# Puncture Position on Wind Turbine Blades and Arc Path Evolution under Lightning Strikes

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**Abstract**

Wind turbine blades are easy to get lightning strikes, which is calling more and more attention in recent years. Impulse voltage was applied on different blade structures and materials to study the puncture position distribution and the arc path inside the blade chamber. The experimental results reflected that most puncture points were located in the sandwich structure and thinner glass fiber cover. There was no obvious connection between puncture position, voltage polarities, and voltage peak values as to the experiment in this paper. However, the surface moisture and the experimental electrode position had significant influence for the puncture position. Arc paths inside the blade chamber considering different puncture positions were also studied. It can be concluded from the experiments that the arc usually consisted of surface-arc part and the air-arc part, in which the length of each part varied with the puncture position, voltage peak values and polarities. The research findings revealed the weak areas on typical blade and as well as the possible arc paths inside the sealed chamber, which will offer guidance for the lightning protection design of blade materials and the whole structure.

**Keywords**: wind turbine blade; sandwich structure; lightning strikes; puncture position; arc path

## 1 Introduction

Renewable energy sources, especially wind energy, are widely applied because of the reduction of the usage of conventional fossil energies and its environment-friendly characteristic. However, with the development of wind farms, lightning strike on wind turbine calls more attention owing to its high structure.

Lightning protection of the wind turbine mainly relies on a receptor-grounding line system currently. The metal receptors installed on the top blade and the blade body (Fig.1) are expected to intercept the downward lightning leader and then lightning current can be safely leaded away by the grounding line connected to the receptors. In recent years, studies aiming to improve the lightning protection method for different wind turbine devices also have been conducted mainly by calculation method. Based on a physically reduced scale model and two calculated models of the main shaft wind turbine bearings, the bearings' electrical impedance was calculated to develop lightning protection method for wind turbine bearings [1]. EMTP-RV was used to calculated the lightning surges in wind turbines to build adequate lightning protection measures In Ref. [2] and Ref. [3].. Transient lightning overvoltage was calculated for designing and optimizing the arresters near step-up transformer inside wind turbine nacelle in Ref. [4]. All the above research provide essentially theoretical support for the lightning protection development of the wind turbine. However, much more work is still needed to be done for practical application.

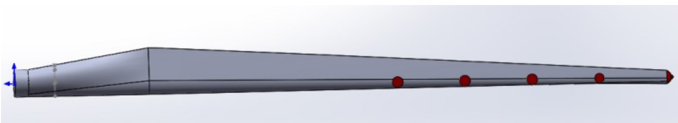


**Fig.1. Receptors on wind turbine blade**

Among all the lightning induced faults, blade damage always involves the highest repair cost, including materials, labor and downtime [1]. When the receptors fail to intercept lightning leader, lightning hits on the blade materials (90% on the top 5 m of the blade) [5] directly. The large impulse voltage will puncture into the sealed chamber of the blade. The huge thermal impact of the lightning induced arc will result in delamination, debonding, shell detachment and tip detachment [6]. For the problem of lightning strikes on blade, most worldwide researchers focus on verifying the reliability of receptor-grounding line system and optimize it to make it protect the wind turbine more effectively [7-13]. Several novel lightning protection methods have been proposed theoretically, and to some extent, some of them have been tested in the laboratory or by simulation method [12,13], but none of them have got wide application right now because of their potential influence on the aerodynamic characteristic.

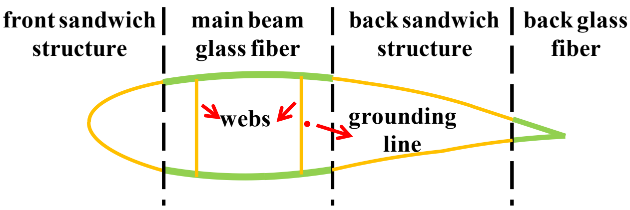
Another aspect to keep the blade away from large destruction is to study the damage process, of which the outcomes can help design the blade structure to make the blade itself stronger to resist the lightning impact effect. Some preliminary current experiments have been done to simulate the thermal explosion effect of lightning induced arc [14-16]. In Ref. [17], lightning arc radius, heat flux distribution inside blade materials and damage depth of blade materials were analyzed by calculation method. However in all of above reports, the “lightning induced arc” is set to specific paths for study’s convenience. But the evolution characteristics of arc path inside the blade chamber have not been studied deeply, which is essential basis of the research on the damage process of blade.

To study the damage process of the wind turbine blade under lightning strikes, impulse voltage experiments have been done to study the puncture position and typical arc paths inside blade. The findings are essential to study the impact force distribution on the whole blade under inside arc paths, which will offer guidance for the lightning protection design of blade materials and structure.

