

Damage mechanism of wind turbine blade under the impact of lightning induced arcs

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Abstract:

It is not clear for the damage mechanism of the blade structure under the effect of the lightning strike arc. In this paper, the damage characteristics of blades under the effect of lightning arc are obtained by the impulse large current experiment. Based on the actual blade structure, An MHD (magnetohydrodynamics) model is built suitable for multi-field coupling of heat-magnetic-airflow and we obtain the temporal and spatial variation of the temperature and pressure. The experimental results show that the blade tends to crack from the position of the trailing edge near the arc attachment point and the crack extends in the direction of the blade root and tip. The length of carbonization damage caused by high temperature of arc is much smaller than the crack length due to the airflow impact. When the down-conductor is placed on the main beam, carbonization damage distributes in the area between the left web and the trailing edge. When placed on the right web, it distributes between the right web and the trailing edge. In the finite element simulation, the temperature of the arc ignited point increases to the peak value and then decreases rapidly and then, it increases to the maximum and tend to stabilize. The high temperature inside the blade region diffuses from the boundary between the pressure surface and the right web to the trailing edge. The pressure of trailing edge increases to the maximum and then oscillates to decrease. The airflow inside the blade continuously oscillates between the right web and the trailing edge. It is recommended to improve the toughness of epoxy resin adhesive and set the down-conductor on the main beam.

Key words: Wind turbine blade, lightning protection, impulse current experiment, damage mechanism,

1. Introduction

With the rapid development of the wind power generation [1], the lightning protection of wind turbines has become a major technical problem that needs to be solved urgently. In many accidents caused by lightning, the blade has become the main lightning strike attachment point due to its huge height [2]. Once suffering lightning strikes, the blade might be damaged, which will bring huge economic losses. The existing wind turbine blade lightning protection system (receptor and down-conductor system) can prevent lightning damage to a certain extent, and related research mainly focuses on the optimal design of the lightning receptor. In the Ref. 3, the authors respectively place two types of receptors on the blades. The first is to place copper circular with a diameter of 25 mm at the location where is 250 mm away from the blade tip and 130 mm away from the leading and trailing edge. The second is to wrap the blade tip in copper. It is found that the lightning protection effect of the second type is better, but sometimes the failure will occur under the positive lightning. In the Ref. 4, the authors find that the metal components in the blade (such as sensors) will reduce the rate of successful attachment, and they propose a design principle of the receptor considering the influence of the metal components. But no specific solution is proposed. In the Ref. 5, the authors find that in the marine environment, when the salt fog is attached to the surface of the blade, the probability of being struck by lightning increases. The closer the salt fog is to the receptor, the greater the lightning strike probability is. Furthermore, it is proposed that advanced marine antifouling coatings should be applied on the surface of the receptor to increase the lightning protection capability. In the Ref. 6, the authors find that the curvature of the receptor affects the lightning strike triggering ability of the blade. The lightning protection effect will be better if the curvature of receptor is smaller. However, the lightning receptor with a small curvature still cannot achieve complete protection against lightning strikes. None of above research can achieve complete protection from lightning strikes. Therefore, consideration should be given to study the mechanism of blade damage under the impact of lightning arc and strengthen the blade's ability to withstand lightning strike.

Vestas company conduct a two-year lightning strike observation on two hundred and thirty-six blades with a length of 39 m, and they find that 88% of lightning strikes locate within 1m from the blade tip, and the rest 12% locate within 5 m from the blade tip [7]. When the lightning strikes blade, current will pass through the blade surface, burning the material near the arc. Toshio Ogasawara et al. pointed out that the Joule heat caused by lightning current can bring thermal decomposition of epoxy resin and gasification of fiber materials, resulting in delamination of material [8]. Zhang et al. studied the pyrolysis reaction process of blade material under the effect of high temperature and analyzed the variation of its polymer degree [9]. Many studies on the damage of blade material have been carried out [10-13]. However, the lightning current transmitting along the internal path of the blade will cause a high-temperature arc and high-pressure shock waves, causing structural damage to the blade [14]. Relevant research on this part is relatively scarce. In Ref.15, The distribution of pressure in the closed cavity under impulse current was tested. However, above studies cannot obtain the characteristics of the structural damage, which fail to reveal the damage mechanism caused by the lightning arc.

55 Injecting a large impulse current into the actual blade can provide the most direct method for studying the effect of the
 56 lightning arc inside the blade. However, when the blade is struck by lightning, the structural damage caused by the high
 57 temperature and pressure is a high-speed dynamic process. It is difficult to observe the damage details and measure
 58 relevant parameters by traditional experimental methods. Therefore, it is necessary to use simulation methods to reveal
 59 the damage mechanism of the blade structure. Wei et al. established an axisymmetric model and used finite element
 60 simulation software to calculate the distribution of ambient temperature field during the fall of the pantograph arc based
 61 on the MHD theory [16]. The basic equations in their model provide reference for this paper, but the blade calculation
 62 area is two orders of magnitude larger than the arc area of Wei's model. Hence, the vector magnetic position method is
 63 replaced by the Biot-Savart law for calculating the electromagnetic field. Zou et al. studied the distribution characteristics
 64 of high-temperature plasma generated by parallel double-wire electric explosion in vacuum [17], which provides a
 65 reference for the physical properties of the arc plasma. Rong et al. used MHD to study the internal fault arc in a closed
 66 vessel and simulate the arc-extinguishing process between the two rod electrodes in the air under the action of AC current
 67 [18]. Their research subjects have good symmetry, but the internal section of the blade is an asymmetrical structure and
 68 has a sharp region. Therefore, special treatment is required for these areas. Yan et al. studied the breaking arc of the circuit
 69 breaker and pointed out that the arc column would not cause significant distortion to the magnetic field at high or low
 70 current [19]. Accordingly, this paper does not consider the distortion effect of the lightning arc column on the internal
 71 magnetic field of the blade. Sun et al. pointed out that the length of the arc was not related to the magnitude of the current
 72 [20]. The above research progress on arc plasma can provide a valuable reference for studying the lightning arc in the
 73 blade and exploring the force characteristics of the blade chamber. However, most of the above studies are based on the
 74 study of symmetrical models. The blade structure is asymmetric. In addition, the lightning arc has a typical arc path and
 75 instantaneous impact effect, which is more difficult to calculate. Therefore, it is necessary to simplify according to its
 76 geometry and computational complexity to improve computational efficiency.

