Chapter

Examination of Lightning-Induced Damage in Timber

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Abstract

The ancient Chinese architectures were constructed using timber as the main building material. Considering that the lightning strike is the primary natural cause of damage to ancient building, the lightning strike damage mechanism of ancient building timber and the related influencing factors are investigated using the representative timber materials from the ancient building. The burning of timber was mainly caused by the heat of lightning arc. The splitting and damage pit of timber were mainly caused by the mechanical force generated by the temperature rise of the injected by lightning current and air shock wave effects of the lightning. These ways all played in different roles under different conditions. The higher the water content of timber was, the easier it was to crack, and the greater the damage depth and the larger the damage area were. It was easy to burn for the dry timber or the loose timber with low density, but it was difficult for the thick timber. When the wood was too thin, the lightning air shock wave could cause damage. This research may provide reference for protection of ancient timber architecture from possible damage caused by lightning.

Keywords: timber, ancient Chinese architecture, lightning strike, water content, fire

1. Introduction

1.1 The timberwork in ancient Chinese architectures

Ancient Chinese architectures have a unique contribution to the world architectural heritage and is part of the three largest global building systems, along with European and Islamic architectures [1]. Ancient Chinese architectures with thousands of years of culture and art have important historical, cultural and artistic values. At the same time, ancient Chinese architectures are an important national human tourism resources and precious cultural heritage, which are irrecoverable. A large number of precious ancient building relics are preserved in China. There were a total of 5,058 national key cultural relics protection units in 2019, including 2160 ancient building relics, accounting for 42.7%, nearly half of the total. It is of great significance to protect these ancient architecture and strengthen the safety for the continuation of ancient Chinese civilization. So the safe protection of these ancient buildings is very important. Preventing the destruction of ancient building by natural disasters, especially protecting ancient building from lightning damage, is an important task of ancient building protection [2].

Timber is widely used as the main building material for most of the ancient Chinese architecture, with the roof trusses of timberwork, such as beams, columns, buckets, arches, purlins, rafters, windows, and other components. As shown in **Figure 1(a)**, the

Sakyamuni Pagoda of Fogong Temple in Shanxi Province with the height of 67.31 m and the bottom diameter of 30.27 m is the highest timber pagoda in the world. The Sakyamuni Pagoda, the Leaning Tower of Pisa and the Eiffel Tower in Paris are known as the "Three Wonders Towers of the World". Generally speaking, ancient architecture shows a per square meter of construction area with 1 m^3 of timber, which is somewhat greater than the timber standards used in modern architecture (not greater than 0.03 m^3). In the Palace Museum in Beijing, one of the largest and best preserved ancient timber architectures in the world, all the palaces are made of timber with about 2 m^3 of timber for a per square meter of construction area, which is shown in **Figure 1(b)**.

The main reason for the heavy use of timber is that the timberwork has the advantages of material and structure. In China, it is easier to obtain many kinds of timber from local areas, and people are good at the process of timber. Compared with stone materials, timber is light with high toughness and good flexibility, which could be widely used in palaces, temples, towers and so on. And even the bracket joint and tenon-and-mortise connection structure, as shown in **Figure 1(c)**, are used in the joint of the timberwork, which increases the toughness of the timber structure. **Figure 1(d)** shows that, in the aspect of structural mechanics, the distinction and cooperation between the load-bearing part and the non-load-bearing part of the timberwork increase the stability and flexibility for the timber frame structure. So the timber structure is widely adaptable which can exist in different forms of buildings in the south and north of China where the climate conditions are significantly different.