## 2 Wind Turbine Blade Materials and Structure

The typical blade structure is a sealed chamber with two stuck shells, and its cross-section is shown in Fig. 2. The green parts are the main beam and back edge made of very thick glass fiber reinforced epoxy resin to guarantee blade strength. The yellow parts are sandwich structures, and their outside covers are usually made of several layers of casted glass fiber, with PVC or other porous materials in the middle to reduce its weight. Blade structure changes when it gets closer to the blade top which will be introduced in experimental samples. There are also two webs (sandwich structure) inside the chamber to hold up the blade structure, and the grounding line is usually laid along the right web.

a) Real blade

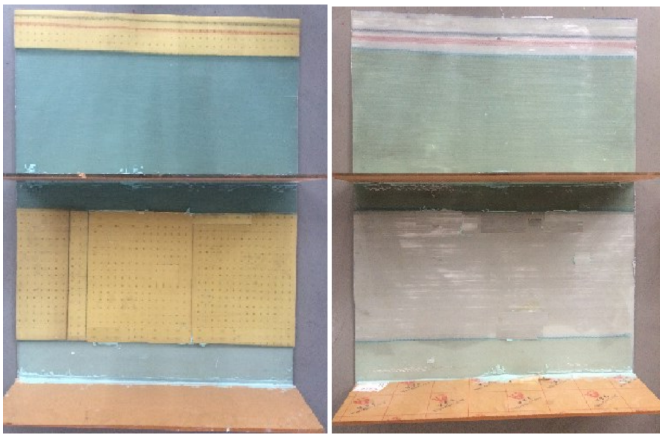



**b) Cross-section of blade**

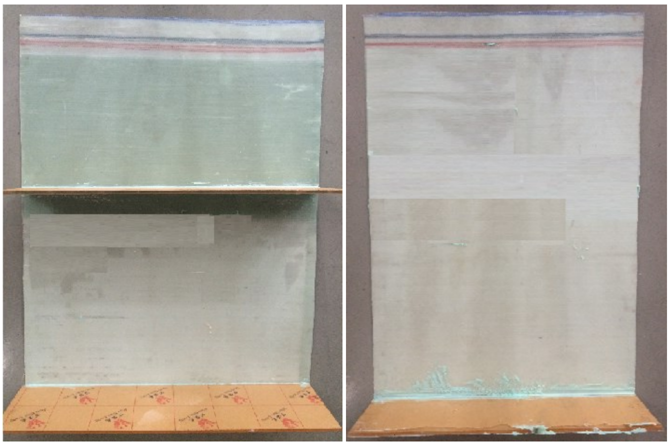
**Fig. 2 Blade structure**

In the impulse voltage experiments, the blade was simplified into an F-structure with only one web (the one in the main beam position) and L-structure without web, and there is also another baffle stuck to the back glass fiber to hold back the arc path developing along the inside surface of the blade materials. Samples simulating different parts of the blade are shown in Fig. 3. The layers of the glass fiber was reduced to 1/2 of the real one considering the limits of the voltage generator, as can be seen in TABLE Ⅰ (for the sandwich structure, there are 2 layers of glass fiber in all, and only one in each side). Sample

A shows blade structure a little far from blade top which has PVC sandwich structure; when it gets closer to the top, PVC disappears, only was glass fiber cover left in its initial position as shown in b). Layers of back edge and main beam reduce gradually; layers of back glass fiber and main beam reduced to the same number as the cover in c) and d) finally. Web also disappears at last in Sample D. The whole size of all samples is 80cm× 99cm, the width of each part are 10cm, 42cm, 35cm, and 12cm respectively (up to down). 99cm was set to simulate a real blade used in a 3 MW wind turbine, and 80cm was to leave enough space to achieve breakdown of blade materials instead of surface arc developing along the cutting edge. To evaluate dimensions *vs* results, smaller samples named E, F, G and H with size of 80cm× 49.5cm were made for comparative analysis.



**a) Sample A (with PVC)** **b) Sample B (removed PVC)**



**c) Sample C(removed back glass fiber)** **d) Sample D (removed main beam and web)**

**Fig. 3. Experimental samples**

TABLE Ⅰ

GLASS FIBER LAYERS OF SAMPLES

| position | main beam | back edge | sandwich structure (cover) |
|---|---|---|---|
| sample A | 7 | 4 | 2 |
| sampleB | 5 | 3 | 2 |
| sample C | 4 | 2 | 2 |
| sample D | 2 | 2 | 2 |

## 3 Experimental Methodology

### A. Experiment on Puncture Position on Wind Turbine Blade

Both experiment A and experiment B were conducted in the State Key Lab of Alternate Electrical Power System with Renewable Energy Sources in North China Electric Power University. Experimental setup A is shown in Fig. 4. Samples were supported to 50cm high by a wood desk. The upper electrode connected to the generator was cylinder with a diameter of 1cm, and the lower electrode stuck on the web was connected to ground to simulate the grounding line in blade.