77 By investigating the lightning strike data of wind farms, the arc path of the experiment is determined. Then we compare
 78 the structural damage of the blade under the impact of large impulse current for different arc ignited positions and arc
 79 paths. Furthermore, based on the MHD theory, the damage mechanism of the blade is studied. COMSOL is used to
 80 calculate the internal temperature and pressure distribution of the blade chamber. The simulation results have a good
 81 correspondence with the experimental results.

82 2. Experimental study on blade structure damage under large impulse current

83 2.1 Experimental set

84 The geometry structure of an actual blade is shown in Fig. 1. It consists of a pressure surface (PS surface) and a suction
 85 surface (SS surface). Two webs support the blade structure, and the down-conductor guides the lightning current to the
 86 ground. The typical paths of lightning strike arc are shown in Fig. 2. The main beam (the middle green part of Fig. 2) and
 87 the trailing edge joint (the right green side of Fig. 2) are made of epoxy resin. The rest (the yellow part of Fig. 2) uses
 88 sandwich material. The round red point indicates the down-conductor. The lightning strike point of the actual blade is
 89 generally located within 5 m from the tip of the blade. Most lightning strike arcs have three typical paths inside the blade:
 90 (1) The lightning strike arc enters from the center right of the PS surface, connects to the down-conductor on the web, as
 91 shown in Fig. 2(a). (2) The lightning strike arc enters from the center right of the PS surface, penetrates the right web,
 92 and connects with the down-conductor on the main beam, as shown in Fig. 2(b). (3) The web plays a supporting role
 93 inside the blade. At the position close to the tip of the blade, the space is narrow and does not need support, so the web
 94 disappears. The lightning strike arc enters from the center right of the PS surface, and then connects with the down-
 95 conductor on the main beam, as shown in Fig. 2(c).

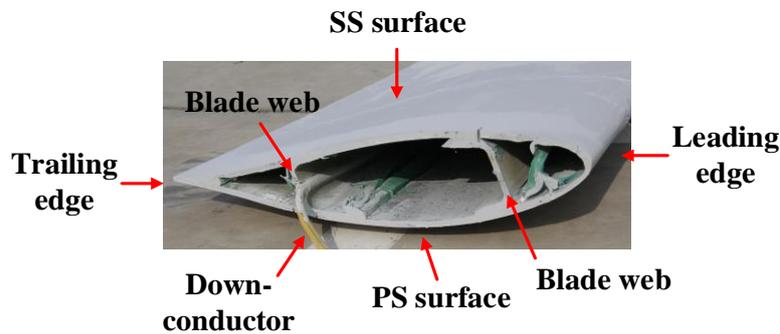


Fig. 1 cross section of an actual blade

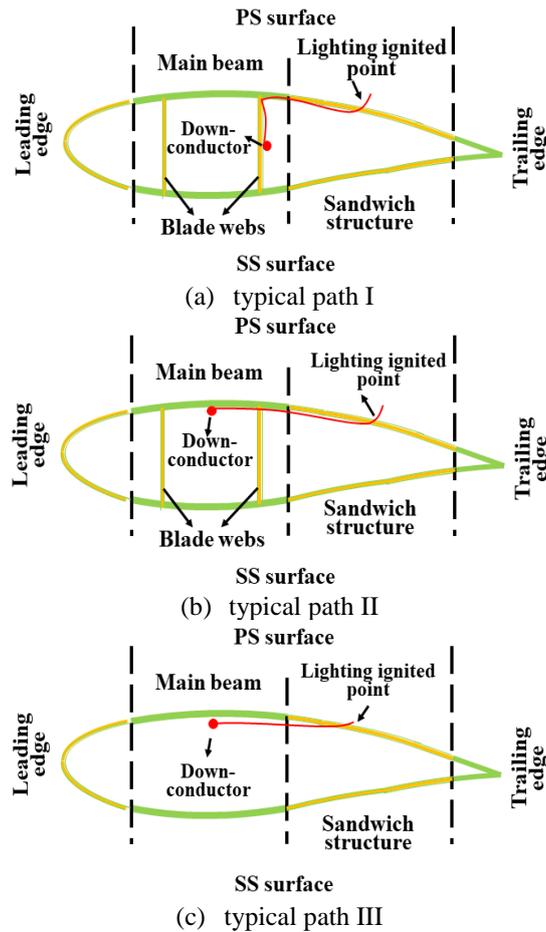


Fig. 2 Typical path of lightning strike arc

96 According to above research results, the experimental scheme is determined as follows: The lightning strike point of
 97 the actual blade is generally located the area within 5 m from the tip of the blade. Hence, three 5-meters-long blades are
 98 adopted as experimental specimen, as shown in Fig. 3. A nickel-chromium wire with a diameter of 0.1 mm is used
 99 to induce the arc. For the first blade, the arc ignited point is located 3 m away from the tip of the blade. The arc path
 100 is shown by the red line in Fig. 2(a). For the second blade, the arc ignited point is located 2 m away from the tip of the blade.
 101 The arc path is shown by the red line in Fig. 2(b). For the third blade, the arc ignited point is located 1 m away from the
 102 tip of the blade. The arc path is shown by the red line in Fig. 2(c). In the experiment, the impulse current generator is used
 103 to generate a negative impulse current with peak value of 150 kA and time duration of 25 μ s/250 μ s. The experimental
 104 platform is shown in Fig. 4.



Fig. 3 5m long specimen cut from the real blade.

