

# Development and validation of a flexible fiber graphene laminated heater for composite adhesive repair

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**Abstract.** Flexible electric heaters are widely employed in the field of in-situ repair of composite structures for aircrafts. However, the existing traditional resistance wire heaters suffer from low damage tolerance, uneven heating, and high energy consumption. In this paper, a flexible Fiber Graphene Laminated heater (FGL heater) is proposed, which exhibits much better thermal efficiency in terms of heating rate, temperature uniformity, and energy consumption. The experimental results demonstrate that the traditional resistance wire heater achieves a heating rate of 0.58°C/s, with a maximum temperature difference of approximately 10°C under a 300W input power, which consumes 81.7×10<sup>3</sup>J to heat from 24.6°C to 100°C. In contrast, under the equal input power, the proposed FGL heater achieves a significantly higher heating rate of 3.8°C/s with a maximum temperature difference not exceeding 7°C. It only consumes 12.1×10<sup>3</sup>J to reach the same temperature, reducing energy consumption by 85.2%. The silicone-encapsulated FGL heater also exhibits a heating rate of 1.1°C/s with a maximum temperature difference not exceeding 4°C. It consumes 45.7×10<sup>3</sup>J, reducing energy consumption by 44%. Furthermore, the proposed FGL heater is capable of composite single-lap repair on the wing leading edge of aircraft, with a curing area temperature difference not exceeding 1°C.

**Keywords:** Fiber graphene laminated heater; Composite adhesive repair; Flexible heater; Energy saving.

## 1. Introduction

Electric heaters based on the Joule effect are widely studied in the fields of aircraft maintenance[1]. When current flows through a conductor, it causes inelastic electron collisions, resulting in Joule heat [2]. In order to meet the demand for high-performance electric heaters, it is necessary to design and prepare electric heaters with characteristics such as flexibility, excellent heating uniformity, fast response, and good thermal stability. Metal and non-metal heating elements with adequate resistivity and temperature coefficients of resistance were commonly utilized in heaters[3]. Yet, resistive filament elements had limited thermoelectric efficiency and were susceptible to issues like oxidation and blowout, constraining their applications.

Conductive materials such as graphene[4], carbon nanotubes[5], and conductive polymers[6] were extensively studied in electric heating. Among them, graphene's electric heating performance demonstrated attractive application prospects [7, 8]. Polyester fabric[9] and PI film[10] were used as flexible substrates to form flexible heaters in conjunction with graphene. However, most polymer substrates had low thermal stability and mechanical properties, and the maximum heating temperature was usually lower than 100°C, which was far below the upper limit temperature that

carbon nanofilm electric heaters could achieve [2]. Glass fiber fabrics were excellent candidates for flexible substrates due to their high temperature resistance, high chemical stability, and high strength [11].

In this paper, a flexible fiber graphene laminated heater (FGL heater) with flexibility, rapid thermal response, and high temperature uniformity will be designed and prepared through hot pressing methods. The graphene film will be embedded between the glass fiber layers to form a strong adhesion and a high thermal conductivity plane, and it will be compared with traditional resistance wire heaters in terms of temperature uniformity, heating efficiency and energy consumption. Furthermore, the composite single-lap adhesive repair of the wing leading edge can be performed by using the FGL heater as the heat source, in combination with a hot bonder.

## 2. Design, manufacturing, and test setup

### 2.1 Design of the flexible Fiber Graphene Laminated heater

As illustrated in the Fig. 1, the structure of the flexible heater with graphene fiber layers consists primarily of a heating layer and an encapsulation layer. The heating layer employs a graphene heating film known for its high electrothermal conversion efficiency, replacing conventional metallic heating elements. The encapsulation layer is crafted from glass fiber fabric/epoxy resin prepreg, offering exceptional adhesion and compatibility. Specific material parameters employed are detailed in Table 1. Building upon the heater, a silicone encapsulation process is carried out to create the silicone-encapsulated FGL heater, which is subsequently compared against the performance of conventional resistance wire flexible heaters with silicone encapsulation.