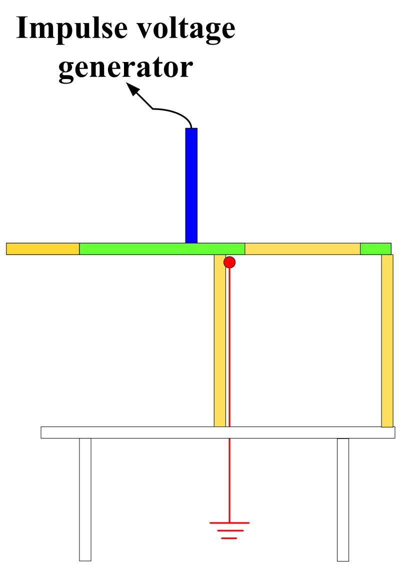



**Fig. 4. Experimental setup A**

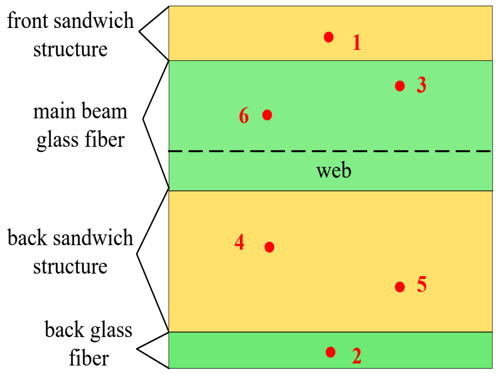
Impulse voltage experiments were conducted with different voltage peak values (with time to peak

1.2μs and decay time to half value of 50μs), voltage polarities, electrode positions and surface moisture. Experimental conditions are shown in TABLE Ⅱ (the upper electrode position is shown in Fig. 5). Compared with 6 electrode positions for lager samples, only 4 electrode positions were chosen for comparative analysis considering the limited space.

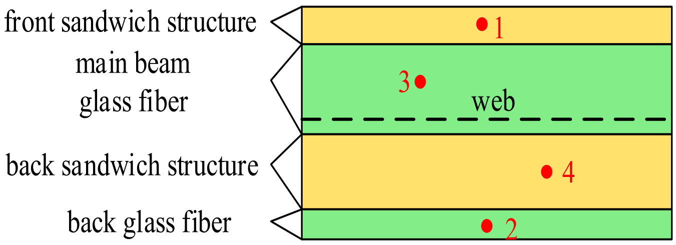
**TABLE Ⅱ**

**EXPERIMENTAL CONDITION OF EXPERIMENT A**

| Type | Condition |
|---|---|
| voltage peak value | initial breakdown voltage to 500kV |
| voltage polarity | negative, positive |
| electrode position | 1,2,3,4,5,6 |
| surface moisture($g/cm^2$) | 0, 0.06 |




**a) Upper electrode positions of larger samples**




**b) Upper electrode positions of smaller samples**

**Fig. 5 Upper electrode positions for experiment A**

**(Electrodes of samples without PVC and thick glass fiber were also located in corresponding positions)**

B. Experiment on Inside Arc Path

Since the weak areas were revealed in experiment A, the inside arc paths under different puncture positions were studied in experiment B, and setup is shown in Fig. 6. Blade materials were drilled in electrical weak areas, and the upper electrode was set to pass through the hole. The lower electrode was still connected to the grounding conductor, but it has a specific distance from the material surface to simulate the real blade structure.

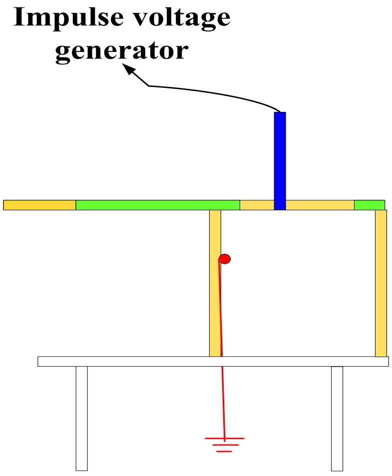



**Fig. 6 Experimental setup B**

Impulse voltage experiments were conducted with different voltage peak values, voltage polarities and electrode positions which are shown in TABLE Ⅲ (the electrode position is shown in Fig. 7). Fig. 7 involved different puncture positions even for smaller samples, so its results could be applied both in larger and smaller samples.

**TABLE Ⅲ**

**EXPERIMENTAL CONDITION OF EXPERIMENT B**

| Type | Condition |
|---|---|
| voltage peak value | initial breakdown voltage to 500kV |
| voltage polarity | negative, positive |
| upper electrode position | 1,2,3,4 |
| grounding electrode position(cm, to the blade material) | 0,6,12 |

