A multi-dwell temperature profile design for the cure of thick CFRP composite laminates

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Abstract
This paper develops a multi-objective optimization method for the cure of thick composite laminates. The purpose is to minimize the cure time and maximum temperature overshoot in the cure process by designing the cure temperature profile. This method combines the finite element–based thermo-chemical coupled cure simulation with the non-dominated sorting genetic algorithm-II (NSGA-II). In order to investigate the influence of the number of dwells on the optimization result, four-dwell and two-dwell temperature profiles are selected for the design variables. The optimization method obtains successfully the Pareto optimal front of the multi-objective problem in thick and ultra-thick laminates. The result shows that the cure time and maximum temperature overshoot are both reduced significantly. The optimization result further illustrates that the four-dwell cure profile is more effective than the two-dwell, especially for the ultra-thick laminates. Through the optimization of the four-dwell profile, the cure time is reduced by 51.0% (thick case) and 30.3% (ultra-thick case) and the maximum temperature overshoot is reduced by 66.9% (thick case) and 73.1% (ultra-thick case) compared with the recommended cure profile. In addition, self-organizing map (SOM) is employed to visualize the relationships between the design variables with respect to the optimization result.

Keywords CFRP · Cure process · Multi-objective optimization · Genetic algorithm · Finite element method

1 Introduction

With the increasing demand for high performance and weight reduction in various fields such as aerospace, navigation and automotive, etc., carbon fiber–reinforced polymer (CFRP) composites have been widely used due to their high specific stiffness and strength. The large-size composite parts, particularly the primary load-bearing structures in aircraft, are generally manufactured by autoclave cure process [1]. Cure process is one of the most important stage determining the final quality of the composite parts. In a cure process, the temperature and pressure boundaries prescribed in the cure profile are imposed to the prepreg to make the resin full polymerization [2]. The cure temperature profile is usually recommended by the prepreg manufacturer, which could provide a guidance for the cure of composite parts. However, the recommended profile is not suitable for all type parts. For instance in the cure of the thick composite parts, the reaction heat cannot be transferred to the surface in time due to the low thermal conductivity of prepreg and the large thickness. The severe temperature overshots would be generated inside the thick composite parts using the recommended profile and lead to resin degradation, non-uniform cure and residual stress [3] of the parts. In industry, the risks associated with temperature overshots in thick composite parts are dealt with by adopting conservative cure cycles or trial and error method. This lead to long processing times and high manufacturing costs.

Therefore, it is desirable to achieve an optimal cure temperature profile that can minimize the temperature over- shoots or other process-induced defects. The optimization of temperature profile should be based on a comprehensive understanding of the physical state of composite parts...
during cure. Several experimental works [4–6] have been conducted to monitor the state evolution in a cure process by using temperature, pressure, and viscosity sensors. However, experimental approach is complicated and costly, and sensors embed in composite part would perturb the cure process [7]. An effective and relatively inexpensive approach is numerical simulation of the cure process. Numerical models of cure process of thermoset polymer composites have been improved from simple one-dimensional finite difference models [8] to advanced three-dimensional finite element models [9]. Compared with the experimental method [10], simulation models could provide comprehensive information during cure in an efficient way, such as the evolutions of the temperature, degree of cure, and residual stress of cured part [11, 12].

Based on the mature numerical models describing the cure process, determination of optimal cure temperature profiles that can minimize cure time and the occurrence of temperature overshoots or other process-induced defects have been addressed in the literature. Lee applied a sequential unconstrained minimization technique (SUM technique) to design an optimal temperature profile with the cooling and re-heating steps to minimize the temperature overshoot [13]. Kennedy combined a semi-analytic gradient evaluation technique with a gradient-based optimization algorithm to find an optimal cure temperature history to maximize the failure load of the specific structure [14]. Vafayan used genetic algorithm and finite element method to minimize a complete objective weighted by temperature difference and cure difference [15]. Wang proposed an optimization method which decomposed the original problem into several sub-problems to reduce the spring-back during the autoclave cure [16]. Aleksendric et al. integrated the artificial neural networks (ANN) and a fuzzy logic algorithm to adjust the cure profile to obtain a desired trend of degree of cure [17]. Struzziero combined the finite element method with a multi-objective genetic algorithm to minimize the cure time and maximum temperature overshoot [18]. Shah used the multi-objective genetic algorithm to optimize the cure temperature profile to minimize residual stresses and the total cure time of asymmetric laminates cured by autoclave [19]. Dolkun obtained a Pareto front of cure profile in multi-dimensional objective space, and cure time, degree of cure difference, and temperature difference were minimized simultaneously [20]. Wang et al. integrated a multiscale process simulation model and multi-objective optimization method to obtain optimized cure profile, which contributes to decreasing the residual stress and cure time [21].

