Self-resistance electric heating of shaped CFRP laminates: temperature distribution optimization and validation

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Abstract
The self-resistance electrical (SRE) heating method to cure the carbon-fiber-reinforced polymer (CFRP) parts possesses the advantages of rapid and volumetric heating, low energy consumption, and low asset investment. But the current SRE heating methods are difficult to uniformly cure the shaped CFRP parts due to the non-uniformly distributed Joule heat power in the parts with a varying cross-sectional area. In this paper, an optimized multi-zone SRE heating method is proposed, in which the uniform heating and curing process of the shaped CFRP part is firstly achieved. By optimizing the orientation of the rectangular zones, the local overheating caused by the voltage gradient and current diffusion between different zones is notably suppressed. Combined with the electro-thermal numerical analysis, the influence of the positional offset of electrodes in two adjacent zones on the temperature uniformity is investigated. Based on this, an automated zone discretization algorithm and the optimal selection method of the zone orientation are established. The proposed method is numerically and experimentally validated with the typical-shaped CFRP parts, and the results are compared with that of the existing SRE heating method. The proposed method realizes that the maximum in-plane temperature difference of shaped CFRP parts is reduced by more than 80%. This method significantly improves the temperature uniformity of shaped CFRP parts during the multi-zone SRE heating process, which provides a potential solution for high-quality and efficient curing of CFRP parts.

Keywords Reinforced polymer · Self-resistance electric heating · Multi-zone heating · Uniform temperature · Curing

1 Introduction
Due to superior mechanical properties such as lightweight and high strength, carbon-fiber-reinforced plastics (CFRP) have gained huge applications in many fields including aerospace, automotive, and maritime [1–6]. The curing process where the CFRP part acquires the geometrical shape and mechanical properties simultaneously is the key step to ensuring the quality of CFRP products. Currently, the autoclave curing process is the dominant technology for curing high-performance CFRP parts [7, 8]. However, owing to the thermal conductive-based heating mechanism, the autoclave curing process presents the disadvantage of thermal lagging, long cycle time, high energy consumption, and high equipment investment [9]. In recent years, out-of-autoclave (OoA) curing technologies have attracted wide attention [10–13]. Among these technologies, the self-resistance electrical (SRE) heating method that directly utilizes the electric current passing through the carbon fiber itself to produce a massive Joule heat can realize a promising curing process with a number of advantages such as volumetric heating, rapid
heating, low energy consumption, and low asset investment [14]. However, at present, the SRE heating method can only uniformly heat the CFRP part with a constant cross-sectional area along the electrical current path, for example, the rectangular blank part. Due to the existence of the varying cross-sectional area, the non-uniformly distributed current density and the Joule heat power are inevitably formed in the non-rectangular or shaped CFRP part. In practical aerospace and other industries, most CFRP parts such as wing-skin and hatch parts are non-rectangular and possess shaped geometries. Therefore, the uniform SRE heating of shaped CFRP parts is a major challenge needing to be solved urgently.

To solve the above challenge, the existing methods can be divided into the following two categories. Both of these reported methods focused on the SRE heating of metal parts, but they could also provide a research basis for the SRE heating of CFRP parts. The first category is the integral compensation (IC) method, where the extra material is added to the edge of the shaped part to form an integral rectangle so that the current density, as well as the Joule heat power of the part, can be uniformly distributed. In the patent published by Benteler Corporation [15], a shaped blank was compensated by using the same material to form a structure with a constant cross-section area, and uniform SRE heating of the compensated structure was achieved, and then the final part was fabricated after the compensated material is cut off. In the patent published by Toyota Corporation [16], a rectangular compensation method for shaped parts with holes was proposed, in which the metal material was used to fill the holes inside the part to extend an additional current path and the uniform current density could be realized. The above methods achieved the uniform SRE heating of shaped metal parts, but they were difficult to avoid introducing a massive redundant material and thus resulted in unnecessary energy consumption. In addition, the practical shaped CFRP parts are usually cured on tools of limited size, and the IC methods are difficult to be achieved under the limited tool boundary size in the curing process.