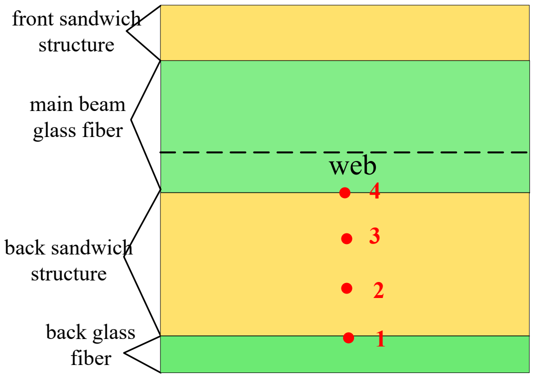


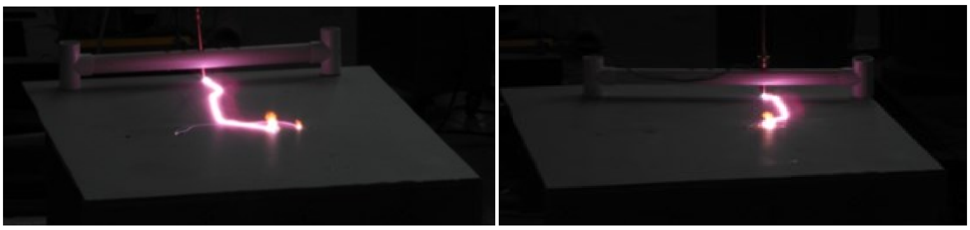

**Fig. 7 Upper electrode positions for experiment B**
**(Electrodes of samples without PVC and thick glass fiber were also located in the corresponding positions)**

## 4 Experimental Results

A. Experiment on Puncture Position on Wind Turbine Blade

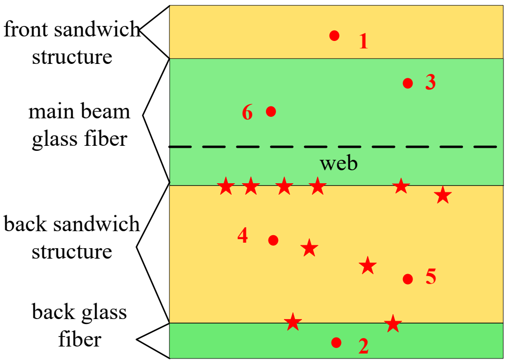
1) Surface arc path and puncture points distribution

All the breakdown paths consisted of surface arc and arc inside the materials, as are shown in Fig. 8 (breakdown at the end of the arc). In some cases, there were more than one arc path in a single experiment. But there were no obvious evidence for the connection between the multi-paths phenomenon and the experimental conditions.

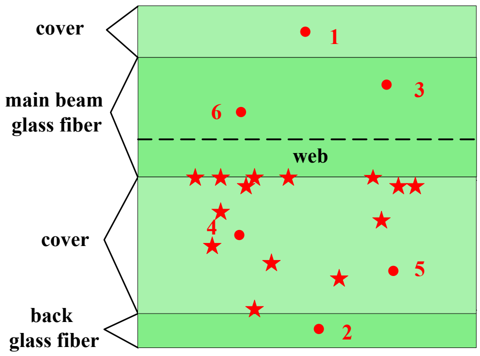


**a) Point 1, 340kV, negative(sample A)** **b) Point 2, 350kV, negative(sample B)**
**Fig. 8 Surface arc path**

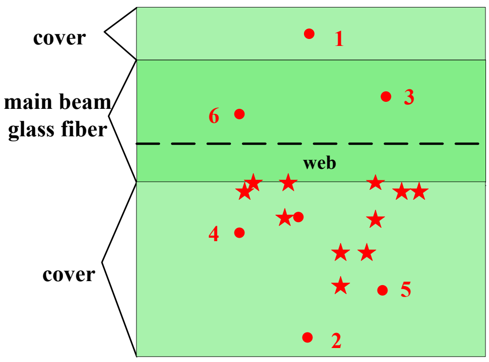
Since the breakdown voltages of sandwich structure and thinner glass fiber cover were much lower than the thick main beam and back glass fiber, all puncture points gathered in the back sandwich structure or lower cover for the larger samples, as is shown in Fig. 9. In the case of smaller samples, nearly all the puncture points fell near the intersection between main beam and back sandwich structure (or lower cover). There is only one puncture point fell inside cover area near electrode position 2 in sample G. All the puncture points gathered on the intersection area for the small samples, and the influence of voltage types and environmental humidity is not obvious. So the roles of polarities, peak values, surface humidity and electrode positions will not be introduced for smaller samples in the following parts.