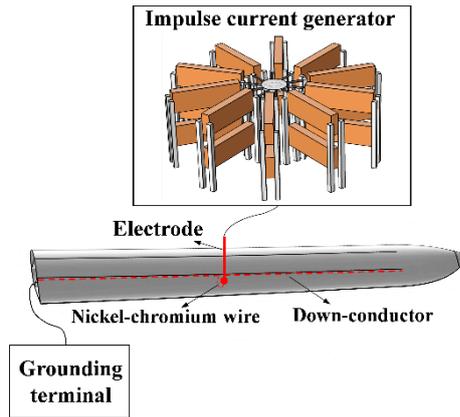


Fig. 4 Experiment platform

105 **2.2 Experimental results**

106 The damage position of the blade is shown in Fig. 5. The location of carbonation damage is near the arc ignited point,
 107 and the structural crack damage is near the trailing edge. The two types of damage are shown in Fig. 6, the left picture
 108 represents carbonization damage, and right picture represents crack damage. When the down-conductor is placed on the
 109 main beam, carbonization damage distributes in the area between the left web and the trailing edge, which is shown in
 110 Fig. 7(a). When placed on the right web, it distributes between the right web and the trailing edge, which is shown in Fig.
 111 7(b). The main experimental results are shown in Fig. 8. The damage caused by large impulse current on the blade are
 112 mainly material carbonization and structural crack. The “0” in Fig. 8 represents the arc ignited point. In Fig. 8, the black
 113 line represents the material carbonization length, and the red line represents the structure crack length. It can be seen from
 114 the Fig. 8 that the carbonization damage is lighter than the structural crack damage.

115 When the arc ignited point is 3 m away from the tip of the blade, the space in the blade chamber near the arc ignited
 116 point is ample. Therefore, the airflow is less affected by blade structure. The crack damage takes the arc ignited point as
 117 the midpoint, and the crack length on both sides of the arc ignited point are not much different. The right web of the blade
 118 just partially carbonizes and not cracks. However, when the arc ignited point is 2 m away from the tip of the blade, the
 119 blade width in the direction of the tip sharply reduces and the space is narrow. The trailing edge is prone to burst under
 120 the effect of impulse airflow caused by the induced arc. The crack size in the direction of the tip of the blade is larger than
 121 the direction of the root. At this time, the right web of the blade has burst, but the left web is not damaged. When the arc
 122 ignited point is 1 m away from the tip of the blade, the damage extends to the tip, and the material of the junction between
 123 the receptor and the skin is torn.

124 The damage on the blade under the effect of the lightning arc is a dynamic process. It is difficult to reproduce all
 125 possible damage process and detail by traditional experiment methods, and actual blades used in the experiment is
 126 expensive. Therefore, it is necessary to build model and carry out simulation based on experimental results to reveal the
 127 mechanism of blade damage.

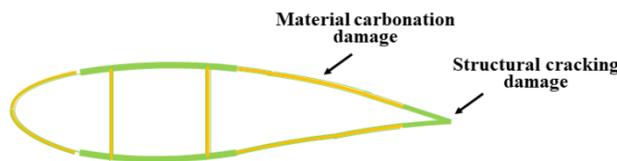
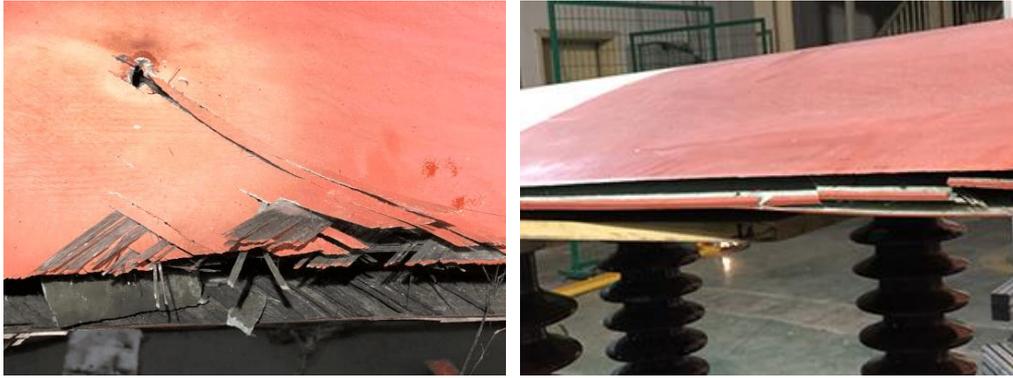


Fig. 5 The location of blade damage cause by large impulse current in the experiment

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(a) carbonization damage (b) crack damage
Fig. 6 Typical damage features of the test blades under large impulse current

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(a) arc path I (b) arc path II
Fig. 7 Inside damage of the blade with different arc paths

Arc ignited position

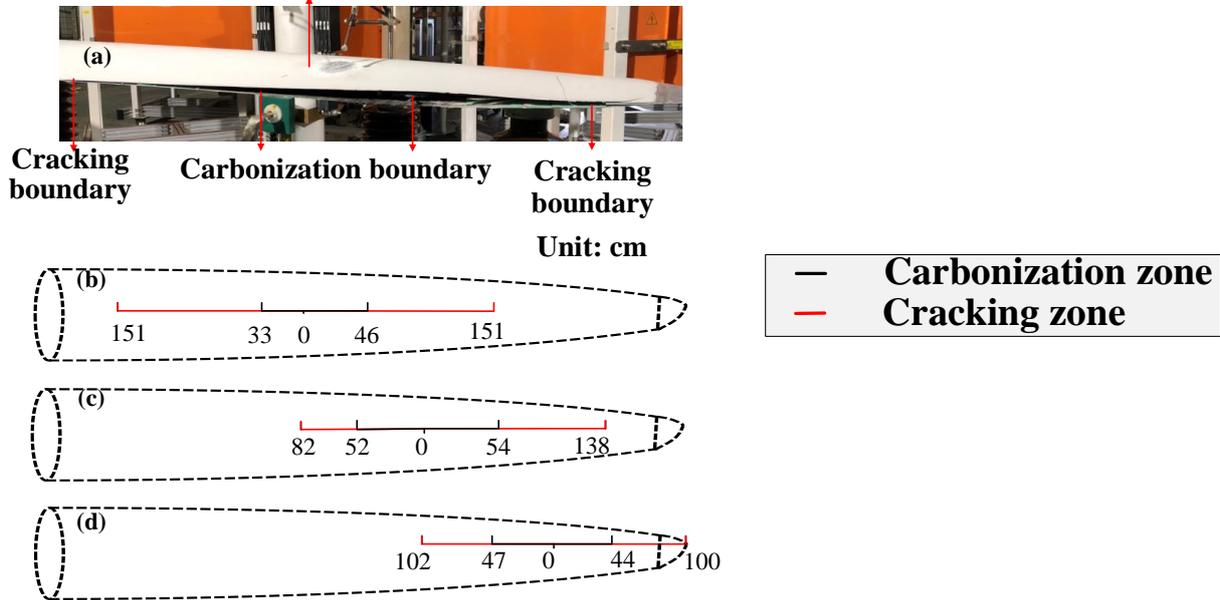


Fig. 8 The length of material carbonization and structure crack

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3. Modeling of the coupling of thermal, airflow fields and electromagnetic

In this paper, the MHD theory is used to establish the lightning arc model and analyze the damage characteristics.