The heating layer consists primarily of a graphene film and electrodes, as illustrated in the Fig. 1(a). The square resistance ( $R_s$ ) and linear resistance ( $R_l$ ) of the graphene film are represented as follows:

$$R_s = \frac{\rho}{d} \quad (1)$$

$$R_l = R_s \cdot \frac{b}{a} \quad (2)$$

where  $\rho$  represents the resistivity of the materials,  $d$ ,  $a$ ,  $b$  is the thickness, electrode spacing and electrode length of the graphene film. The square resistance of the thin film is usually measured using the four-probe method, and subsequently, the linear resistance of the thin film is determined by equation (2). The power ( $P$ ) of the graphene film is calculated using the following equation:

$$P = \frac{U^2}{R_l} = \frac{U^2}{R_s} \cdot \frac{b}{a} \quad (3)$$

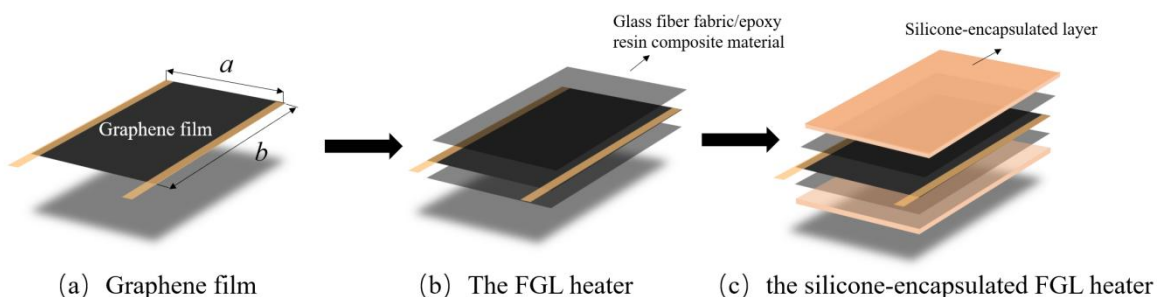


Fig. 1 Schematic diagram of the FGL heater

Table 1 Material properties of the FGL heater

Material	Parameter	Value
Glass fiber fabric/epoxy resin composite material	Tensile strength	480 MPa
	Tensile modulus	28 GPa
	Flexural strength	480 MPa
	Flexural modulus	14 MPa
	Thickness	0.20 mm
	Size	270×270mm <sup>2</sup>
Graphene heating film	Heating temperature range	0~200 °C
	Thickness	0.10 mm
	Size	250×250mm <sup>2</sup>

**2.2 Manufacturing of the flexible Fiber Graphene Laminated heater**

This study involves the fabrication of two FGL heaters. One of them is encapsulated using silicone gel for subsequent experimental comparison. To ensure the secure attachment of the heating electrodes, metal wires with exposed ends are soldered onto the graphene film with the aid of tin soldering, as depicted in Fig. 2(a). As shown in Fig. 2(b), the mold's surface is cleaned by wiping with a mold-release agent. As illustrated in Fig. 2(c), sealing glue is applied around the base, and after placing the lower mold in right position, isolation film, adhesive, demolding fabric and the test piece, are sequentially laid out. After confirming the presence of airtight conditions, a vacuum is established by an air compressor, which pressure is maintained at 80 kPa or higher. The composite materials are cured for 90 minutes under 120°C temperature conditions using a hot bonder. Once the entire heating process is completed, it is cooled down to 60°C before demolding, resulting in the final formation of the FGL heater, as presented in Fig. 2(d).