In the case of thick composite parts, a two-dwell cure temperature profile is usually considered. For the ultra-thick parts, it is expected that increasing the dwell could achieve improvement in temperature overshoot compared to standard cure profiles. Sorrentino defined a preliminary methodology which inserting an additional dwell placed between the two original dwell to avoid resin degradation and decrease the temperature overshoot [22, 23]. The duration of the additional dwell is heuristically determined and needs further study to be optimal. Jahromi used a trained dynamic ANN instead of finite element calculation and the non-linear programming algorithm to design multi-dwell temperature profile with the objective to minimize the maximum temperature difference during the curing [24]. However, the study only considered the improvement of cure quality and the cure time was pre-defined.

This paper is devoted to develop a multi-dwell temperature profile design methodology for thick CFRP composite laminates. Compared with the existed studies, the influence of the number of dwells on the optimization results is investigated. The two objectives, i.e., the cure time and maximum temperature overshoot in the cure process, are minimized simultaneously using a multi-objective genetic algorithm (GA). A thermo-chemical coupled simulation model of the cure process is combined with the GA. The proposed methodology is applied to the cure of a thick AS4/8552 laminate. The optimization result shows the cure time and temperature overshoot are effectively decreased by the multi-dwell temperature profile design.

## 2 Thermo-chemical coupled model of the cure process

### 2.1 Theoretical formulation

During the cure process, the composites are subjected to external temperature profile. The cure reaction of resin depends on the temperature. Meantime, the cure reaction of the resin releases the heat. Therefore, the heat transfer process and the cure reaction process couple with each other. To solve this problem, a thermo-chemical coupled simulation incorporating the heat transfer model and cure kinetics model is considered in this study. The thermo-chemical coupled heat transfer equation is expressed as [25]:

$$\rho C_p \frac{\partial T}{\partial t} = K_{xx} \frac{\partial^2 T}{\partial x^2} + K_{yy} \frac{\partial^2 T}{\partial y^2} + K_{zz} \frac{\partial^2 T}{\partial z^2} + \dot{q}$$  

(1)

where $\rho$ and $C_p$ are the density and specific heat capacity of the composites, respectively, $T$ is the current temperature, $K_{ii}$ ($i = x, y, z$) is the conductivity of the composites in
different directions, and \( \dot{q} \) is the internal heat released in the cure reaction, which can be quantitatively expressed as:

\[
\dot{q} = \rho_r V_r H_r \frac{d\alpha}{dt}
\]  

(2)

where \( \rho_r \) is the density of the resin, \( V_r \) is the volume fraction of the resin, and \( H_r \) is the heat generated by the complete reaction of unit mass of resin. \( \frac{d\alpha}{dt} \) is the instantaneous cure rate of the resin and can be determined by the cure kinetics model and material type. In this study, the AS4/8552 prepregs are adopted and the cure kinetic model used in [26] is employed as:

\[
\frac{d\alpha}{dt} = k \alpha^m (1 - \alpha)^n
\]

(3)

where \( \alpha \) is the degree of the cure. \( m \) and \( n \) are reaction orders obtained by fitting the result of DSC experiment. \( k \) is reaction rate constants expressed as follows:

\[
k = A e^{(-\Delta E/RT)}
\]

(4)

where \( A \) is pre-exponential factor, \( E \) is the activation energy for the chemical reaction, \( T \) is the absolute temperature, \( R \) is the universal gas constant, and \( \alpha_C \) is the diffusion constant, which can be calculated by:

\[
\alpha_C = \alpha_{C0} + \alpha_{CT} T
\]

(5)

where \( \alpha_{C0} \) is the constant when the temperature is absolute zero, and \( \alpha_{CT} \) is the slope in the linear relationship between temperature and \( \alpha_C \). Parameter values of the cure kinetics model from [26] are used in this study and listed in Table 1.