The second category is the multi-zone compensation (MZC) method, where the shaped part is divided into several rectangular zones by introducing multiple pairs of electrodes and the power of each zone is independently controlled by a specific generator [17–19]. Hübner et al. [20] developed an MZC method where the metal sheet was compensated with similar material and several paralleled rectangles were formed. By utilizing multiple independent power generators, the heating power could be independently controlled according to the length of each rectangle. To minimize the compensational material usage, Demazel et al. [21] proposed a solution where the part was split into several rectangular strips activated by multiple generators, and they optimized the orientation and dimensions of rectangular strips to reduce the material and energy usage. The above MZC methods achieved uniform SRE heating of shaped parts with lower energy consumption and material usage compared to the IC methods. However, although the current MZC methods can achieve an acceptable temperature field within the net-shaped area, there is still a large temperature gradient within the entire conductive structure, especially at the adjacent area between different rectangular strips. This can be attributed to that the existing methods do not consider the transverse voltage gradient and the transversely diffused current between different zones, which are caused by the positional offset of the electrodes in adjacent zones and result in local overheating and the large in-plane temperature gradient (in-plane temperature difference greater than 60 °C). But the maximum temperature difference with which most CFRP materials would not present thermal degradation is below 20 °C when the average temperature reaches 120 °C. [22]. Hence, it is necessary to improve the MZC methods considering the transverse current diffusion between adjacent strips to achieve uniform SRE heating of shaped CFRP parts.

In this paper, an optimized multi-zone SRE heating method considering the minimized positional offset of the electrodes in adjacent strips is proposed, in which the transverse voltage gradient and the local overheating caused by current diffusion are notably suppressed by optimizing the orientation of strips. The uniform heating and curing process of the shaped CFRP part is firstly achieved by using the proposed method. Combined with the COMSOL Multiphysics® electro-thermal model, the influence of the positional offset of electrodes in adjacent strips on the temperature uniformity is investigated. Based on this, an automated zoning algorithm and the optimal selection method of the strip orientation are established. The results of the SRE heating temperature field for the typical-shaped CFRP parts under the proposed and traditional methods are compared. In addition, for a practical-shaped CFRP wing-skin part, the multi-zone SRE heating processes are implemented using the multi-power system, and the effectiveness in improving the temperature uniformity of the presented method is evaluated. This method significantly improves the temperature uniformity of shaped CFRP parts during the SRE heating process, which provides a potential solution for the high-quality and efficient curing of CFRP parts.

2 Influential analysis of the strip structures on the temperature field

The current MZC methods can potentially realize the uniform SRE heating for the shaped CFRP parts. However, the existing methods do not consider the transverse voltage gradient caused by the positional offset of the electrodes in adjacent strips, which results in local overheating. Specifically,
in the MZC method, the shaped CFRP part with the curved boundary is discretized into numbers of rectangular strips, so both ends of the adjacent strips may be misaligned, which brings in the positional offset of electrodes. Therefore, to find an optimal solution that can minimize the in-plane temperature difference, this section analyzes the influence of the strip structure that has the positional offset of electrodes on the temperature field via the electro-thermal FEM (finite element modeling) method.

### 2.1 Electro-thermal finite element modeling

The 3D electro-thermal FEM using COMSOL Multiphysics® software is developed to simulate the SRE heating process. In the multi-zone SRE heating method, the shaped part is discretized into multiple rectangular strips. In order to simplify the analysis process, a local structure with two adjacent strips is selected in the 3D model, where the strips are misaligned and the ground (GND) and voltage–current condenser (VCC) electrodes have variable positional offset. This model is based on Joule’s law and the solid heat transferring theory [23–25]. The thermal and electrical parameters of the cross-plied CFRP laminate are shown in Table 1.

3D geometry model. As shown in Fig. 1, each strip has the same thickness and width, and the variable positional offset of the GND (0 V) and VCC (high voltage) electrodes of two strips is defined as $l$, and the lengths of the strips are $L_1$ and $L_2$, respectively ($L_1 = L_2$). Define the relative offset of electrodes as: ${llL_2}$. The maximum length of $L_1$ and $L_2$ is set to 400 mm, and the corresponding maximum VCC voltage is given by 1 V.

Concepts definition. The strip orientation is defined as the direction along the connection line between the VCC and GND electrodes in a specific rectangular strip. Under ideal conditions, there is no voltage gradient in the transverse orientation between the two adjacent strips, and the current is expected to flow along the strip orientation.