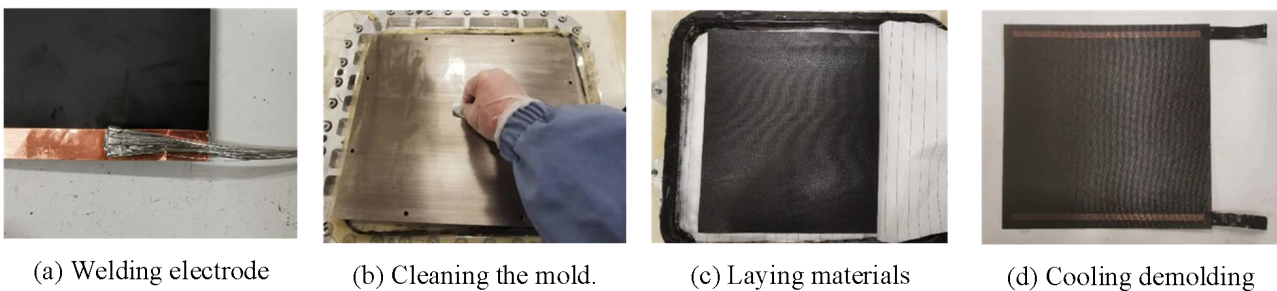


Fig. 2 Preparation process of the FGL heater

**2.3 Test system**

The heating performance test setup primarily consists of the power system, temperature measurement system, and energy measurement system, as illustrated in Fig. 3. The power system employs a constant-voltage direct current power capable of delivering a maximum output voltage and current of 400V and 18A, respectively. The temperature measurement system comprises a temperature measuring device and an UTi260B infrared thermal imager. Six K-type thermocouples are methodically affixed at regular intervals on the surfaces of distinct heater types using high-temperature adhesive tape. The temperature measuring instrument collects data from the FGL heater using thermocouples. The infrared thermal imager enables visual inspection of the heating uniformity of the FGL heater. The energy measurement system utilizes an AT24 DC meter to record and export real-time voltage and current data.

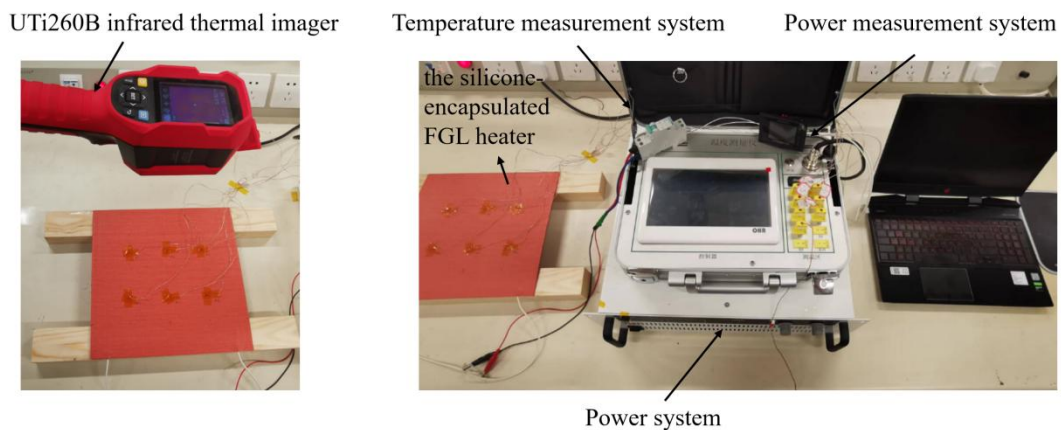


Fig. 3 Schematic diagram of heating experimental system

### 3. Results and discussion

Based on the above setup, an experimental study of the proposed FGL heater is initiated. Firstly, the thermal performance characteristic of the FGL heater is investigated in aspects of temperature distribution, heating efficiency and energy consumption under a 300W input power. Following this, a comparative analysis is conducted to evaluate the heating performance of the FGL heater in comparison to the silicone-encapsulated FGL heater and traditional the resistance wire flexible heater. Subsequently, the efficacy of the FGL heater is verified through a composite single-lap repair on the wing leading edge.

#### 3.1 Performance comparison of different heater

##### 3.1.1 Temperature uniformity

Fig. 4 demonstrates the thermal imaging of different heaters at the equal input power. As seen in this Fig. 4(a), regarding the FGL heater, the midsection consistently exhibits a slightly higher temperature compared to the surrounding areas. As observed in Fig. 4(b), after undergoing silicone gel uniformization, the FGL heater's surface demonstrates excellent temperature uniformity. In Fig. 4(c), The resistance wire flexible heater is constructed by arranging a zigzag pattern of wires, which causes unavoidable gaps, resulting in an overall uneven heating distribution. Moreover, any damage to the wire at any location can lead to an open circuit, signifying a very low damage tolerance.