However, under the condition of ancient construction, it is difficult to deal with the timber by anti-corrosion and fire prevention technology, which makes it difficult to preserve the ancient architecture. Timber in the ancient architecture is prone to fire, which is the fatal defect of timberwork. In particular, the burning caused by lightning is very dangerous because it is difficult to control and prevent. The material of timber is an organic matter composed of cellulose and lignin, and its main chemical components are carbon, hydrogen and oxygen. Most of ancient

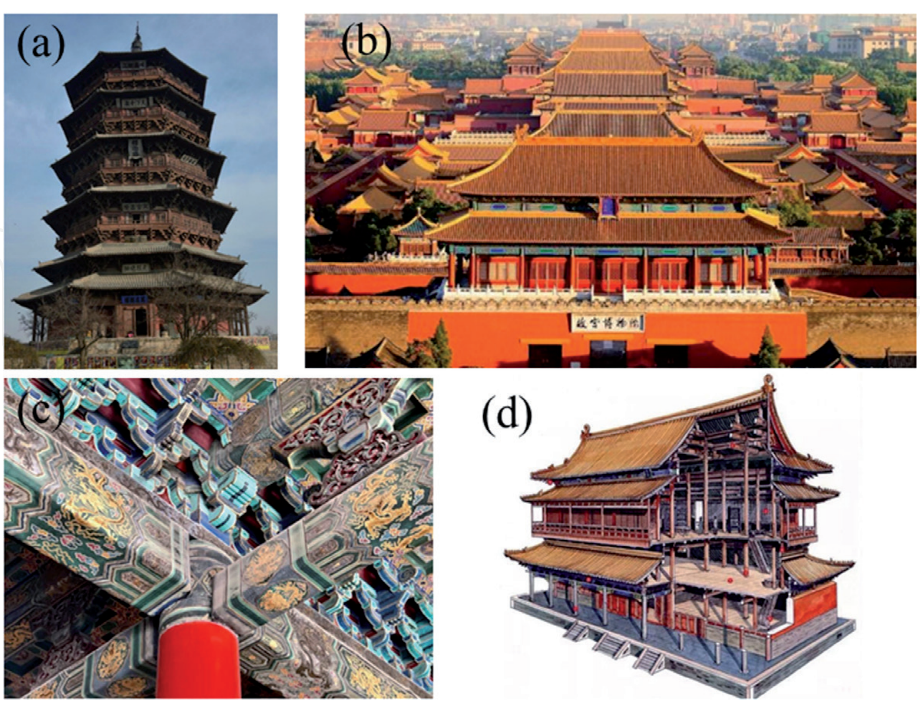

Figure 1.
(a) The Sakyamuni Pagoda of Fogong Temple in Shanxi Province built in 1056 is the highest timber pagoda in the world. (b) The Palace Museum in Beijing with the history of 600 years is one of the largest and best preserved ancient timber architectures in the world. (c) The bracket joint and tenon-and-mortise connection structure in the Palace Museum in Beijing. (d) The diagram for the timber framework with load-bearing part and the non-load-bearing part ((d) from the Internet).

architectures used high quality timber with high oil content, such as pine, cypress, camphor, nanmu, etc. The timber of ancient building have experienced long histories of possibly hundreds of years, so the moisture content of the timber is far lower than that of the normal dry wood (normal value of 12% - 18%), but the oil content is still very high. Furthermore, the timber in ancient architecture becomes rotten and loose in texture, so it is easier to burn after being struck by lightning.

In addition, the layout of ancient architecture with high building density emphasized the balance and symmetry of architectural design. And the form of "courtyard" and "courtyard house" are always adopted, which results in the lack of fire separation and enough safety space. If one of them is struck by lightning, it is easy to spread horizontally, which results in the burning for all of them. Moreover, this kind of structure characteristics also makes it difficult to put out the fire for the ancient architecture.

Due to the material, structures and other characteristics of ancient architecture, events such as lightning-induced fires or lightning strike damage occasionally occur [3, 4]. **Figure 2(a)** shows that, on August 27, 1987, the Jingyang Palace of the Palace Museum in Beijing was caught fire after struck by lightning and the hooks on the timber fell off, causing the plaque to fall to the ground. In the summer of 1992, the Xianling Building of Ming Tombs in Beijing was completely burned by lightning. **Figure 2(b)–(d)** show that, on May 11, 2004, the Great Buddha Temple in Shanxi Province was directly struck by lightning, resulting in a fire, and some buildings and important cultural relics were destroyed. On August 2, 2005, the Dragon Pavilion of Baiquan scenic spot in Henan Province was completely destroyed because of fire after being struck by lightning. On August 11, 2008, the Buddhist Sutra of Chongning Temple in Jiangsu Province was destroyed partially on fire caused by lightning strike.