The properties of composites are evaluated with the rule of mixture. The specific heat capacity of the composites \( C_p \) is calculated as [27, 28]:

\[
C_p = V_f C_f + (1 - V_f) C_r
\]

(6)

where \( V_f \) is the volume fraction of the fiber. \( C_r \) and \( C_f \) are the specific heat of the resin and fiber, respectively.

Similarly, the thermal conductivity of composites in longitudinal direction \( K_{xx} \) and transverse direction \( K_{yy} \) and \( K_{zz} \) is computed as follows:

\[
K_{xx} = V_f K_{ff} + (1 - V_f) K_r
\]

(7)

where \( B = 2(K_r/K_{ff} - 1) \), \( K_{ff} \) and \( K_{ff} \) are the thermal conductivities of the fiber in longitudinal direction and transverse direction, and \( K_r \) is the thermal conductivity of the 8552 epoxy resin. The thermal properties of AS4 fiber and 8552 epoxy resin from [27, 28] are listed in Table 2.

### 2.2 Numerical validation

In this study, ABAQUS is used to solve the thermo-chemical coupled heat transfer model. The cure kinetics model of the resin, specific heat capacity, and thermal conductivities of the composites is all implemented through the user subroutines UMATHT and USEFLD. To verify the accuracy of the thermo-chemical coupled simulation model, a cure simulation of a composite plate sample from literature [29] is conducted and compared with the reported result. The example is illustrated in Fig. 1. Due to the symmetry, only one-eighth of the model is employed wherein the coordinate axes are fixed at center point. The model is meshed using 4800 three-dimensional eight-node linear heat transfer brick elements (DC3D8) and connected with 5859 nodes. Within the simulation, the temperature boundary fitted with [29] is applied on the external surfaces, i.e., \( S(75,y,z), S(x,25.4,z) \), and \( S(x,y,200) \). Figure 2 describes the details of the temperature variation: The first and second

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**Table 1** Cure kinetics model of 8552 epoxy resin

| Parameters | Value |
|------------|-------|
| \( A \) [s\(^{-1}\)] | 70,000 |
| \( E \) [J/mol] | 65,000 |
| \( m \) | 0.5 |
| \( n \) | 1.5 |
| \( C_r \) | 30 |
| \( \alpha_{C0} \) | -1.515 |
| \( \alpha_{CT} \) [K\(^{-1}\)] | 5.171 \times 10^{-3} |
| \( H_r \) [J/K] | 574,000 |

**Table 2** Thermal properties of AS4 fiber and 8552 epoxy resin

| Parameters | Value |
|------------|-------|
| \( K_r \) [W/(m-K)] | 0.148 + 3.43 \times 10^{-4} T |
| \( K_{ff} \) [W/(m-K)] | 2.4 + 5.07 \times 10^{-3} T |
| \( K_{ff} \) [W/(m-K)] | 7.69 + 1.56 \times 10^{-2} T |
| \( C_r \) [J/(kg-K)] | 931 + 3.47 T |
| \( C_f \) [J/(kg-K)] | 750 + 2.05 T |
| \( \rho \) | 1790V_f + 1300(1 - V_f) |
| \( V_f \) | 0.574 |
heating rates are both 2.5° C/min. The first dwell is 116° C for 60 min and the second dwell is 177° C for 120 min. As for the other surfaces, symmetrical boundary condition is imposed.

The simulation results are shown in Fig. 3. The histories of the temperature and the degree of cure at point A and point B are compared with the literature data. As can be seen, the simulation result coincides well with the literature data.

3 Multi-objective optimization

3.1 Problem description

Two cases of AS4/8552 unidirectional laminates, i.e., the 24 mm thick laminate and the 50-mm ultra-thick laminate are considered respectively. Twenty-four millimeters and 50 mm are the typical dimensions of thick and ultra-thick composite parts which are common accepted in aerospace engineering [18]. The standard two-dwell temperature profile illustrated in Fig. 4 is used to simulate the cure process of the two laminates by using the thermo-chemical coupled simulation model: The first and second heating rates are both 2° C/min, the first dwell is 110° C for 60 min, and the second dwell is 180° C for 160 min. Due to the cure reaction is implemented in the heating and temperature holding stages, the cooling stage is not considered in the simulation [23, 24].