3.1 Fluid dynamics equations

Equations (1)-(3) are the continuity equation, the momentum conservation equation and the energy conservation equation.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \quad (1)$$

$$\frac{\partial p \mathbf{u}}{\partial t} + \rho (\nabla \cdot \mathbf{u}) \mathbf{u} = -\nabla p + \nabla \cdot [\mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] - \frac{2}{3} \mu (\nabla \cdot \mathbf{u}) \mathbf{A} + \rho \mathbf{g} + \mathbf{J} \times \mathbf{B}, \quad (2)$$

$$\frac{\partial (\rho C_p T)}{\partial t} + \nabla \cdot (\rho C_p T \mathbf{u}) = \nabla \cdot (k \nabla T) + \sigma E^2 + q_{rad} + q_n, \quad (3)$$

$$q_{rad} = 4\alpha k (T^4 - T_0^4), \quad (4)$$

138 Where, ρ is the fluid density, p is the pressure, T is the temperature, u is the fluid velocity, R_s is the constant, μ is the
 139 dynamic viscosity, g is the gravity acceleration, C_p is the fluid constant pressure heat capacity, k is the thermal conductivity,
 140 q_{rad} is radiant heat, q_n is referred to viscous heat.

141 In the equation (2) momentum conservation equation, the Lorentz force of the arc plasma in the magnetic field is taken into
 142 consideration. Since the plasma particle mass is very light, the influence of gravity is ignored and ρg is equal to 0. In
 143 the energy conservation equation, the Joule heat of the arc is equal to σE^2 . Since the viscous dissipation term does not
 144 generate extra heat in the energy conservation equation, q_n is equal to 0.

145 For the thermal radiation term q_{rad} , it is determined by the simplified equation (4) [21], where α is the Boltzmann
 146 constant, k is the absorption coefficient, T is the arc temperature, and T_0 is the environment temperature.

147 3.2 Lightning arc geometry model

148 Based on the experimental results shown in the second paragraph of Section 2.2, the geometry model used for the
 149 simulation is determined. For the arc path in Fig. 2(a), a cross section 3 m away from the blade tip is taken as research
 150 subject. Since the experimental results show that the right web does not crack, only the right side of the right web is
 151 considered as arc area. That is called model I. For the arc path in Fig. 2(b), a cross section 2 m away from the blade tip
 152 is taken as research subject. The experimental results show that only the right web bursts and the left web have no structural
 153 damage, so only the right side of the left web is considered as arc area. Due to the blocking effect of the right web, a
 154 portion left area is a non-arc area. That is called model II. For the arc path in Fig. 2(c), a section 1 m away from the blade
 155 tip is taken as research subject, which is called model III. The red line in Table 1 indicates the arc plasma area, and the
 156 blue area is the calculation area.

Tab. 1 Geometry models adopted in the simulation

Section types of blade		Calculation domain

158 **3.3 Arc plasma model**

159 The arc path is assumed as a straight line. For the model I, the real arc path is a polyline. each segment is solved
 160 separately and added together. In the arc area shown by the red line in Table I, for the following two reasons, it is assumed
 161 that the direction of the current density J is parallel to the current-leading wire.

162 On the one hand, the current density is formed by the movement of the arc plasma. The average velocity of the airflow
 163 in the direction of vertical to the current-leading wire is 1020 m/s, and the longest distance from the PS surface to the SS
 164 surface is about 0.3 m. The time is 0.29 ms required for the diffusion of the airflow from the current-leading wire to SS
 165 surface. Hence, it is considered that the diffusion of the arc plasma pushed by the airflow is instantaneous in the direction
 166 of vertical to the current-leading wire, and the current density J does not have component in this direction. On the other
 167 hand, in the experiment, the current flows in the direction of the current-leading wire, therefore the most arc plasma
 168 generated by the current moves in the same direction. The current density is formed by the movement of the arc plasma,
 169 so the direction of the current density J is parallel to the current-leading wire.

170 The assumption of J is as follows: it is the maximum at the current-leading wire, set as J_{\max} , and decreases exponentially
 171 downward, set as 0 at the SS of the blade. Since the exponential function cannot reach 0, a small number of 0.1 is used to
 172 instead. Based on the assumptions above, the current density can be obtained by equation (5) and equation (6).

$$\int_0^{L_{ss}} J(r_1) dl = I, \quad (5)$$

$$J(r) = J_{\max} \exp(-ar), \quad (6)$$

$$I(t) = \begin{cases} I_{\text{peak}} \frac{t}{t_m} & t < t_m \\ I_{\text{peak}} \exp[-\alpha(t-t_m)] & t > t_m \end{cases}, \quad (7)$$

173 L_{ss} is the distance from the SS surface to current-leading wire, and r_1 is the vertical distance from any point in the
 174 calculation domain to the current-leading wire. a is a constant. I is the injection current, the value of which is obtained by
 175 equation (7). I_{peak} is the peak value of impulse current, being 30 kA and 150 kA, t_m is the peak time of impulse current,
 176 being 25 μs according to experimental data, α is referred to attenuation constant, being 0.003.

177 **3.4 Electromagnetic field equation**

178 The arc is a fluid with electrical conductivity, and electromagnetic field inside it would affect the characteristics of the
 179 fluid, such as pressure and temperature. In order to calculate the Joule heat and the Lorentz force, it is necessary to figure
 180 out the distribution of the electric field and magnetic field.