By referring to Fig. 5, it becomes evident that the FGL heater maintains a notably uniform temperature profile. At 120°C, the maximum temperature difference is a mere 4°C. However, some significant temperature disparities are observed at 70°C and 80°C. This variation can be attributed to the absence of silicone encapsulation on the outer surface, which leads to rapid temperature increases. The temperature uniformity of the silicone-encapsulated FGL heater is far less affected by temperature fluctuations. Throughout the heating process, the maximum temperature difference remains consistently below 4°C. In contrast, as the temperature increases, the resistance wire flexible heater exhibits increasingly substantial temperature differences, reaching a maximum difference of 10°C at the heating target temperature of 120°C.



(a)The FGL heater (b)The silicone-encapsulated FGL heater (c)The resistance wire flexible heater

Fig. 4 Thermal imaging of different heaters

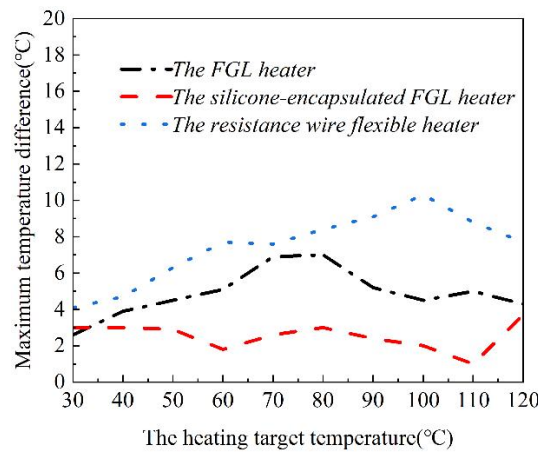


Fig. 5 Different heaters' maximum temperature difference

### 3.1.2 Heating efficiency

Fig. 6 provides the time evolution of different heaters' temperature under the equal power. It's clearly apparent that the FGL heater boasts the highest heating efficiency, taking only 20 seconds to raise the temperature from 24.6°C to 100°C, with a heating rate of 3.8°C/s. The silicone-encapsulated FGL heater exhibits a slightly reduced heating efficiency, with a heating rate of 1.1°C/s. Conversely, the traditional resistance wire flexible heater is relatively slower, with a heating rate of just 0.58°C/s. Hence, the FGL heater's heating efficiency is 3.5 times higher than the silicone-encapsulated FGL heater and 6.6 times higher than the traditional resistance wire flexible heater.

Table 2 shows the energy consumption of different types of heaters during the temperature increase from 24.6°C to 100°C. It can be seen from the figure that the FGL heater exhibits the lowest energy consumption during the temperature rise, at  $12.1 \times 10^3$  J. This represents an 85.2% reduction in energy consumption compared to resistance wire flexible heaters. Under identical experimental conditions, the silicone-encapsulated FGL heater consumes  $45.7 \times 10^3$  J, which is a 44% reduction in energy consumption compared to resistance wire flexible heaters. The experimental results demonstrate that employing graphene film as the heating element effectively reduces the energy consumed during outside maintenance of flexible heaters.



