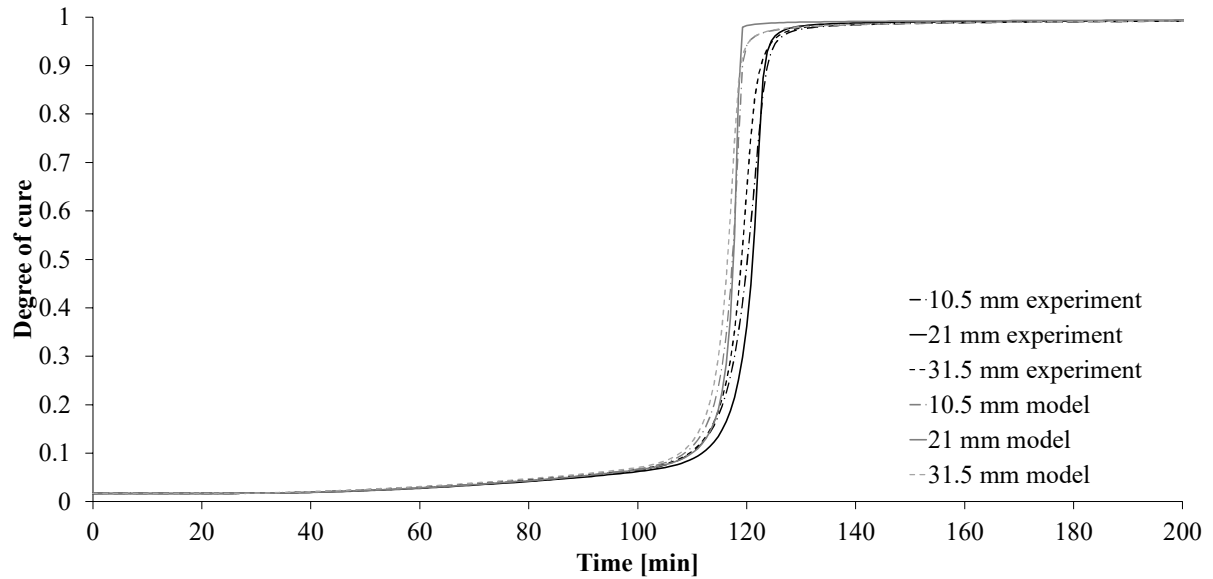
Figure 8 shows the 41 mm thick carbon fibre/epoxy flat panel after the completion of the cure process. The temperature data acquired during the process are illustrated in Figure 9a alongside the cure simulation prediction. The temperature profiles at the lower and top surface were used as boundary conditions. The applied cure temperature profile on the sample resulted in a maximum temperature overshoot at the part middle surface of about 25°C, highlighting the aggressive character of the thermal profile used. For this manufacturing trial, the presence of an exotherm allows the thorough investigation of the cure model capabilities compared to the experimental results. The comparison shows a good agreement between the cure simulation and the experiment, proving the accuracy of the model in estimating the thermal gradient and especially temperature overshoot, which is of significance in the case of thick components. The average absolute error is about 1.8°C. This low value of error evidence the accuracy of the simulation to represent conduction effects, heat generation due to the reaction and other non-linearities in the curing material successfully.



Figure 8 UD Composite flat panel



a)



b)

Figure 9 Cure model validation: a) temperature b) degree of cure

3.3. Active control tool validation

Figures 10 and 11 show the cured cable and the results of the active control tool implementation. The evolution of the degree of cure and glass transition temperature, calculated using the temperature data on the cable surface and centre, are also depicted in Figure 11. The thermal profile applied on the outer surface of the cable highlights the stepwise operation of the active control. At any instance, the active control algorithm identifies the maximum temperature for the next increment at which the predicted maximum temperature overshoot does not exceed the