Electro-thermal coupled FEM. The electric Joule heating model of CFRP laminate is established to simulate the Joule heating process of the CFRP laminate during the SRE heating process. The thermal balance equation is given by the following equation [26]:

$$\rho \cdot C_p \cdot \frac{\partial T}{\partial t} = \nabla (k \nabla T) + \vec{E} \cdot \vec{J} - \dot{Q}_{losses}$$

(1)

where $\rho$ and $C_p$ are the density and specific heat capacity of the CFRP material, respectively. $k$ is the thermal conductivity tensor. The generated heat per unit time and volume is the dot product of the electric field and the current density ($\vec{E} \cdot \vec{J}$). $\dot{Q}_{losses}$ is the external heat dissipation per unit volume of composite material. The current density is expressed by the simplified form:

$$\vec{J} = \vec{\sigma} \vec{E}$$

(2)

where $\vec{\sigma}$ is the electrical conductivity tensor.

The relevant material parameters are shown in Table 1, and the data were obtained from actual measurements of CFRP composite parameters by previous work [27].

Voltage control method in the FEM. To ensure that the temperature in each strip is equal, it is necessary to apply a specific value of VCC voltage according to the material and dimensions of each strip. In the FEM, the VCC voltage of each strip is proportionally controlled according to the monitored deviation of the temperature feedback from the target temperature. Assuming that the temperature distribution of each strip is uniform and the temperature value is only affected by the VCC voltage of that area, the heating rate $r$ of that strip can be derived by the simplified equation:

$$r = \frac{\sigma \cdot U^2}{C_p \cdot \rho \cdot L^2}$$

(3)

where $\sigma$ is the electrical conductivity along the lengthwise direction (S/m), $U$ is the VCC voltage (V), and $L$ is the length of that rectangular strip (m). From the equation, the
heating rate $r$ of a single strip is only related to the length $L$ and the VCC voltage of that strip, and is independent to the thickness and width. Therefore, the VCC voltage is approximately proportional to the length $L$ of each strip if the heating rate $r$ of each strip is required to be equal.

The above section introduces the FEM method of the multi-zone SRE heating process in a local structure with two adjacent strips. The following sections give the detailed analysis of the temperature field distribution and its formation mechanism under different positional offset parameters of the GND and VCC electrodes.

### 2.2 The influence of positional offset of electrodes on the temperature field

Based on the above model, the temperature and the electrical field under different positional offset parameters of the GND and VCC electrodes are investigated.

Firstly, focus on the positional offset of GND electrodes in two adjacent strips, as shown in Fig. 2. When there is no positional offset two GND electrodes, the parallel and equidistant equipotential lines are formed inside the strips, as shown in Fig. 2a. Therefore, as shown in Fig. 2b, the current does not diffuse transversely but is evenly distributed in the strip, which makes the final temperature field uniformly distributed. However, due to the complex contour of the shaped part, the final position of the adjacent strips could possibly be arranged, as shown in Fig. 2d. In this case, the GND end of the upper strip is located in the middle of the lower strip, which directly leads to a transverse voltage difference of about 0.1 V. Hence, it can be seen that the equipotential lines are bent, and the current lines in Fig. 2e are not distributed at equal intervals but are locally concentrated, which means the higher current density is presented in these concentration points. Naturally, due to the increased current density, local overheating occurs, while the other side of the strip is not effectively heated as shown in Fig. 2f, and the maximum in-plane temperature difference reaches 100 °C.

To sum up, if the existing MZC method does not consider the GND positional offset of each strip, electrical field non-uniform distribution will cause the local overheating and the non-uniform temperature field.

In order to quantitatively analyze the influence of the positional offset of the GND electrodes on the temperature field, change the value of the relative offset of GND from 0 to 100%, and the change of the maximum in-plane temperature difference is shown in Fig. 3. Set the length of $L_1$ and $L_2$ equal to 400 mm, and apply the same VCC voltage of 1 V to both strips. The value of each dot in Fig. 3 is measured when the average in-plane temperature reaches 120 °C. As is shown in Fig. 3, the greater the relative offset of the GND electrodes, the greater the in-plane temperature difference in both strips. When the relative offset exceeds 90%, the in-plane maximum temperature difference has reached more than 300 °C. The upper limit offset value that can result in an acceptable
in-plane temperature difference (≤ 20 °C) is 8.2% in this case.