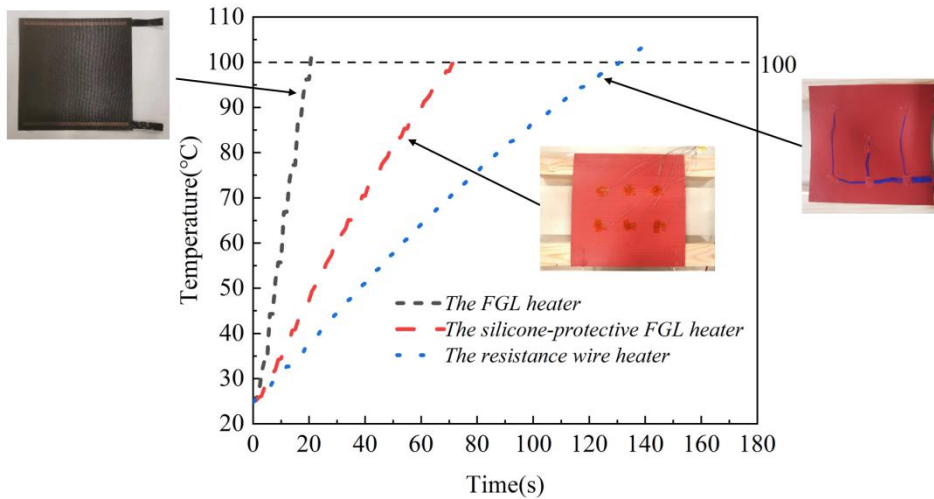


Fig. 6 Time evolution of different heaters’ temperature

Table 2 Energy consumption of different types of heaters

Type	The FGL heater	The silicone-encapsulated FGL heater	the resistance wire flexible heater
Energy consumption/J	$12.1 \times 10^3$	$45.7 \times 10^3$	$81.7 \times 10^3$
Energy reduction proportion	85.2%	44%	\

### 3.2 Composite single-lap repair using the flexible Fiber Graphene Laminated heater



Fig. 7 Schematic diagram of composite single-lap repair experiment on the wing leading edge

Fig.7 depicts the composite single-lap repair experiment setup, which incorporates a custom-developed hot bonder and the test specimen in addition to the test platform outlined in Fig. 3.

Fig. 8 presents the process of composite single-lap repair experiment on the wing leading edge. To begin with, a through-hole damage with a diameter of 21 mm was fabricated on the NACA0018 wing model, as shown in Fig. 8(a). After the adhesive bonded repair, a visual inspection revealed the complete disappearance of the damage on the wing leading edge surface. The repair patch

adhered closely to the wing leading edge, displaying a flat surface without any cracks or depressions. The curvature of the patch perfectly matched the leading edge, ensuring it had no impact on the aerodynamic performance of the wing of aircraft. Fig. 8(c) displays the thermal imaging during the repair process using the FGL heater. The temperature difference within the cured area remained within a range of 1°C, demonstrating that the FGL heater possesses strong stability and uniformity.

In summary, it's entirely feasible that utilizing the FGL heater as the heat source for in-situ adhesive repairs on complex aircraft wing surfaces.

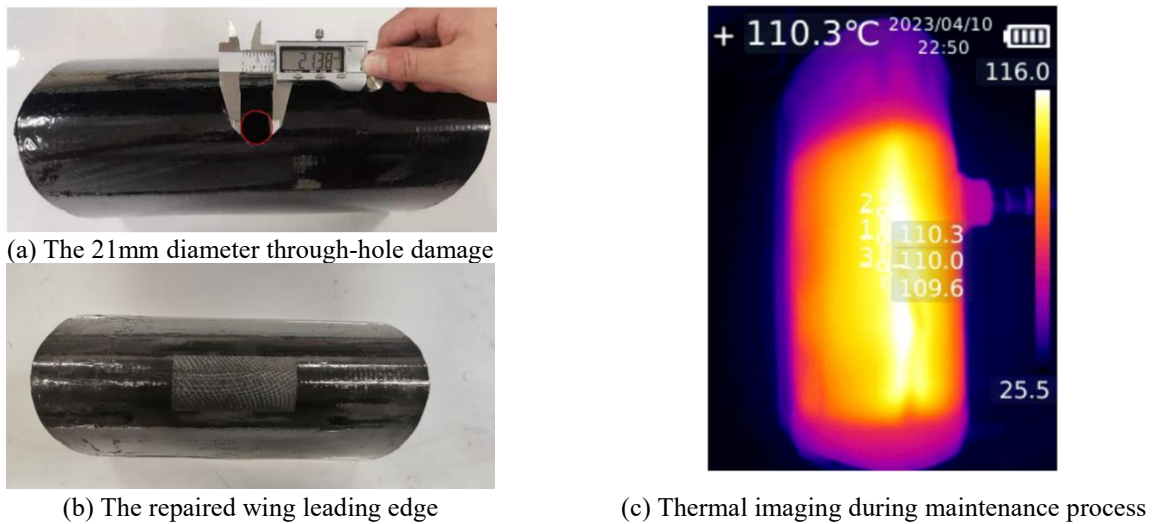


Fig. 8 Process of composite single-lap repair experiment on the wing leading edge

#### 4. Conclusion

In this paper, a novel FGL heater is proposed, which employs graphene film as the heating element. The heater exhibits excellent heating uniformity and efficiency, making it a perfect replacement for resistance wire flexible heaters. Characteristics of the FGL heater, including temperature distribution, heating efficiency and energy consumption are investigated. The effectiveness of the heater was verified through a composite single-lap repair on the aircraft wing leading edge.