allowable limit or if it does the predicted time to the occurrence of overshoot is sufficiently long to allow cooling down before the process reaches this point. It can be observed that the applied thermal profile does not present a typical behaviour of two or three dwell profiles. The part is initially heated up to 112°C followed by a cooling step at 107°C for approximately 5 min. This is because a cure temperature of 112°C at the beginning of the process results in temperature overshoots higher than the allowable threshold. However, this particular temperature is accepted by the active control tool initially, since the time at which the predicted temperature overshoot occurs is greater than Δt_{sf} . When Δt_{exo} becomes lower than the allowable time limit, the cure temperature at that time becomes not acceptable anymore and thus a lower dwell temperature is applied compensating for the difference between ΔT_{max} and ΔT_{lim} . In this way, the thermal profile becomes more aggressive avoiding at the same time unacceptable temperature overshoots. Two longer dwells follow at 113°C and 117°C for 5 min and 4 min respectively, before the final post cure at 150°C for approximately 15 min. The cure process terminates after 77 min, when the degree of cure reaches 0.95. The maximum temperature overshoot measured is equal to 8.8°C, which is lower than ΔT_{lim} . A reduction of about 70% in cure duration is achieved compared to the nominal thermal profile utilised for a cable with the same diameter. The nominal profile, recommended by the resin supplier, illustrated in Figure 12, comprises two dwells at 95°C and 150°C for 180 min and 30 min respectively, resulting in a cure duration of about 244 min, whilst the maximum overshoot is below 5°C.



Figure 10 Round cable after the completion of curing stage

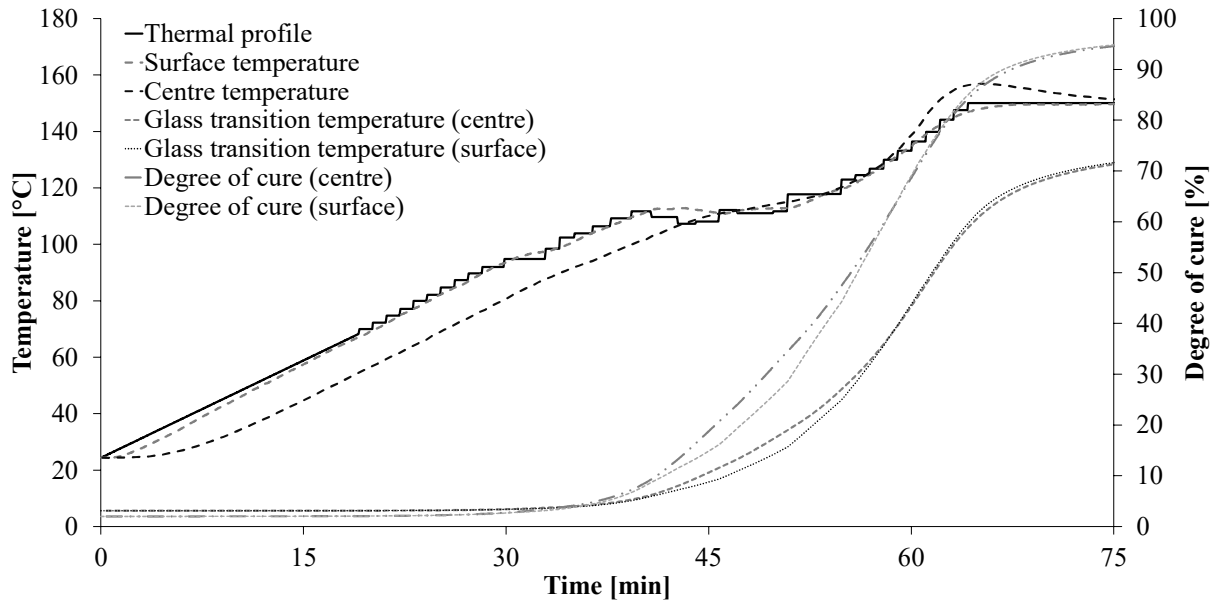


Figure 11 Active control tool results; optimal thermal profile, cable temperature and degree of cure.