181 According to Ohm law, the electric field strength E is obtained by equation (8). The distribution of magnetic induction
 182 B can be obtained according to Biot-Savart's law shown as equation (9).

$$E = J/\sigma, \quad (8)$$

$$B = \int \frac{\mu_0 I(t)}{4\pi} \cdot \frac{dl \times e_{r_2}}{r_2^2} + \int \frac{\mu_0 I'(t)}{4\pi} \cdot \frac{dl \times e_{r_2}}{cr_2}, \quad (9)$$

183 Where, σ is the conductivity, μ_0 is the magnetic permeability, dl is the line integral element, e_{r_2} is the unit direction
 184 vector between the current element and the point to be calculated, r_2 is the distance between the point to be determined
 185 and the direction vector, $I'(t)$ is derivative of the current value versus time, c is the speed of light.

186 **4. Simulation results and discussion**

187 In this section, we figure out temporal and spatial variation of temperature and pressure and the mechanism of blade
 188 damage under lightning arc is revealed. Furthermore, $I_{\text{peak}}=30$ kA is selected to study the damage of lightning arc to the
 189 blade. Based on the data of temperature at point A and pressure at point B, we propose some suggestions to enhance the
 190 ability of lightning protection for the blade.

191 **4.1 Case study ($I_{\text{peak}}=150$ kA)**

192 In order to verify the rationality of the simulation model, results when $I_{\text{peak}}=150$ kA are selected to compare with the
 193 experimental phenomena. The temperature at point A (arc ignited point) and the pressure at point B (trailing edge) in the
 194 Fig. 9 are analyzed.

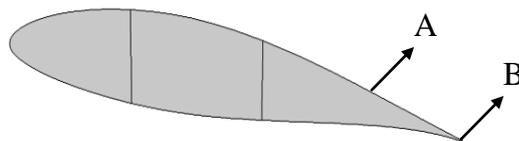


Fig. 9 Simulation analysis diagram (A represents arc ignited point and B represents the trailing edge of the blade)

195 **4.1.1 Temperature analysis at point A**

196 The main material of the blade surface is epoxy resin. Epoxy resin would be destroyed under high temperature and
197 decomposed into small molecular products. Chatterjee et al. found that the pyrolysis temperature was concentrated at
198 hundreds of kelvins for different types of epoxy material [22]. The damage to the epoxy material would be more severe
199 if the temperature is higher.

200 Fig. 10 shows the temperature of point A for model I. As can be seen from the figure, the temperature at point A
201 increases rapidly and then decreases after reaching the first peak value. It starts increasing again until reaching the second
202 peak value. Finally, it fluctuates around 1549 K until stabilizes. This value (1549 K) is much larger than pyrolysis
203 temperature for epoxy material, indicating that the blade would be carbonized.

204 From the perspective of heat conduction, we analyze the reasons for the above phenomena. Due to the narrow space at
205 the junction of the right web and PS surface, heat flow is easy to accumulate, so the high temperature area appears here
206 firstly. The heat starts to convect in the blade cavity. Then it is conducted from the region with high temperature to the
207 region with low temperature, at the same time, the high temperature region gradually spreads toward the trailing edge
208 along the PS surface. For this time, the temperature of point A increases rapidly. However, lightning has a transient effect
209 and short duration. After the lightning current tends to be 0, There is no new heat to be generated. The original heat inside
210 the blade diffuses from PS surface with high temperature to SS surface with low temperature. For this time, the
211 temperature of point A decreases. On the other hand, the heat generated by the lighting arc on the right web diffuses
212 toward the trailing edge. The two diffusion interact to form a high temperature region. Furthermore, the heat spreads
213 around, and the temperature at point A increases again. Finally, the heat is evenly distributed, the temperature of point A
214 tends to be stable.

215 The above phenomenon is analyzed combining with the dynamic image shown in Fig. 11. At 0.2 ms, the high
216 temperature area appears at the boundary between the right web and the PS surface. From 0.2 ms to 0.5 ms, the high
217 temperature area diffuses to the trailing edge of the blade along PS surface. At this time, the temperature of the point A
218 would suddenly increase, reaching the first peak value in Fig. 10. From 0.5 ms to 2 ms, the high temperature area gradually
219 moves downward, and the temperature of the point A drops until reaching the minimum value in Fig. 10. From 2 ms to 5
220 ms, the high temperature area spreads inside the blade chamber, and the temperature of the point A increases again until
221 around 1549 K. After 5 ms, the temperature in the blade chamber tends to be a same value and reaches a stable state,
222 which is called stable temperature.

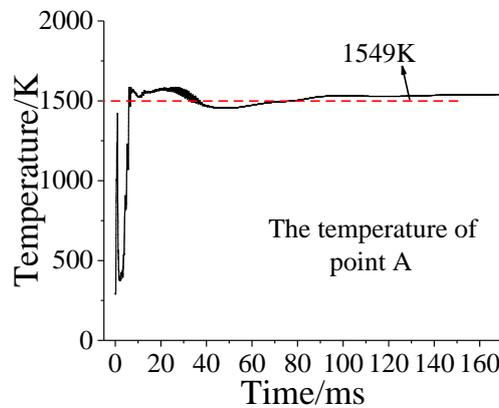
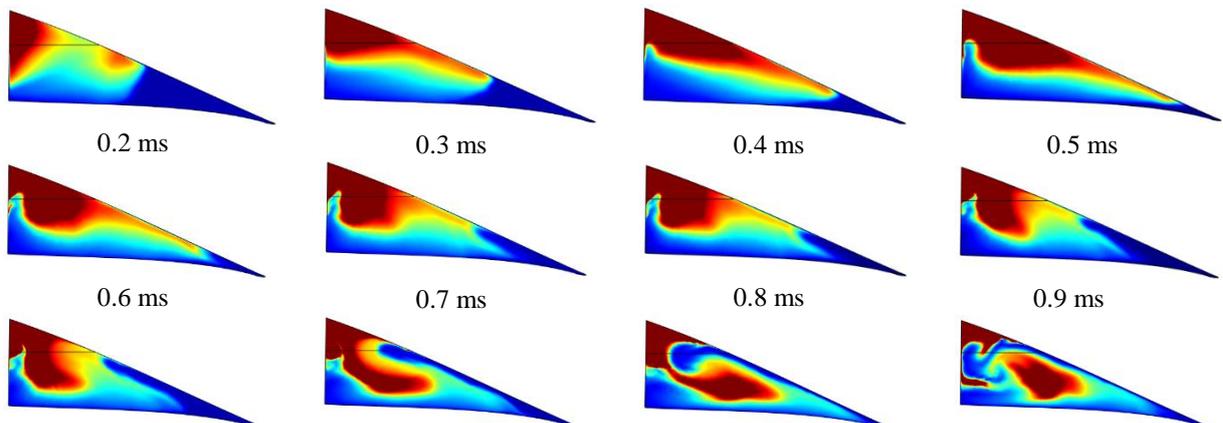