Secondly, the influence of the VCC electrode positional offset in two adjacent strips on the temperature field is also investigated. According to the Eq. 3, the VCC voltage is proportional to the length $L$ of each strip if the heating rate $r$ of each strip is required to be equal. Therefore, if there is no positional offset of GND electrodes, as shown in Fig. 4a, the voltage values applied to the VCC electrodes that are offset to each other should be related to the lengths of corresponding strips. As is shown in Fig. 4a, in this case, although there is a positional offset between the two VCC electrodes, there is no transverse voltage gradient, and the equipotential lines are still parallel and equidistant. Hence, there is no local concentration of the current lines, and the final temperature field remains uniform, as shown in Fig. 4b and c.

However, in the actual voltage control process, due to the fluctuation of the input voltage and heat dissipation, the VCC voltage of each strip cannot always maintain in a stable condition, which directly results in the transverse voltage gradient and the accompanying local overheating. Therefore, it is necessary to adjust the parameters of the generators to ensure that the input voltage can be stable as much as possible, and thermal insulation for the entire part is also required to minimize the thermal dispassion difference of different strips.

It can be seen from the above analysis that the positional offset of electrodes between adjacent strips has significant impact on the uneven temperature distribution, especially for the positional offset of the GND electrodes. On the other hand, the positional offset of the VCC electrode has little effect on the temperature field, but it is necessary to ensure that the input VCC voltage value remains in a stable state. Based on this conclusion, the minimized positional offset of the GND electrodes is required in the multi-zoning process.

### 3 Multi-zoning methodology for uniformly heating of shaped CFRP parts

Based on the analysis in Sect. 2, the fundamental to improving temperature uniformity is to find a strip orientation that minimizes the transverse voltage gradient and the accompanying local overheating. To achieve this target, this chapter firstly develops an automated strip discretization algorithm and then establish an optimized multi-zoning method to select the optimal orientation.

#### 3.1 Automated strip discretization algorithm

In this section, the automatic strip discretization (ASD) algorithm considering the boundary constraints is established. The overall idea of the ASD algorithm is to discretize the CFRP part into a minimum number of strips under the boundary constraints along with a certain orientation, and then to quickly iterate this discretization operation from all orientations between 0 and 180°.

As shown in Fig. 5, for an arbitrary CFRP part, there are two boundaries to be considered in the ASD algorithm. The inner boundary is the net-shaped boundary (the contour line of the unfolded surface for the 3D part) of the CFRP part, which is also the cutting path after the cure. The outer boundary is the contour of the CFRP preform during the fiber placement, which ensures that there is enough space to place auxiliary materials such as vacuum sealing tape at the edge of the tool [28]. For a certain strip orientation, the ASD algorithm is based on the computation principle by the intersections of the lines and the two boundaries that determined the position and size of each strip. This principle can ensure maximum usage of the material inside two boundaries and a minimized number of strips in each orientation.

For example, as shown in Fig. 5, firstly, a horizontal line is drawn from the lowermost vertex of the inner boundary to get the tangent and intersection with the

![Fig. 4 Schematic of positional offset of VCC electrodes influence. a Influence on the electric potential field, b influence on the current line, c influence on the temperature field](image)
inner and outer edges, respectively. Secondly, the intersection with the left outer border and the right vertex of the inner border are selected to draw vertical lines 1 and 1’ up. Thirdly, compare the lengths of 1 and 1’, and select the vertical line 1 that is shorter and that surrounded the inner boundary and not beyond the outer boundary after forming the rectangle as the side of the first rectangular area. Fourthly, a horizontal line passes through the intersection of vertical line 1 and the inner boundary, which is the upper boundary of the first rectangular area. Then the left and right ends of the first upper boundary are extended again, intersecting the inner and outer boundaries, respectively. The intersection of the strip boundary control is selected again, and a vertical line is drawn from the selected intersection, extending upwards. Then compare the lengths of 2 and 2’, and take the vertical line 2 that could surround the inner boundary and not beyond the outer boundary after forming the rectangle as the side of the second rectangular area. Each orientation of strip discretization takes about 1 s to calculate, and the calculation process of all orientations between 0 and 180° takes about 1 min.