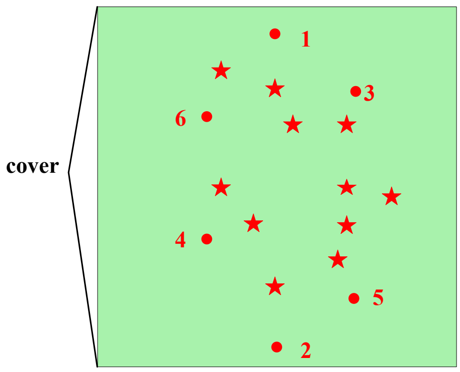



a) Sample A




b) Sample B



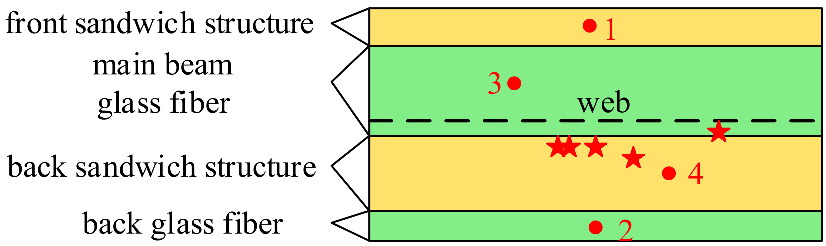




c) Sample C

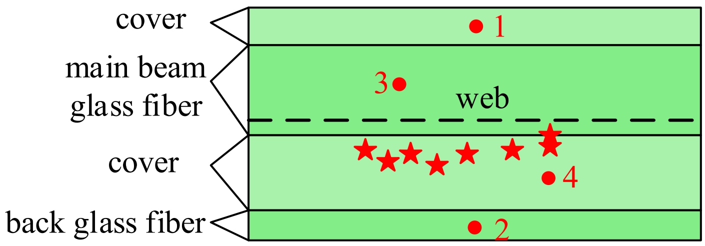
d) Sample D

**Fig. 9. Puncture points distribution of larger samples**

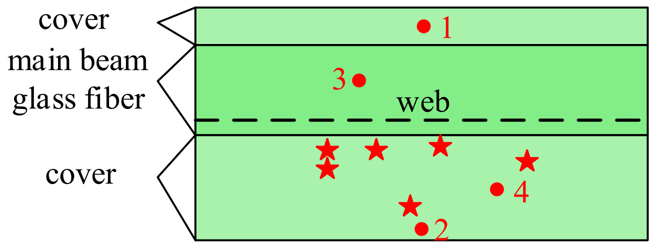
**(Red star is puncture position, and red dot is upper electrode position)**