Fig. 10 Variation of the temperature of the point A with time



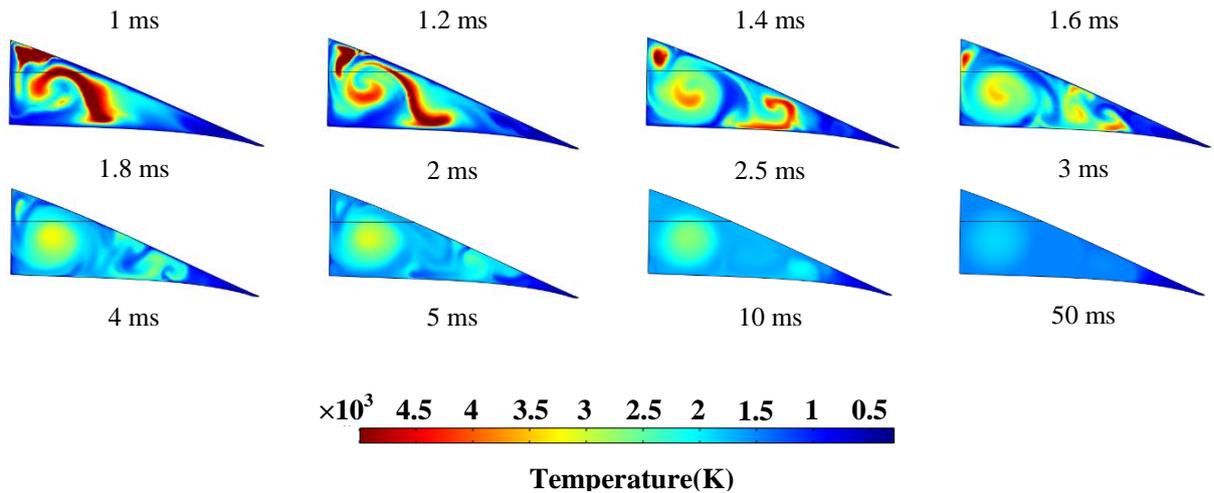


Fig. 11 Temperature diffusion process inside the blade

223 For model II and model III, the change of point A is similar to that in Fig. 10. The stable temperature for all models in
 224 simulation and the length of material carbonization near arc ignited point in experiment are listed in Table 2.

Tab. 2 Stable temperature in the simulation and length of carbonization in the experiment

Type	Simulation Results		Experiment Results	
	Stable Temperature (K)		Length of Material Carbonization (cm)	
Model I	1549		33	
Model II	2603		52	
Model III	2501		47	

225 By comparing the stable temperature of point A and the carbonization length near the arc ignited point, it is found that
 226 they have a positive correlation. The higher the temperature in the simulation, the more serious carbonization of the
 227 material in experiment, which verifies the correctness of the simulation results.

228 **4.1.2 Pressure analysis at point B**

229 At the trailing edge of the blade, the PS surface and SS surface are glued by an epoxy adhesive, as shown in Fig. 12.
 230 The large impulse current generates high-speed airflow, and the pressure act on the PS and SS surface, thereby causing
 231 damage to the epoxy resin adhesive. This kind of damage is called T-peeling, as shown in Fig. 13.

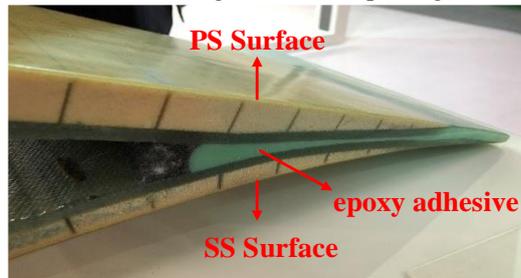


Fig. 12 Blade trailing edge

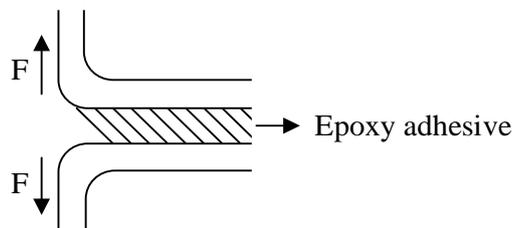


Fig. 13 A diagram of T-peeling

232 The T-peel strength refers the ability that two bonded samples resist to be peeled. The T-peel strength of epoxy resin
 233 ranges from 3 to 11 N/mm. The width of the trailing edge epoxy adhesive is 2.1 cm in the experiment. According to this,
 234 T-peel strength of blade trailing edge is calculated. As shown in the equation (10), the maximum pressure that the trailing
 235 edge can withstand is 231 N.

$$21\text{ mm} \times 11\text{ N/mm} = 231\text{ N}, \quad (10)$$

236 Fig. 14 shows the pressure of point B for model I. Firstly, the pressure of point B quickly reaches the peak value, then
 237 shows a trend of fluctuation and the amplitude decrease with time, finally reaches a stable value. In Fig. 14, the maximum
 238 pressure at the trailing edge is 2.03×10^7 Pa. According to a standard "Adhesives, T-peel strength test method for a flexible-
 239 to-flexible test specimen assembly" published by China Chemical Industry Association [23], a $2.5 \text{ cm} \times 5 \text{ cm}$ facet is taken
 240 on the trailing edge of the blade in Fig. 15. As shown in equation (11), the pressure of the trailing edge is 25375 N. This
 241 value is much larger than 231 N, indicating that the trailing edge of the blade would crack.