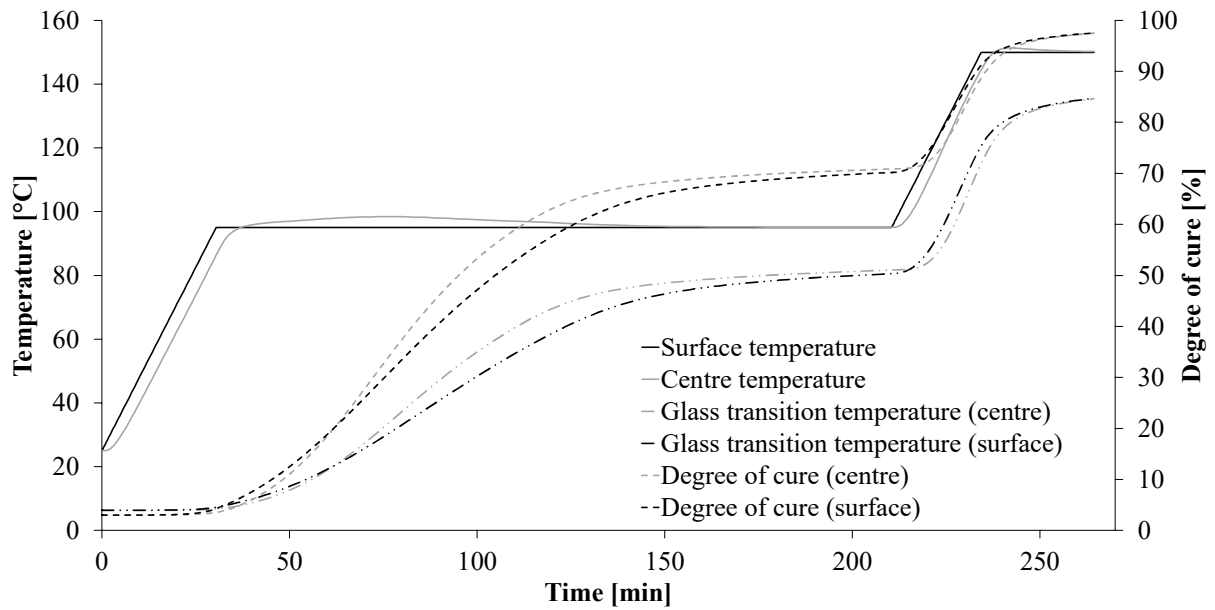


Figure 12 Nominal cure cycle results; cable temperature and degree of cure evolution.

3.4. Comparison of active control and off-line optimisation

The solution provided by the active control tool was compared with the results of off-line optimisation based on an exhaustive search of the design space of possible cure model solutions. The design variables of the optimisation are the parameters of the two-dwell cure profile illustrated in Figure 13a, i.e. the temperature (T_1) and the duration (Δt_1) of the first dwell. The range of thermal profile parameters T_1 and Δt_1 considered was 70-150°C and 5-120 min respectively. The second dwell duration (Δt_2) was not considered as a design variable due to the definition of

cure time as the time at which a certain leave of cure is reached, whilst the second dwell temperature (T_2) and heating rate were constant and equal to 150°C and 2.3°C/min respectively. The total number of cure model evaluations was 931.

Figure 13b shows the outcome of the exhaustive search alongside the result for the nominal cure cycle and the implementation of active control. The competitive nature of the temperature overshoot and cure duration leads to an L-shape Pareto front of the optimal design points. A thermal profile with T_1 and Δt_1 equal to 106 °C and 15 min respectively results in a total duration of 79 min, whilst the maximum temperature overshoot is about 10 °C, which is the maximum temperature overshoot allowed. The comparison highlights the capability of the active control algorithm to obtain a solution with performance close to that of optimal solutions obtained by the exhaustive search, for similar levels of temperature overshoot. Setting a different temperature overshoot constraint in active control would have resulted in a different cure profile than the one followed in Figure 11, but with performance similar to that of the point of the Pareto front of the exhaustive search that corresponds to the same level of overshoot. In addition, the active control algorithm can adapt to measured variations in process conditions, e.g. differences between the nominal and actual temperature on the surface of the part, without using an optimisation scheme performed off-line for a specific part. The active control algorithm requires only the thermal history of the curing part and uses thickness as an input. Therefore, it can be used for different cable diameters in a generic manner. The control scheme can also adapt to potential thermal disturbances during the process finding in real time the optimal solution. Therefore, active control can be used to optimise the cure process subject to in situ variations within the limits set by certification processes. This is a crucial advantage over an off-line solution, such as the one obtained by the exhaustive search, the accuracy of which would be subject to controlling variations in surface temperature of the component.