Two different three dimensional thick and ultra-thick models are established respectively. The geometric size of a and b are 60 mm and 24 mm in thick case, while 100 mm and 50 mm of a and b denote the ultra-thick case, as shown in Fig. 5a. The thick model is discretized into 1800 DC3D8 elements with 2304 nodes and the ultra-thick model is discretized into 2916 DC3D8 elements with 3610 nodes. The boundary conditions of the both models are listed as below: The top surface contacting with the vacuum bag is assumed to be convective with the air in the autoclave; hence, the temperature profile defined by cure process acts as the boundary condition. The convective heat transfer coefficient between the air and the laminate ranges from 30 to 100 W/m² [30, 31] and 50 W/m² is used in this study. The side surfaces are set to be adiabatic owing that the silicone rubber wrapped on the surfaces possesses well thermal insulation performance. The bottom surface contacting with the metal tool is applied the ambient temperature.

The predicted temperature and degree of cure distributions of the thick and ultra-thick models after cure process are presented in Fig. 6. It is seen that the distribution law of the temperature and the degree of cure is similar for the two models with different thicknesses, and the same result also appears in [20]. Besides, the maximum temperature and degree of cure overshoots during cure process occurs between the center and bottom. The reason is that with the cure process proceeding, the heat released by this cure reaction causes the temperature of the composite to increase compared with the temperature boundary, while the area close to the top and bottom surfaces loses part of heat due to heat exchange. In this regard, it is reasonable to adopt the two points to further explain the evolution of the maximum temperature overshoot during the cure process. The two points are also addressed in Fig. 5a.
Figure 7 presents the simulation results of the temperature and degree of cure history of the center and bottom of the two laminates. Severe temperature overshoots are both observed at the beginning of the second dwell. The maximum temperature difference between the center and bottom reaches 46.5°C for the thick laminate. For the ultra-thick laminate, the temperature overshoot becomes more serious and the maximum temperature difference reaches 94.6°C. The distributions of the temperature together with the degree of cure at the section view of the model are illustrated. The simulation results have clearly shown that large temperature overshoot is induced in the thick composite laminates. Moreover, the increase of the thickness of laminates would aggravate the overshoot dramatically. Therefore, it is desirable to develop an optimization method to reduce the gradients of the temperature for composite parts with large thickness.

3.2 Optimization method

Multi-objective optimization is regarded as an effective method that can effectively find the trade-off of the conflict objectives. In this study, the aim of the multi-objective optimization is to minimize the cure time and temperature overshoot through optimizing the cure temperature profile. In order to study the effect of the number of dwell on the optimization result, a four-dwell temperature profile and a two-dwell temperature profile are both considered in the optimizations for the two laminates. The general form of the temperature profiles is illustrated in Fig. 8. The four-dwell profile is parameterized using 12 parameters: the heating rate \( a_1, a_2, a_3, a_4 \), the duration of dwell \( t_1, t_2, t_3, t_4 \), the temperature difference between the first dwell and initial temperature \( \Delta T_1 \), and the temperature difference between two adjacent dwells \( \Delta T_2, \Delta T_3, \Delta T_4 \). The two-dwell profile is parameterized using 6 parameters: the heating rate \( a_1, a_2 \), the duration of dwell \( t_1, t_2 \), the temperature difference between the first dwell and initial temperature \( \Delta T_1 \), and the temperature difference between two adjacent dwells \( \Delta T_2 \). These parameters serve as design variables. The ranges of the design variables and the minimum increment for each parameter are listed in Tables 3 and 4. Considering the reliability of the process control of autoclave, the design variables are needed to be iterated discretely with a minimum increment. The minimum temperature difference 0.1 is used in the optimization iteration to ensure that the design variable, i.e., temperature changes as precisely as possible. After the final iteration is completed, the current obtained cure profile...
may possess a large number of dwells and the duration of the dwell would be short. Such cure profile is difficult to realize and adopt in real engineering application. Hence, it is necessary to adjust the dwell numbers. At this point, 5°C is used to judge the adjacent dwell of the current obtained cure profile. If the difference of two adjacent dwells is less than 5°C, these dwells would be fused into one dwell.