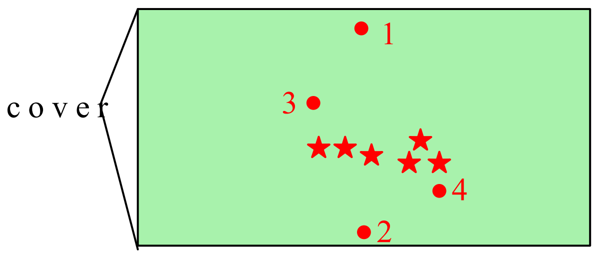

**a)sample E**




**b)sample F**




**c)sample G**

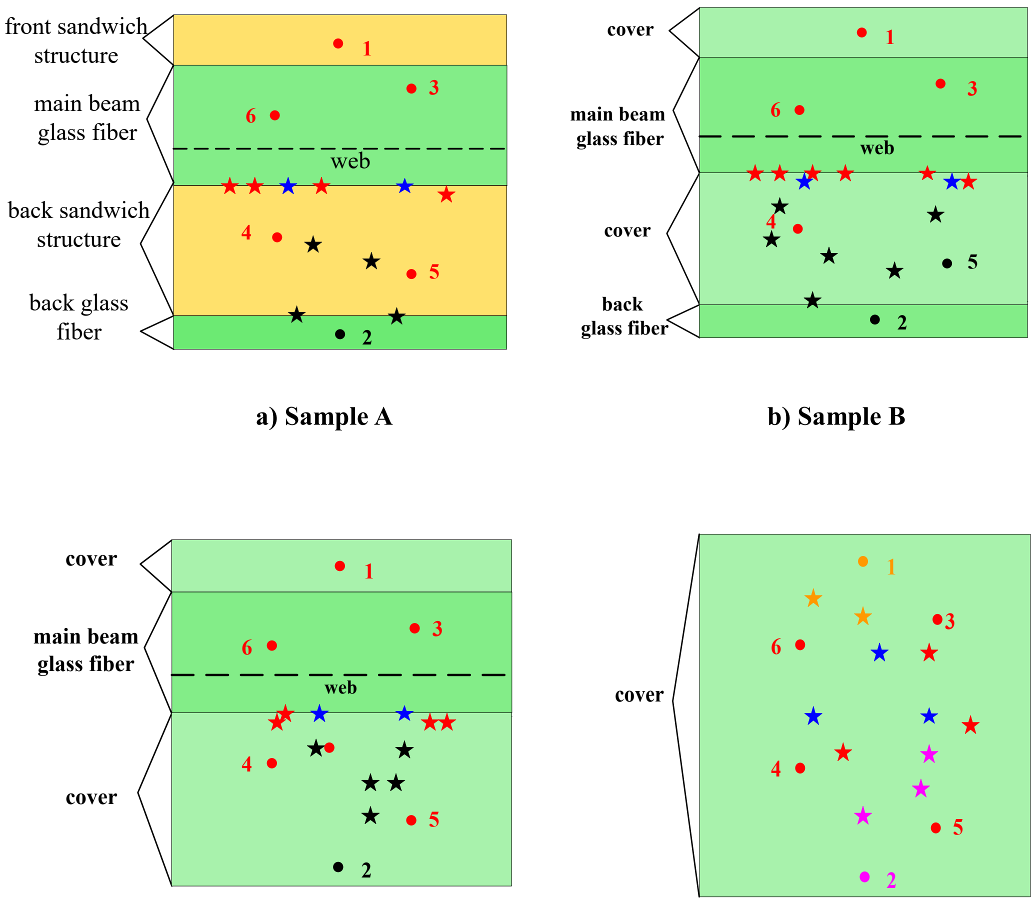



**d)sample H**

**Fig. 10. Puncture points distribution of larger samples**

2) Influence of upper electrode position

Puncture position changed with the upper electrode location in the case of larger samples, as is shown in Fig. 11. When the electrode was put on position 2, it intended to breakdown in the back sandwich structure (or lower cover). Also a few of puncture points fell on the intersection between back glass fiber and back sandwich (or lower cover). However, most puncture points fell near the intersection between main beam and back sandwich (lower cover) when electrode was put in the other positions. For the case of sample D, puncture points distributed on the whole materials because all the structure was made of only two layers of glass fiber.



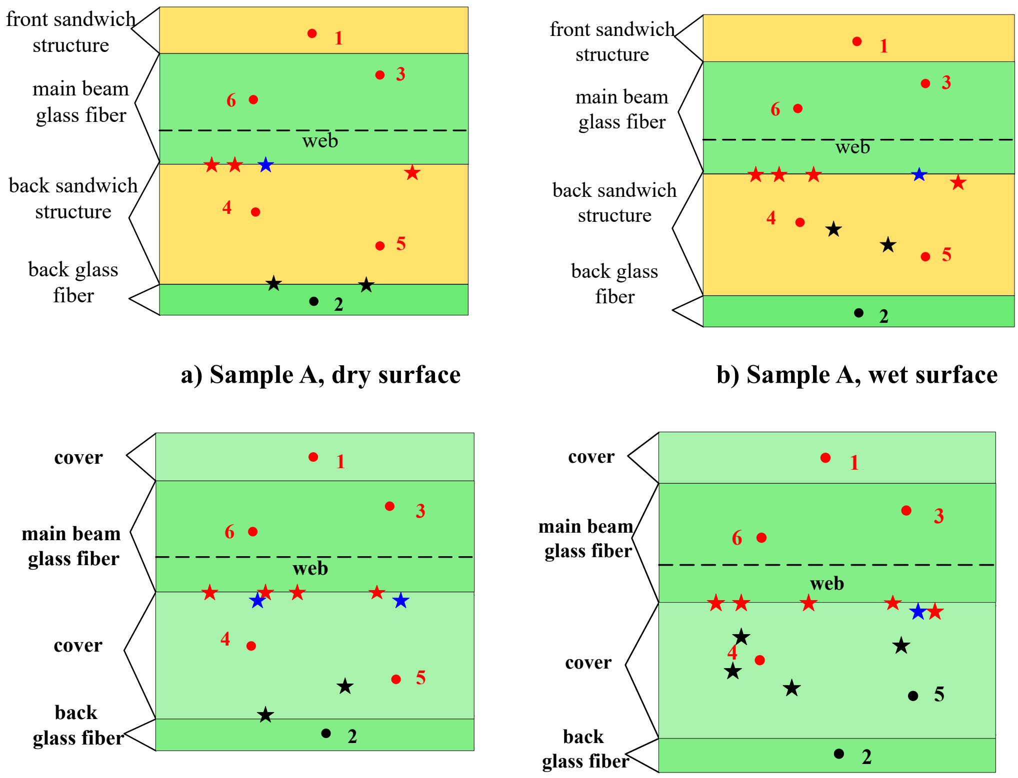

**a) Sample A** **b) Sample B**

**c) Sample C** **d) Sample D**

**Fig. 11. Puncture points distribution under different electrode positions of larger samples (The star color is in accordance with its corresponding dot color, and the blue stars are the common puncture points for electrode in different positions)**

3) Influence of surface humidity

Surface humidity had significant influence on the puncture position distribution, as can be seen in Fig.12. When the surface was dry, all the breakdown occurred in the intersection line between main beam and the back sandwich (or cover area). However, the inside sandwich areas easily got breakdown when water was sprinkled on it. What was more, the breakdown voltage was much lower when the surface was wet.




a) Sample A, dry surface b) Sample A, wet surface

c) Sample B, dry surface d) Sample B, wet surface

**Fig. 12. Puncture position distribution under different water moisture**

It can be supposed that when sprinkling water on the blade surface, surface flashover voltage decreased greatly and was easy to develop a longer distance [18-20]; what's more, since non-uniform water column formed on the surface, the electric field distribution was distorted; especially when a large amount of electric charges gathered in the water column, the electric field intensity increased to a high value even under a lower voltage, which caused breakdown of sandwich materials under a much lower voltage.