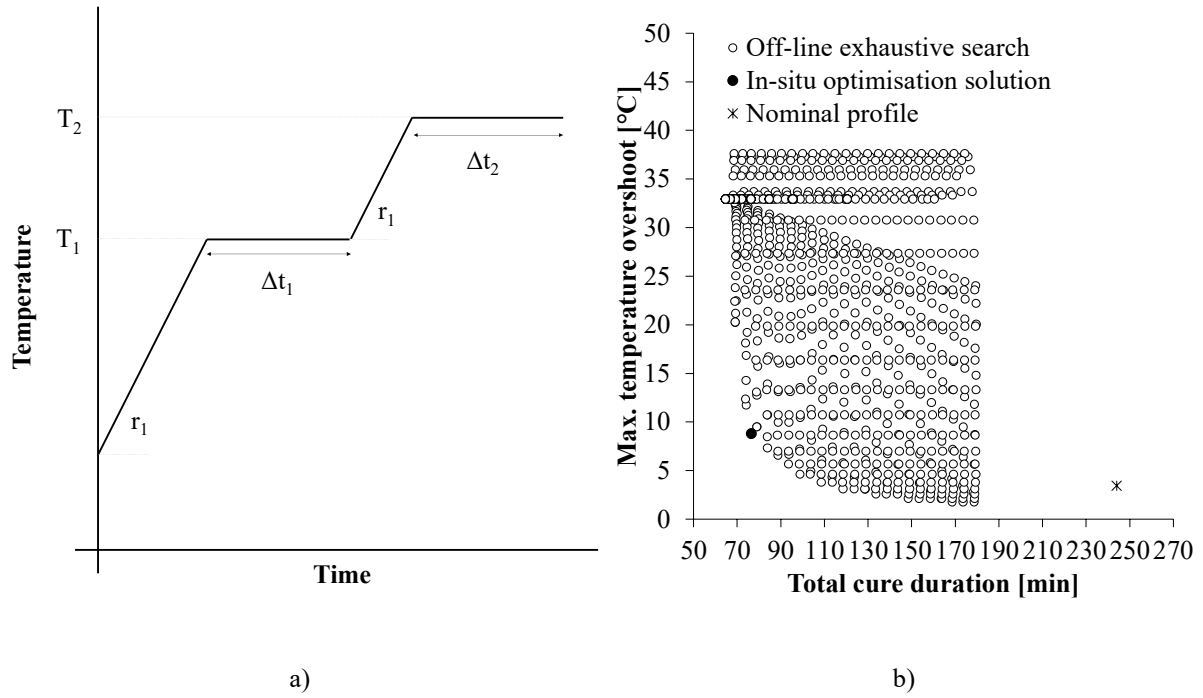


Figure 13 a) Two dwell profile b) Comparison between exhaustive search and active control results

4. Conclusions

The active control tool developed in this study integrates cure model predictions with real time monitoring data driving the cure process to a faster cycle by selecting optimal cure temperatures while respecting to temperature overshoot constraints. The active control implementation in the curing of a thick round carbon fibre/epoxy cable has reduced the duration of the process by about 70% compared to nominal profiles keeping the maximum temperature overshoot below a generally considered acceptable limit of 10 °C. The solution found by the active control lies on the L-shape Pareto front of off-line optimisation design points highlighting the capability of the method to drive in real time the process to optimal solutions. The active control can be utilised for various cable diameters using the same cure model and deal with process uncertainty manifested as deviations in thermal conditions in comparison to the prescribed cure cycle. The simplification of the cure model to 1-D solution reduces significantly the computational time. In the case of more complex parts, where a FE model becomes computationally cumbersome, a surrogate cure model can be developed allowing the utilisation in real time during the process.

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