It should be noted that the minimum degree of cure at the end of cure process (denoted by \( \alpha_{\text{min}} \)) is constrained to 0.9, which is a necessary constraint during optimization to ensure that composite part is fully cured. The optimization problem is formulated as:

\[
\text{Find } \mathbf{X} = (a_i, \Delta T_i, t_i) \\
\text{Min } t_{\text{cure}}, \Delta T_{\text{max}} \\
S.T. \quad \alpha_{\text{min}} \geq 0.9
\]  

where \( a_i, \Delta T_i, t_i \) are design variables describing the cure profile, \( t_{\text{cure}} \) is the cure time, and \( \Delta T_{\text{max}} \) is the maximum temperature difference during the cure process.

Considering the discrete nature of the design variables, non-dominated sorting genetic algorithm (NSGA-II) \([32]\) is adopted to solve the optimization problem in this study. The efficiency and reliability of the algorithm were tested with 9 classical calculation examples and the results proved that NSGA-II is able to approximate the Pareto-optimal front quickly \([33]\). The NSGA-II algorithm is combined with the finite element simulation to implement the multi-objective optimization.

The flowchart of optimization is illustrated in Fig. 9. An interface linking the NSGA-II with the ABAQUS Solver is implemented in python. Firstly, the variables population is generated in a random way to create a new cure profile. Secondly, the interface reads the parameter values of the cure profile and updates the temperature boundary condition in the script file. The script file is then implemented to execute the thermal-chemical coupled simulation in ABAQUS. The temperature and the degree of cure during the cure process are calculated and stored for post-processing. The results of maximum temperature difference \( \Delta T_{\text{max}} \), cure time \( t_{\text{total}} \), and minimum degree of cure \( \alpha_{\text{min}} \) are extracted into a text file. The interface reads the results and sends them to the NSGA-II to generate

![Fig. 5 Illustrations of the geometric model and the applied boundary conditions](image)

![Fig. 6 Simulation results after cure process. (a) Temperature and (b) degree of cure distributions are in the thick model, and (c) temperature and (d) degree of cure distributions are in the ultra-thick model](image)
The temperature and degree of cure, (e) the temperature distribution, and (f) the degree of cure distribution for the ultra-thick model populations. A total 8000 cure profiles are generated for cure simulation during the optimization process to obtain the optimal Pareto front, which takes about 20 h for a

Fig. 7 Simulation result under the recommended cure profile: (a) the temperature and degree of cure history, (b) the temperature distribution, and (c) the degree of cure distribution for the thick model. (d) a new group of variables. The algorithm parameters are listed in Table 5. The number of generation is 80 and each generation contains 100 independent variable

Fig. 8 Temperature profiles to be optimized: (a) four-dwell profile, (b) two-dwell profile
computer with a quad-core processor (2.8 GHz) and 50-GB memory.

### 4 Optimization results and discussion

The solutions obtained from multi-objective optimization are a series of non-inferior Pareto front, which includes all the optimal solutions presented in objective space. Figure 10 shows the optimal Pareto fronts for the thick and ultra-thick laminates subjected to the four-dwell profile. X and Y axes represent the two objectives, respectively. As shown in Fig. 10, the Pareto fronts can be divided into three regions: (1) a vertical region in which cure time can be reduced significantly with large temperature overshoot; (2) a horizon region in which temperature overshoots are reduced significantly with long cure time; and (3) a corner region which achieves a good balance between the cure time and temperature overshoot. The temperature overshoots are reduced with relatively low time consuming.

Moreover, the Pareto fronts from four-dwell and two-dwell profile optimization as well as the result from original recommended profile for the thick and ultra-thick laminates are presented in Fig. 11. It can be seen that the result from original recommended profile presents long cure time and high temperature overshoot. For both the thick and ultra-thick laminates, the Pareto points of the two-dwell profile optimization are shifted up compared to the Pareto front of four-dwell profile optimization. With the same cure time, the four-dwell optimization result obtains a lower temperature overshoot. It is clearly shown that the increase of dwell expands the design space and generates the superior solutions. This improvement is more obvious for the ultra-thick laminate, as illustrated in Fig. 11b. Compared with the two-dwell optimization, with the same cure time of 9000 s, the maximum temperature overshoot by the four-dwell optimization is further reduced by 12°C in the ultra-thick laminate and 6°C in the thick laminate.