Comparison experiments between the FGL heater and the traditional resistance wire flexible heater revealed that the FGL heater exhibits uniform surface temperature distribution and excellent electric heating performance. At 120°C, the maximum temperature difference of the FGL heater is less than 4°C, while the traditional resistance wire flexible heater reaches a maximum temperature difference of 10°C. When considering heating efficiency under a 300W input power, the FGL heater's heating efficiency is 3.5 times higher than that of the encapsulated heater and 6.6 times higher than the traditional resistance wire flexible heater. Additionally, in contrast to traditional resistance wire flexible heaters, the FGL heater consumes 44% less energy. Finally, the composite single-lap repair experiment on the wing leading edge affirms that the FGL heater heating is uniform during composite repairs and is adaptable to complex aircraft surfaces.

#### 5. Acknowledgment

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## References

- [1] Yong Cheng, LongYingYang. Thermo-Profile Research of Wedge-Shape Composite Repairing Using Heat-Blanket[C]. Proceedings of the 17th National Academic Conference on Composite Materials (Sub Forum on Composite Material Manufacturing Technology and Equipment)2012:242-4.
- [2] LinXiang Guo, XinYing Hu, GuanQun Zhu , Qi Jiang , Kun Jiang, ZhiYang Liu. Preparation of Embedded Silver Nanowires/ Polyimide Composite Films and Application of Electric Heater. Chemical Industry Times. 2023;37:1-6.
- [3] Xin Sun, Wei Qiao, BingWei Shi,CuiPing Shi. The Summarize and Development Tendency of Electric Resistance Heaters. Internal Combustion Engine & Parts. 2020:45-8.
- [4] Choi H, Choi JS, Kim J-S, Choe J-H, Chung KH, Shin J-W, et al. Flexible and Transparent Gas Molecule Sensor Integrated with Sensing and Heating Graphene Layers. SMALL. 2014;10:3685-91.
- [5] Shobin LR, Manivannan S. Enhancement of electrothermal performance in single-walled carbon nanotube transparent heaters by room temperature post treatment. SOLAR ENERGY MATERIALS AND SOLAR CELLS. 2018;174:469-77.
- [6] Ramadhan ZR, Han JW, Hong J, Park SB, Kim JH, Wibowo AF, et al. Conductive PEDOT:PSS on surface-functionalized chitosan biopolymers for stretchable skin-like electronics. ORGANIC ELECTRONICS. 2021;94.
- [7] Yang G-h, Bao D-d, Liu H, Zhang D-q, Wang N, Li H-t. Functionalization of Graphene and Applications of the Derivatives. JOURNAL OF INORGANIC AND ORGANOMETALLIC POLYMERS AND MATERIALS. 2017;27:1129-41.
- [8] Xue Xia QM, Cong Wang,Xiao Zhou. Influences of Graphene Nanosheets on Thermal Conductivity and Mechanical Properties of Carbon Fiber/Polypropylene Composites. Composites Science and Engineering. 2019;1:11-4.
- [9] Hong X, Yu R, Dong Y, Wan J, Zhang H, Zhu C. Electric heating behavior of flexible knitted fabrics comprising reduced graphene oxide, with emphasis on resistance temperature-sensitive behavior and decoupling of contact resistance. JOURNAL OF INDUSTRIAL TEXTILES. 2022;51:3131S-48S.
- [10] DaoHui Zhou, PinDe Yuan, Ming Xin. Study on Low Temperature Heating Method of Pure Electric Vehicle Power Battery. Auto Electric Parts. 2018:15-7.
- [11] PeiJun Ji,QiuRen Ou, Liang Zhao, Ming Yang, ShuCheng Bai. Studied on the Properties of 9518 Resin/Glass Fiber Fabric Composites. Hi-Tech Fiber and Application. 2010;35:28-30+42.