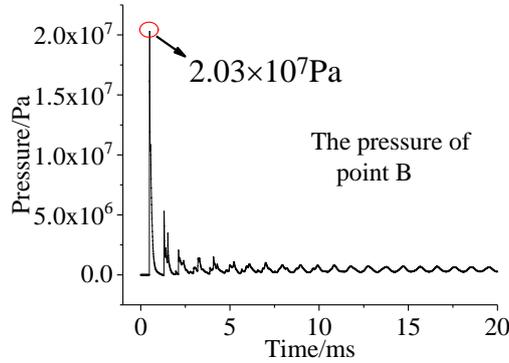


Fig. 14 Variation of the pressure of the point B with time

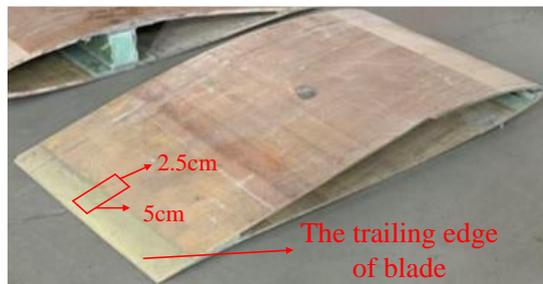
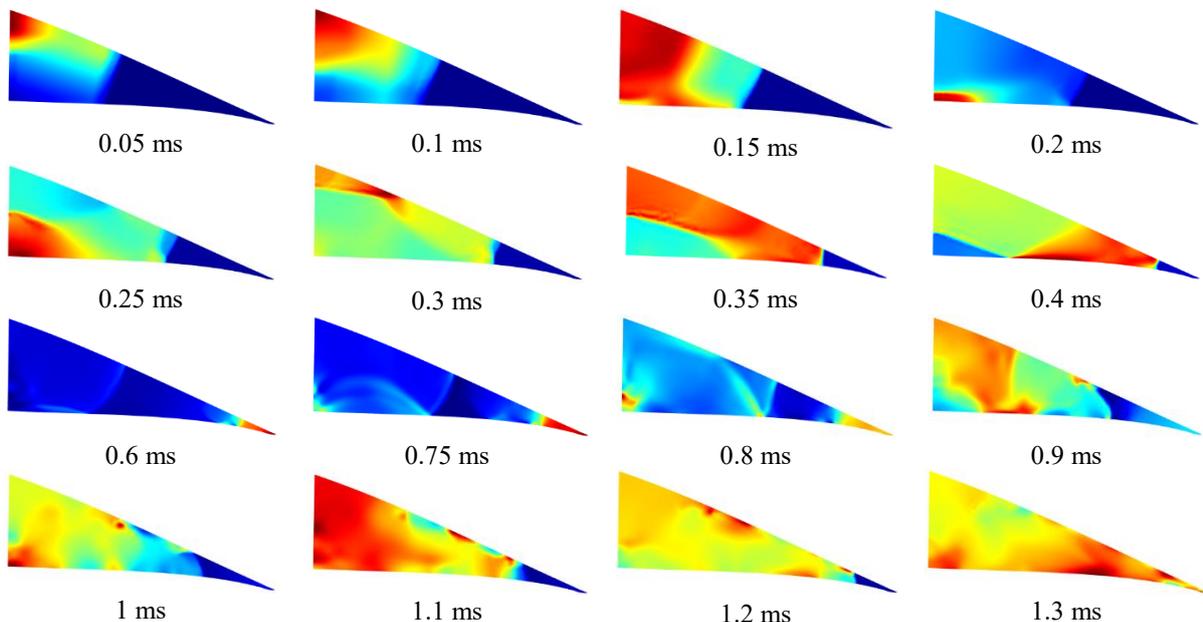


Fig. 15 A $2.5 \text{ cm} \times 5 \text{ cm}$ facet on the trailing edge of the blade

$$0.05 \text{ m} \times 0.025 \text{ m} \times 2.03 \times 10^7 \text{ Pa} = 25375 \text{ N}, \quad (11)$$

242 The above phenomenon is analyzed combining with the dynamic image shown in Fig. 16. The area with high pressure
 243 first appears at the junction of the right web and the PS surface, and then the airflow diffuses downward. After diffusing
 244 to the junction of the right web and the SS surface, the airflow diffuses towards the trailing edge and the pressure of point
 245 B increases rapidly. After the pressure of point B reaches the first peak value shown in Fig. 14, the airflow diffuses
 246 between the trailing edge and the right web back and forth.



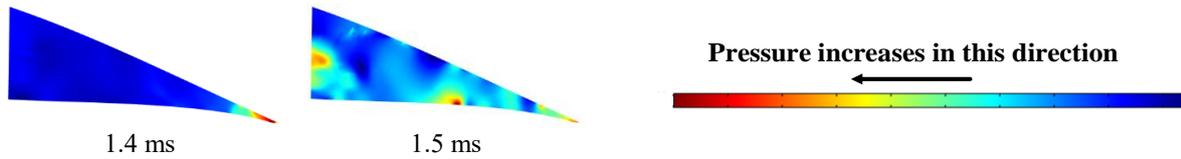


Fig. 16 Pressure diffusion process inside the blade

247 For model II and model III, the pressure change of point B is similar to that in Fig. 14. The maximum pressure for all
 248 models in simulation and the crack length of trailing edge in experiment are listed in Table 3. In particular, the space of
 249 blade tip is narrow, which is easy to cause high pressure accumulation. The length of the crack in the direction of blade
 250 tip is easily affected by its narrow structure, thus it is not counted in Table 3. The length of crack in the Table 3 is the
 251 length of the crack in the direction of the blade root starting from the arc ignited point.

Tab. 3 Maximum pressure in the simulation and length of crack in the experiment

Type	Simulation Results	Experiment Results
	Maximum Pressure ($\times 10^6$ Pa)	Length of Crack (cm)
Model I	20.3	151
Model II	16.4	82
Model III	18.0	102

252 By comparing the maximum pressure of point B and the crack length of trailing edge, it is found that they have a
 253 positive correlation. The higher the pressure in the simulation, the larger the crack length of the trailing edge in the
 254 experiment, which verifies the correctness of the simulation.

255 The peak value of lightning current is 150 kA in above research, however, the probability of $I_{peak}=150$ kA is small.
 256 Orville et al. observed the lightning phenomenon in the United States from 1989 to 1999 and found that the median of
 257 the I_{peak} was around 30 kA [24]. Therefore, $I_{peak}=30$ kA is selected to study the damage of lightning arc to the blade. In
 258 the following paper, the point A and B represent same meaning as that in Fig. 7.