This section establishes the ASD algorithm, which can rapidly realize the strip discretization of a shaped CFRP part along with all orientations between 0 and 180° in seconds. The ASD algorithm provides a basis for the optimal selection of orientation to improve the temperature uniformity during the SRE heating process.

3.2 Optimal selection method of strip orientation

According to the conclusion of Sect. 2, the smaller positional offset of the GND electrodes of adjacent strips can lead to a more uniform temperature field, and the offset of VCC electrodes is independent to the temperature field. Therefore, the method to select the optimal orientation aim to find an orientation in which the positional offset of the GND electrodes is the smallest one among that of all orientations. Considering the discretization result along each orientation which obtained two different sides (waiting for assignment of VCC and GND end) from the ASD algorithm, before calculating the positional offset of the GND electrodes, it is necessary to determine the side of the applied GND electrode. The specific steps to find the optimal strip orientation are as follows, as shown in Fig. 6.

1. Starting from the initial strip orientation (0°), calculate the position offsets of all adjacent rectangular strips, as shown in Fig. 6. In this case, initial orientation has four strips and has three positional offsets on each side. Offsets at both sides of strips are named as \( l_a \), \( l_b \), \( l_c \), and \( l_1 \), \( l_2 \), \( l_3 \), separately.

2. Record the maximum offset of both sides of the adjacent strip, and take the side with the smaller offset as the GND electrodes. In the case of the initial orientation, \( l_b \) and \( l_3 \) are the maximum offsets, and \( l_b \) is the smaller one. So take the side (blue) with a smaller positional offset as the GND electrode side.

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**Fig. 5** Schematic of the ASD algorithm

**Fig. 6** Schematic of optimizing the strips orientation according to the minimum positional offset of GND electrodes
3. The optimal strip orientation has the smallest offset of the GND electrode position among all strip orientations. After that, the maximum positional offset of the GND electrodes of all orientations between 0 and 180° is obtained, and the strip orientation with minimum positional offset is selected as the best strip discretization orientation. In this case, the optimal orientation is \( \theta_{\text{opt}} \), where the minimum positional offset of GND electrodes is 0 mm.

From the above method, an optimal orientation that minimizes the positional offset of GND electrodes can be rapidly optimized for an arbitrary-shaped CFRP part. This orientation is expected to be the optimized multi-zoning solution to improve the temperature uniformity. Next, the effectiveness of this method is discussed and analyzed with the simulation results of two typical CFRP parts.

### 3.3 FEM validation and comparative analysis

Two typical-shaped CFRP parts are selected to test the presented method. These parts both present an irregular shape and cannot be uniformly heated by the traditional SRE heating method, as shown in Fig. 7. By running the ASD algorithm, the results of the maximum positional offset of the GND electrodes along with every orientation (0–180°, step length 2.8125°, 64 steps) can be computed. According to the optimal selection method described above, the optimal orientation can be found among the results. Then, the SRE heating temperature fields of the shaped parts are simulated by the COMSOL software under both the initial and optimized orientations. The specific analysis is as follows.

The results of the maximum positional offset of the GND electrodes for the wing-skin and the hatch part are shown in Fig. 8a and b. As can be seen, for the wing-skin part, the optimized orientation is 95.6°, where the maximum positional offset of the GND electrodes is 24.3 mm. For the hatch part, the optimized orientation is 30.9°, where the maximum positional offset of the GND electrodes is only 2.94 mm. The rectangular strip arrangements of the initial orientation and the optimal orientation are shown in Fig. 8 c, d. It can be clearly seen that by regulating the orientation of the strip, the positional offset of the GND electrodes is significantly reduced. The reductions of 84.97% and 94.42% for the wing-skin and hatch parts are respectively achieved.