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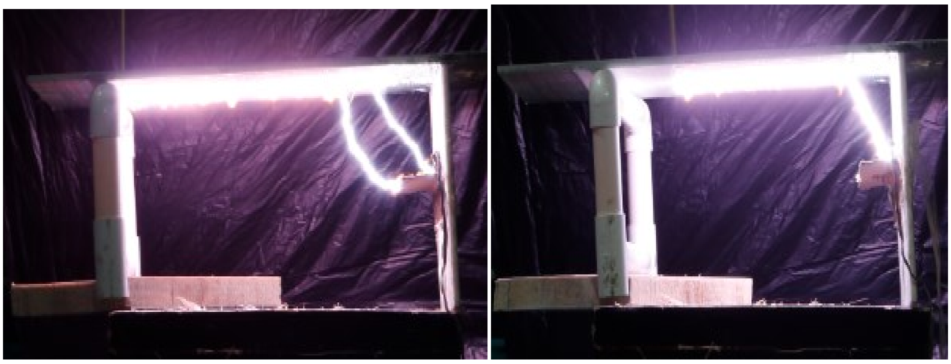
## B. Experiment on Inside Arc Path

According to the Experiment A, the sample D might get punctured everywhere on the blade. Since the webs disappear and the grounding line is stuck to the blade surface, the inside arc paths will always develop along the blade for sample D. So the paper does not introduce the inside arc path in this case. For the other samples, the experimental positions were set to 1,2,3,4 in Fig. 7.

1) Typical arc path

All the arc paths consisted of surface-arc and air-arc, as is shown in Fig. 13. In some cases, there were more than one arc path in a single experiment.

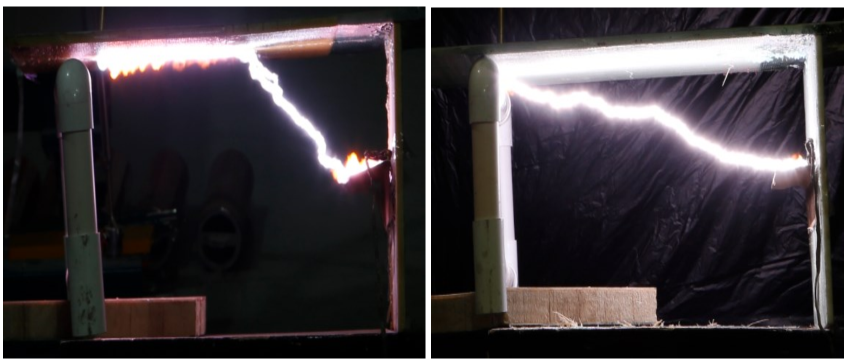


**a) Point 1, 400kV, negative** **b) Point 2, 500kV， positive**

**Fig. 13 Inside arc paths (grounding electrode 12cm)**

2) Influence of the voltage polarity

The initial breakdown voltage was obviously lower when positive voltage was applied. It can be seen in Fig. 14 that, when negative voltage was applied, arc intended to develop along the material surface, while air arc occupied a larger portion in the positive voltage experiments. As is known that positive breakdown voltage of air is much lower than negative one. So it is supposed that in the competing process of all arc paths, the air arc has a higher possibility to get a successful development under positive voltage. The statistics of surface arc length is shown in TABLE ⅣVand TABLE Ⅴ.



**a) Negative voltage b) Positive voltage**

**Fig. 14 Arc paths under different voltage polarity**

**(Point 1, grounding electrode 12cm, 360kV)**

**TABLE Ⅳ**

**SURFACE ARC LENGTH UNDER NEGETIVE VOLTAGE (average value, cm)**

| Grounding electrode distance | 12 | 6 | 0 |
|---|---|---|---|
| 1 | 37.2 | 39.4 | 42.5 |
| 2 | 21.6 | 23.7 | 30.8 |
| 3 | 12.3 | 15.4 | 19.2 |
| 4 | 6.7 | 6.7 | 7.5 |

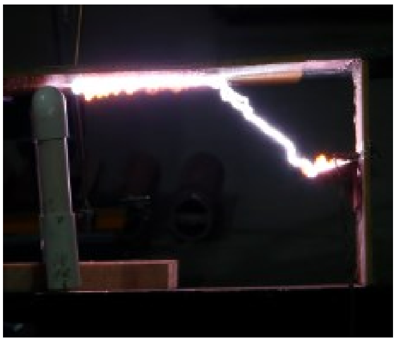
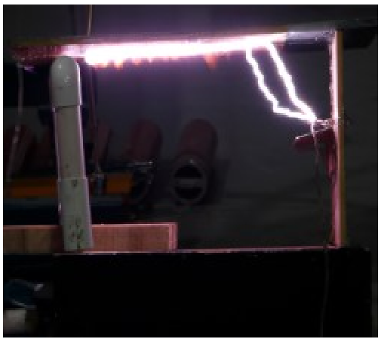
**TABLE Ⅴ**