4.2 Case study ($I_{peak}=30$ kA)

260 The arc paths shown in the top and bottom picture in Table 1 represent a same kind of layout of down-conductor in the
 261 blade, so they are referred as arc path I in next study. The arcing path in the middle picture of Table 1 is called the arcing
 262 path II. In addition, a section 5 m away from the tip of the blade is included in the study.

4.2.1 Temperature analysis at point A

264 Comparing the temperature change of point A for different position of arc ignited points and arc paths, it is found that
 265 their peak values are concentrated at 430-500 K, and their trends are similar. Fig. 17 shows the temperature with time of
 266 point A for arc path I and the arc ignited point is 3 m away from blade tip. Temperature of point A increases rapidly to a
 267 peak value of 472 K, and then begins to slowly decrease. The maximum temperature is lower than the temperature
 268 required for the carbonization of the blade material. But the heat distortion temperature of the adhesive between the web
 269 and surface is 338 K recommended by Germanischer Lloyd company [25]. At this time, the failure of the adhesive should
 270 be noticed.

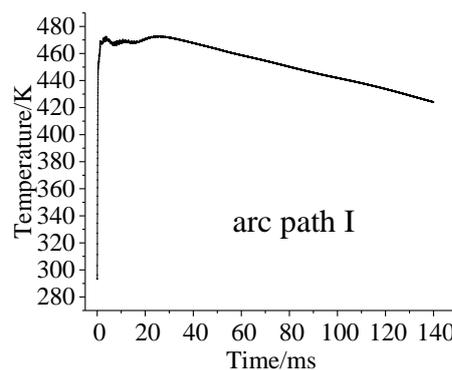


Fig. 17 Variation of the temperature of the point A with time

4.2.2 Pressure analysis at point B

271 The pressure of point B is analyzed for different position of arc ignited points and arc paths, as shown in Fig. 18.
 272 According to equation (11), the maximum pressure is put into equation (11) and calculated. Results (125-268 N) are close
 273 to the maximum pressure of the trailing edge can withstand (231 N). Hence, it is hard to judge whether the trailing edge
 274 of the blade would crack. When the position of arc ignited is the same point in Fig. 18, the maximum pressure for the arc
 275 path I is greater than the arc path II, and the closer the arc ignited point to the tip, the larger the maximum pressure is.
 276 The above results indicate that when the lightning strike point is close to the tip of the blade, the risk of damage to the
 277 blade would increase. From the view of lightning protection, it is recommended that the layout of the down-conductor in
 278 the blade adopts the form shown in the middle picture of Table 1.
 279

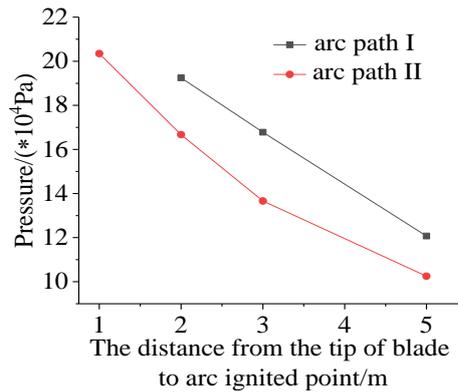


Fig. 18 Maximum pressure for different arc ignited positions and arc paths

280 The number of the peak value is figured out (red circles in the Fig. 19) from 0 ms to 30 ms for different position of arc
 281 ignited points when arc path I is adopt, as shown in Table 4. It is found that the trailing edge of the blade would suffer
 282 more impacts if the arc ignited point is closer to the tip of blade. In Ref. 26, they found that the dynamic compressive
 283 strength of the material would gradually decrease if the number of the maximum value of the pressure increases, which
 284 might cause material damage. From the perspective of strengthening the lightning resistance of the blade, the blade
 285 manufacturer should improve the toughness of the epoxy adhesive material to resist multiple consecutive impacts.

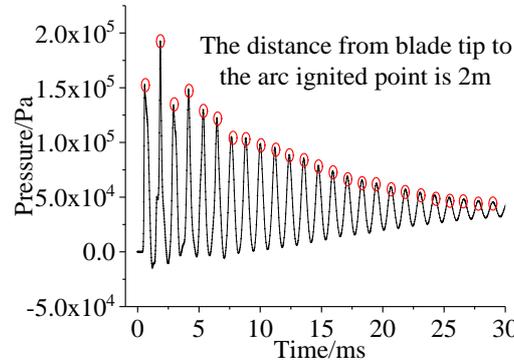


Fig. 19 Variation of the pressure of the point B with time

Tab. 4 The number of the peak value of the point B pressure in the simulation

The distance from the tip of blade to arc ignited point	The number of the peak value of the point B pressure
3 m	13
2 m	18
1 m	25

286 **5. Conclusion**

287 Experiment and simulation were conducted to study the damage mechanism of wind turbine blade under the impact
 288 of lightning induced arc. In this paper, the following conclusions have been drawn.

- 289 1. In the experiment, the blade tends to crack from the position of the trailing edge near the arc attachment point and the
 290 crack extends in the direction of the blade root and tip. The length of carbonization damage caused by high temperature
 291 of arc is much smaller than the crack length due to the airflow impact. When the down-conductor is placed on the
 292 main beam, carbonization damage distributes in the area between the left web and the trailing edge. When placed on
 293 the right web, it distributes between the right web and the trailing edge.
- 294 2. In the simulation, the temperature of the arc ignited point increases to the peak value and then decreases rapidly and
 295 then, it increases to the maximum and tends to stabilize. The high temperature inside the blade region diffuses from
 296 the boundary between the pressure surface and the right web to the trailing edge. The pressure of trailing edge
 297 increases to the maximum and then oscillates to decrease. The airflow inside the blade continuously oscillates between
 298 the right web and the trailing edge.
- 299 3. It is found that the temperature of the arc ignited point has a positive relationship with the length of the material
 300 carbonization in the experiment, so does the pressure of trailing edge with the length of the trailing edge crack. The
 301 above results verify the rationality of the simulation model.
- 302 4. From the perspective of lightning protection, it is recommended that the down-conductor is set between on the main
 303 beam and improve the toughness of the epoxy adhesive material to resist multiple consecutive impacts.

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