The multi-zone SRE heating processes of two parts under the initial and optimized strip orientations are further simulated by the FEM method. The two different strip arrangements of the wing-skin part obtained different simulation results. The simulated temperature field of the wing-skin part is shown in Fig. 9a and d. First, the side of the left end is selected as the GND electrodes, and the maximum offset among GND electrodes reaches 161.7 mm. There are three local overheating spots, and the temperature on the left side of the part is very low. This is attributed to that there is a large transverse potential gradient and the current density is non-uniform, as shown in Fig. 9b. The maximum average temperature difference reaches 66.4 °C, as shown in Fig. 9c. The temperature field after optimizing the orientations of the strips is shown in Fig. 9d. It can be seen that the maximum average temperature difference is only 2.61 °C, as shown in Fig. 9f, which reduces by 96.1% after optimizing the orientation of the strips. In Fig. 9e, the positional offset of the GND electrodes of the strip is only 24.3 mm, and the transverse potential gradient can be almost ignored as shown in Fig. 9e. The current density is uniformly distributed, and there is no obvious overheated point. Therefore, the temperature uniformity of the wing-skin part is effectively improved by using the optimized multi-zoning method.

Figure 10 shows the simulated results of the hatch part. Figure 10a gives the temperature field of the non-optimized SRE heating method where the strip orientation is 0°. The right side of the part is the GND electrodes, and the maximum positional offset of the GND electrodes is 52 mm. The entire left end of the part exhibits overheating, and the maximum average temperature difference reaches 34.8 °C, as shown in Fig. 10c. In Fig. 10b, the current density of the left side is greater than that of the right side, leading to a non-uniform distribution of Joule heat. After optimizing the strip orientation, the temperature uniformity shows a significant improvement, as shown in Fig. 10d. The maximum average temperature difference is only 7.41 °C, as shown in Fig. 10f, which is reduced by 78.7% compared to that of the non-optimized part. In Fig. 10e, the potential gradients and current densities at the VCC and GND electrode position are uniformly distributed.

The above content demonstrates the effectiveness of the proposed method on two typical-shaped CFRP parts. Regarding the robustness of the method in different cases, the proposed method is based on the optimization after traversal calculation of all orientation of strips, and to a certain extent, an optimal orientation could always be found, but the optimization performance for some complex parts may decline.

This chapter presents the optimized multi-zoning method for the shaped parts, which can significantly decrease the
Fig. 8  Optimizing results of two typical parts. a, b Maximum positional offset of the GND electrodes for the wing-skin and the hatch part. c, d The rectangular strip arrangements of the initial and optimal orientation for the wing-skin and the hatch part.

(a) [Graph showing positional offset vs. strip orientation.] (c) [Graph showing positional offset vs. strip orientation.]

(b) [Graph showing positional offset vs. strip orientation.] (d) [Graph showing positional offset vs. strip orientation.]

Fig. 9  Simulated results of the wing-skin part. a Temperature field of non-optimized strips wing-skin part. b Current line and potential line of non-optimized wing-skin part. c Temperature data of non-optimized strips wing-skin part. d Temperature field of optimized strips wing-skin part. e Current line and potential line of optimized wing-skin part. f Temperature data of optimized wing-skin part.

(a) [Temperature field image.] (b) [Current line and potential line image.]

(c) [Temperature data graph.] (d) [Temperature field image.] (e) [Current line and potential line image.]

(f) [Temperature data graph.]
positioned offset of the GND electrodes by optimizing the strip orientation, and further notably improve the temperature uniformity because the transverse voltage gradient between strips and the accompanying local overheating is effectively suppressed. Through this method, the maximum in-plane temperature difference of the shaped CFRP parts is controlled within 10 °C, which meets the actual curing requirements. Next, in order to further verify the effectiveness of the method, the experimental validation is carried out on the wing-skin part.

4 Experimental validation

This chapter demonstrates the experimental cases of the wing-skin parts cured by the traditional SRE heating methods and the multi-zone SRE heating method with the optimized strip orientations. The following sections introduce the experimental arrangement and results, respectively.