In order to validate the optimization result, a reasonable cure profile should be selected among the numerous cycles on the Pareto front. As a matter of fact, it can be learned that the selection criteria is how to distribute the weights of the cost and quality. That is to say, a relatively balanced result between the cure time and the maximum temperature overshoot is prioritized. Therefore, for the thick case, the cure profile whose cure time is 8837 s is selected because the maximum temperature overshoot is reduced slightly and the cure time is still greatly improved. The same treatment is also referred in [18, 34]. The evolution history of the temperature and degree of cure at center and bottom surface of laminate from the four-dwell optimization are shown in Fig. 12a. The optimized value of design variables are listed in Table 6. The temperature of first and second dwell after optimization is much lower than the recommended profile. The decrease in temperature slows the cure reaction and avoids the dramatic accumulation of the reaction heat, which benefits the reduction of the temperature overshoot. After the second dwell, the center temperature starts to exceed the bottom surface temperature and the degree of cure is close to 0.5. Then, the cure rate increases rapidly. At the end of the cure process, the degree of cure at the bottom surface is 0.92. The maximum difference of degree of cure is 0.11, which indicates that the distribution of degree of cure is more uniform after optimization. The cure time and maximum temperature overshoot before and after optimization are shown in Table 7. Compared with the recommended profile, the four-dwell profile can reduce the cure time by 51.0% and temperature overshoot by 66.9%.

For the ultra-thick laminate, a cure profile whose cure time is 12,535 s is selected under the same criteria. The evolution history of the temperature and degree of cure at center and bottom surface of laminate from the four-dwell optimization are shown in Fig. 12b. Compared with the recommended profile, the first heating rate is significantly decreased. The first dwell temperature of the optimized profile is almost unchanged while the second dwell temperature is greatly reduced. The decreases in heating rate and the second dwell temperature is able to slow the cure reaction and thus avoids the dramatic accumulation of the reaction heat.

Moreover, the optimized profile increases the third and four heating rates and decreases the durations of the third and four dwells. By this way, the violent curing reaction could be translated from holding stage to heating stage. As a result, when the temperature and cure rate of the laminate center are increased due to exothermic heat generation and accumulation, the temperature and cure rate of the laminate surface are also increased by the heating air, which prevents

### Table 3 Range of design variables in four dwell profile

| Parameters          | Variation range | Minimum increment |
|---------------------|-----------------|-------------------|
| $a_1, a_2, a_3, a_4$ [°C/min] | 0.5–5.0         | 0.1               |
| $t_1, t_2, t_3, t_4$ [s]  | 60–4500         | 60                |
| $\Delta T_1$ [°C]    | 60–120          | 0.1               |
| $\Delta T_2$, $\Delta T_3$, $\Delta T_4$ [°C] | 0–60            | 0.1               |

### Table 4 Range of design variables in two dwell profile

| Parameters          | Variation range | Minimum increment |
|---------------------|-----------------|-------------------|
| $a_1, a_2, a_3, a_4$ [°C/min] | 0.5–5.0         | 0.1               |
| $t_1, t_2, t_3, t_4$ [s]  | 1200–9000       | 60                |
| $\Delta T_1$ [°C]    | 60–120          | 0.1               |
| $\Delta T_2$, $\Delta T_3$, $\Delta T_4$ [°C] | 0–120           | 0.1               |
the occurrence of large temperature difference between the center and the surface of laminate. Compared with the recommended profile, the four-dwell profile can reduce the cure time by 30.3% and temperature overshoot by 73.1%.

Pareto front can effectively demonstrate the relationship between the objective functions of the multi-objective optimization. Trade-off relationship is observed between the curing time and the maximum temperature difference from Fig. 11. However, from the Pareto front results of Fig. 11, only the relationship between the objective functions can be observed. It is difficult to understand the relationships between the design variables and the objective functions. Self-organizing map (SOM) can provide a visualized result and enlighten designer how the design variables affect the optimization objectives [35]. Therefore, in this study the relationships between the design variables and the objective functions for thick and ultra-thick laminates are visualized by using SOM.

Figure 13 presents the maps of the twelve design variables and two objectives of the four-dwell profile optimization of thick laminate. Each cluster in the map has a value and is represented by a specific color. The label of each map indicates the lower (blue color) and upper (yellow color) limits of the solutions of the design variable. The collection of the clusters in same location of each map constitutes an optimized cure profile. The corresponding objective values can be found in the same location of objective maps. Thus, the relationships between the design variables and the objective functions can be easily observed in a visualized way.