**SURFACE ARC LENGTH UNDER POSITIVE VOLTAGE (average value, cm)**

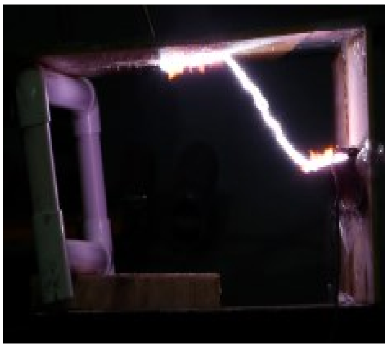
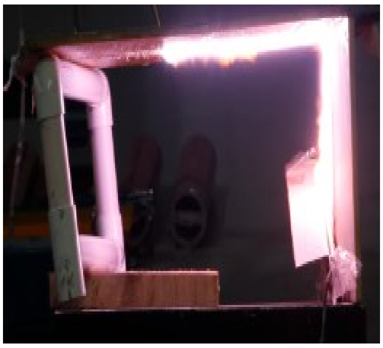
| Grounding electrode distance | 12 | 6 | 0 |
|---|---|---|---|
| 1 | 25.3 | 37.8 | 42.5 |
| 2 | 19.1 | 22.1 | 30.8 |
| 3 | 3.5 | 8.4 | 19.2 |
| 4 | 0.5 | 0.7 | 7.5 |

3) Influence of the voltage peak value

As can be seen in Fig. 15, the inside arc consisted of surface-arc and air-arc. The arc intended to go through air when the peak value was lower, but it intended to go along the surface (take the negative voltage experiments for an example) when the peak value increased. One possible theory can explain this phenomenon: when larger impulse voltage was applied, a huge vertical component of electrical field intensity made the charged particles impact the blade material strongly. The impact resulted in temperature increasing near the blade surface, which in turn leads to gas thermal ionization. This process accelerated the arc developing along the blade surface [21].

**a) Point 1, 360kV** **b) Point 1, 440kV**

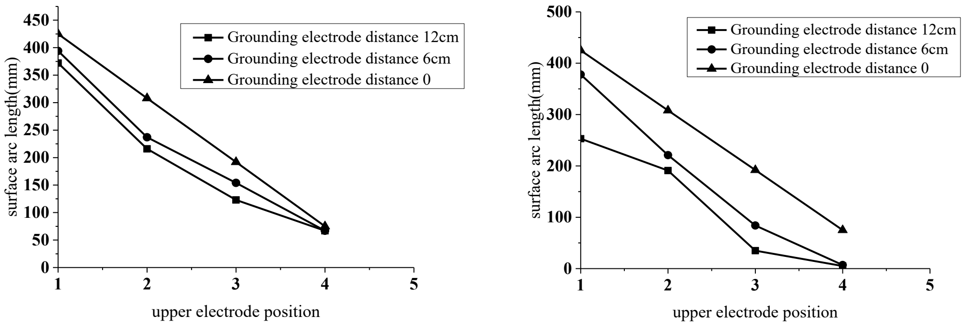
**c) Point 2, 280kV** **d) Point 2, 500kV**


**e) Point 3, 240kV** **f) Point 3, 440kV**

**Fig. 15 Arc paths under different peak value of applied voltage (Grounding electrode position 12cm)**

4) Influence of the electrode position

Puncture position definitely influence the art paths, as is shown in Fig. 16. As the upper electrode got nearer to the web position and the grounding electrode went far away from the blade materials, surface arc length decreased gradually. The arc types (air arc or surface arc) and arc length may have different damage to the blade.




**a) Surface arc length under negative voltage    b) Surface arc length under positive voltage**

**Fig. 16 Arc paths under different electrode positions**

## 5 Conclusion

Impulse voltage experiments were conducted to study the weak areas and inside arc paths under different voltage parameters, surface humanity, and puncture position. Conclusions can be obtained that:

(1)Back sandwich position(or the glass fiber cover), especially the area near its intersection with main beam is the weakest field easy to get lighting strikes, so measures should be taken to strengthen its electrical properties.

(2) For the samples with PVC sandwich structure, the blade width is relatively larger and the grounding line is far away from the blade surface, so arc paths with different sizes and types were observed. It will generate rather long surface arc or air arc, especially when it punctures near the back glass fiber.

(3) When it gets closer to the blade top, the blade width, as well as the distance between grounding line and blade surface, is getting smaller, so most arc paths are shorter surface ones.

(4)Although there are less positive lightning than negative ones, but positive lightning voltage usually has much higher peak value. Since the positive breakdown voltage is lower than the negative ones, the positive lightning strikes are much more severe. In addition, as can be seen in the experiments' results, heavy surface water moisture reduces the breakdown voltage of the sandwich materials significantly, which would be a huge threat for the blade safety under lightning strikes.

**6 Acknowledgement**

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