Fig. 10 Simulated results of the hatch part. a Temperature field of non-optimized strips hatch part. b Current line and potential line of non-optimized hatch part. c Temperature data of non-optimized strips hatch part. d Temperature field of optimized strips hatch part. e Current line and potential line of optimized hatch part. f Temperature data of optimized hatch part

4.1 Experimental arrangement

Material The CFRP material system UIN10000/T800 unidirectional prepreg (China Weihai Guangwei Composite Co., Ltd) with a resin content of 30% and a thickness of about 0.1 mm per layer is employed in this study. The lay-up sequence schematic of CFRP laminates with electrode arrangement is shown in Fig. 11. For the wing-skin part, 30 layers of unidirectional UIN10000 prepreg are stacked with a sequence of 0°/90°, and the size of the final cured part is about 600 mm long, 180 mm wide, and 3 mm thick. The red copper electrodes of 0.02-mm thickness with a purity of 99.7% is layer-by-layer stacked along the side edge of multiple CFRP strips. As illustrated in Fig. 12, the edge of each stack of electrodes is connected to a cable. Each cable

Fig. 11 Schematic of CFRP laminates lay-up sequence and electrode arrangement

Fig. 12 Arrangement schematic of the DC power supply, thermocouples and cables
with silicone rubber insulation can suffer a maximum current of 50 A and a Q235 steel tooling with thick of 8 mm is used. In the SRE curing process, the polyimide film (Meixin Insulation Materials Co., Ltd) is used for insulating between the composites and the metal tooling. The auxiliary material used in the experiment is purchased from supplier Airtech International, Inc., such as the L500Y vacuum bag, PMMA release film, and B150 breather.

**Multi-generator-based heating system** Shaped CFRP parts are heated by a multiple direct current (DC) generator-based heating system, where the output voltage of each generator is independently controlled by a proportional–integral–derivative (PID) controller [29, 30]. The maximum power output of each DC generator (SZPAIER Co., Ltd) is 500 A, and the rated power is 5 kW. Each PID temperature controller (AI516P, Xiamen Yudian Auto Tech Co., Ltd) receives the corresponding temperature feedback from a specific K-type thermocouple (WRNK-191, Xingke Co., Ltd.) that is contacted with the target strip. The PID controller continuously calculates an error value $e(t)$ as the difference between the desired setpoint ($SP$) and a measured process variable ($PV$) and applies a correction based on proportional, integral, and derivative terms (denoted by $P$, $I$, and $D$, respectively). The temperature values of all the strips are recorded by a temperature recorder TP700 (Shenzhen Top Purui Electronics Co., Ltd). The SRE heating temperature field under the heating process is observed by the infrared (IR) thermal image camera (FLIR A300). In addition, for the case of the traditional SRE heating process with the integral electrodes, 3 distributed thermocouples are simultaneously applied, and their average temperature is calculated in real time and feedback to a single PID controller.

**Vacuum bagging** The whole bagging system from the bottom to the top consisted of tooling, polyimide, wing-skin part, peel-ply, isolator, breather, and vacuum bag, as shown in Fig. 13. By placing a polyimide film with a thickness of 0.05 mm as an insulating layer between the tooling and the wing-shaped part, the electric current passing through the inside of the material is prevented from being conducted into the steel mold. The curing process is performed under a vacuum bag pressure of 0.095 MPa. Cables are welded by the solder with the copper electrodes. The cables are also sealed by the sealing tape between the vacuum bag and the tooling. Three different wing-skin parts including the integral electrode connected part (traditional), the multi-zone part with the initial strip orientation (non-optimized), and

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**Fig. 13** Arrangement schematic of the vacuum bagging process

**Fig. 14** Bagging arrangement photos of the a integral electrodes (traditional SRE method) part, b multi-zone part with non-optimized strip orientation, and c multi-zone part with optimized strip orientation
the multi-zone part with optimized strip orientation are produced as shown in Fig. 14.

4.2 Result and discussion

The presented multi-zone heating method considers the minimized positional offset of electrodes in adjacent strips, and can suppress the transverse voltage gradient and the accompanying local overheating. By demonstrating the IR images and the temperature curves, this section demonstrates the effectiveness of the presented method in improving the temperature uniformity of shaped parts in the SRE heating process.

Figure 15 a shows the IR image of the wing-skin part heated by the traditional SRE heating method where the integral electrodes are used at the edge of the part. A hot spot appears at the center area near to the VCC electrode, but the right corner of the part remains in cold. The maximum in-plane temperature difference among the measured points T1–T4 reaches 89.6 °C as shown in Fig. 15b. This is attributed to that the current density and the generated Joule heat are unevenly distributed in the part due to the irregular shape of the conductive structure. As a result, as shown in Fig. 16a, because the right corner of the part is not heated to the vitrification temperature, the material is still soft, sticky, and not rigid enough.