From Fig. 13, it can be found that the color distribution of the maps of heating rates are similar with the map of maximum temperature difference, whereas opposite with the map of cure time. Therefore, in order to reduce the maximum temperature difference, the heating rates should be decreased, whereas to shorten the cure time, the heating rates should be increased. The influences of other variables can be derived by the same way. For instance, the maps of $\Delta T_i$ are opposite with the map of maximum temperature difference and the maps of $t_i$ are similar with the map of cure time. It can be concluded that the increase of the values of $\Delta T_i$ could reduce the maximum temperature difference. The cure time can be reduced by the decrease of $t_i$.

In the ultra-thick laminate, the relationships between the design variables and the objective functions are more complicated compared with the thick laminate. The maps of $a_1$ and $\Delta T_1$ are similar with maximum temperature difference, whereas opposite with cure time. The maps of $t_i$ have a similar color distribution with cure time. The

### Table 5 Parameters of NSGA-II

| Parameters               | Value |
|-------------------------|-------|
| Number of generations   | 80    |
| Number of individual in the population | 100   |
| Crossover distribution index | 15    |
| Mutation distribution index | 15    |
Fig. 10 Pareto fronts for (a) thick and (b) ultra-thick laminates

Fig. 11 Optimization result for (a) thick and (b) ultra-thick laminates

Fig. 12 Evolution history of the temperature and degree of cure for (a) thick and (b) ultra-thick laminates
Table 6  Value of design variables in optimized profile

|                | 24-mm laminate | 50-mm laminate |
|----------------|----------------|----------------|
| $a_1$, $a_2$, $a_3$, $a_4$ [°C/min] | 2.3, 2.1, 3.6, 4.8 | 1.1, 3.5, 4.5, 4.5 |
| $t_1$, $t_2$, $t_3$, $t_4$ [s] | 6000, 3000, 600, 840 | 720, 4560, 600, 600 |
| $\Delta T_1$ [°C] | 64.6 | 85 |
| $\Delta T_2$, $\Delta T_3$, $\Delta T_4$ [°C] | 39.1, 21.5, 39.8 | 14.4, 24.0, 60.0 |

Table 7  Simulation result of optimized and recommend profiles

|                | Thick laminate | Ultra-thick laminate |
|----------------|----------------|----------------------|
| Cure time [s]  | Temperature difference [°C] | Cure time [s] | Temperature difference [°C] |
| Optimization   | 8837 | 15.37 | 12535 | 25.6 |
| Recommend      | 18,000 | 46.5 | 18,000 | 94.6 |

Fig. 13  Self-organizing map of optimization result in thick laminate case
maps of the other design variables indicate a complicated nonlinear relationship between the variables and the objective functions (Fig. 14).

5 Conclusions

A multi-objective optimization method is proposed to design the multi-dwell temperature profile of the CFRP composite laminates with large thickness. Based on the finite element analysis, thermo-chemical coupled cure simulation is performed to evaluate the evolutions of temperature and degree of cure of the composites. Through the optimization with NSGA-II algorithm, the maximum temperature difference and cure time are both significantly reduced. The two-dwell and four-dwell temperature profiles are both considered in the optimization to investigate the influence of the number of dwell on the optimization result. It is concluded that the four-dwell profile helps to achieve the optimization objective more effectively for the thick composite laminates. Compared with the recommended profile, the four-dwell profile can reduce the cure time by 51.0% (thick case) and 30.3% (ultra-thick case) and the maximum temperature difference by 66.9% (thick case) and 73.1% (ultra-thick case). Furthermore, the SOM is used to visualize the relationships between the design variables and the objectives. By the SOM analysis, it is possible to easily convey to the designer how the temperature profile variables affect the cure time and the temperature overshoot.

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Author contribution Wenchang Zhang: conceptualization, methodology, writing—original draft, conceptualization, software, data curation, and validation. Yingjie Xu: investigation, writing—review and editing, funding acquisition, and supervision. Xinyu Hui: methodology, data curation, and validation. Weihong Zhang: supervision and visualization.

Availability of data and materials The raw/processed data required to reproduce these findings cannot be shared publicly but is available upon request.

Declarations

Ethics approval Work was conducted ethically with no human test subjects.

Consent to participate Work was conducted with no human test subjects.

Consent for Publication Work has consent to publish.

Competing interests The authors declare no competing interests.
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