Figure 15c shows the multi-zone SRE heating temperature field under the initial orientation (0°) of strips where the GND side has a maximum positional offset of 161.7 mm. Obviously, although the power of each strip is independently controlled according to the temperature feedback, a uniform temperature field is not formed in the part as expected. Specifically, the IR image shows the thermal accumulation at the corner of contiguous lines between strips. The maximum in-plane temperature difference measured by the thermocouples T1–T5 is 43.7 °C as shown in Fig. 15d. During the curing process, to reduce the temperature difference between the strips, an attempt is made to cool down the early stage of the dwelling process, but the improvement is not noticeable. In addition, the IR image shown in Fig. 15c is consistent with the simulated temperature field in Fig. 9a. This shows that in the actual
SRE heating process, a transverse voltage gradient is also formed between different strips, which leads to the current lines gathering at these areas, causing multiple undesired overheating points. In Fig. 16b, the corresponding hot points show a serious thermal degradation of the resin after curing, which is unacceptable to the performance of the material even within the net shape of the part. It can be seen from the results that the existing MZC method does not consider the offset of electrodes of adjacent strips, and it will be difficult to achieve a uniform SRE heating of the shaped part.

Figure 15e illustrates the SRE heating temperature field under the optimal strip orientation (95.6°) where the GND side has a positional offset of only 24.3 mm. It can be seen from the figure that there is no local overheating in the entire part surface, which is highly consistent with the simulated temperature field in Fig. 9d. The maximum in-plane temperature difference measured by the thermocouple T1–T4 is only 6.6 °C, which is 84.9% decreased compared to that of the non-optimized method, and meets the curing requirement that the maximum temperature difference is less than 20 °C when the average temperature is 120 °C during the curing process of CFRP materials. This shows that through the optimized multi-zone SRE heating method proposed in this paper, an optimal strip orientation that has the minimized offset of the GND electrodes can always be found, so that the transverse voltage gradient and the accompanying local overheating can be effectively suppressed. However, it can also be seen from Fig. 15e that the temperature at the edge of the part is lower than that at the center area, which is due to the heat absorption of the larger area of the tooling, which can be improved by applying insulation to the tooling and parts. In Fig. 16c, the final wing part obtains a smooth surface where no uncured or thermal degradation area can be found.

From the above result, it is concluded that by using the presented method, the optimal strip orientation considering the minimized positional offset of the electrodes can be found, which realizes a notable improvement of the temperature uniformity for the shaped part during the SRE heating process. The maximum in-plane temperature difference of the optimized wing-shaped part is only 6.6 °C, which is 84.9% lower compared to the SRE heating method with that of the non-optimized multi-zone SRE heating method.

5 Conclusion

In this paper, an optimized multi-zone SRE heating method is proposed, in which the uniform SRE heating and curing process of the shaped CFRP part is firstly achieved. The MZC method-based multi-zone SRE heating has been successfully applied in the metal blank heating processes. However, the existing methods do not consider the transverse voltage gradient caused by the positional offset of the electrodes in adjacent strips, which results in local overheating and the unacceptable large temperature gradient. In the proposed method, by optimizing the orientation of the rectangular strips, the local overheating caused by the voltage gradient and current diffusion between strips is notably suppressed. From the result of the electro-thermal numerical analysis, the positional offset of the GND electrodes has a significant impact on the final temperature uniformity, and the offset of VCC electrodes has less influence on the temperature field under the thermal isolation condition. Based on this influential law, an automated zoning algorithm and the optimal selection method of the strip orientation are established. Based on the numerical and experimental validations on the typical-shaped CFRP parts, the proposed method realizes a significant reduction of more than 80% of in-plane temperature difference compared with the existing SRE heating method.

Furthermore, the influence of uneven heat in-plane dissipation on the temperature field should be further considered to improve the temperature uniformity of the SRE heating process. The proposed method firstly realizes the SRE heating of the shaped CFRP part with a uniform temperature distribution, which provides a potential solution for the high-quality and efficient curing of practical CFRP parts.

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 Declarations

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