Most ancient buildings are nationally important cultural tourism resources, as well as precious cultural heritage sites with irrecoverable properties. The timber of ancient buildings is easy to burn after lightning [5], which leads to the rapid and complete disappearance of many specimen components with historical information. At the same time, after lightning damage, the mechanical support performance of timber decreases, which brings hazards to the safety of the overall structure of ancient buildings. Thus it is of great significance to investigate the causes and ways of lightning damage to the ancient buildings timber.

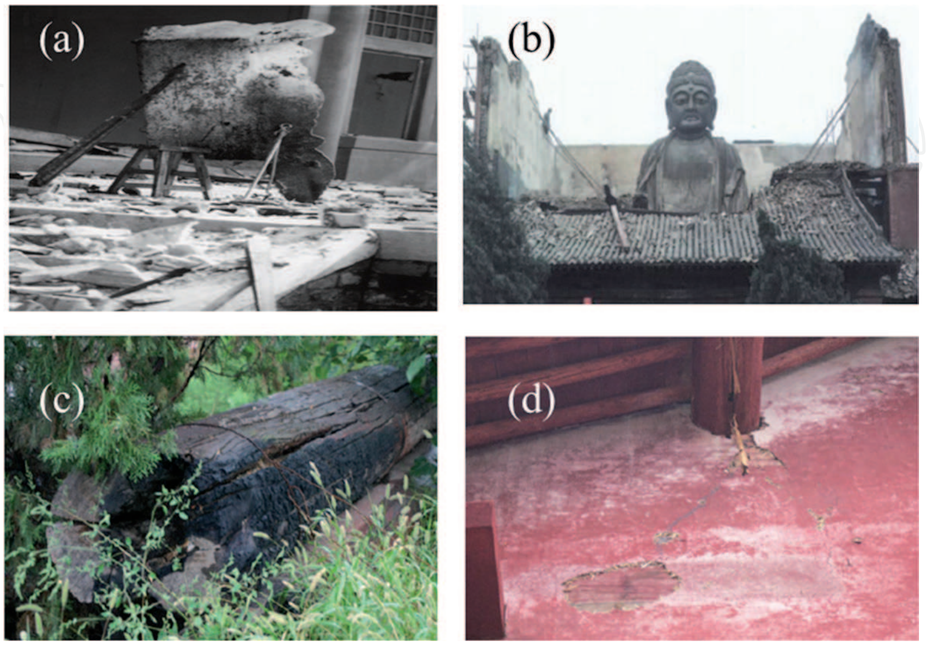

Figure 2.
(a) The Jingyang Palace of the Palace Museum in Beijing after the lightning strike in 1987. (b), (c), (d) The Great Buddha Temple in Shanxi Province after the lightning strike.

1.2 The research process of the lightning strike

At present there are few research results on the damage caused by lightning to the ancient buildings timber. In addition, previous studies on lightning damage and destruction mainly focused on artificial composite materials, metal objects or lightning forest fire. The direct damage effects of lightning currents on graphite and epoxy composite laminates were studied experimentally, and the change laws of the fiber damaged areas, and the maximum damage thicknesses over the electric charge quantity, current peak value, and action integral were analyzed by Hirano et al. [6]. The combustion damage of carbon fiber composites caused by lightning stroke and the residual strength after lightning strike are theoretically analyzed and numerically simulated by Wang et al. [7]. Furthermore, they also conducted lightning impulse tests on the composite materials [8]. The experimental results showed that the high potential, temperature and thermal stress generated at the moment of lightning strike mainly expand symmetrically along the maximum direction of conductivity at the top of the composite.

In the research of forest fire caused by lightning, a small lightning fire simulation experimental platform with local forest combustibles as experimental materials was built firstly by Latham et al. to obtain the ignition probability logistical equation of different combustibles [9]. A lightning test bench to calculate the energy for lightning-induced inflammable ignition was also developed by Darveniza et al. [10]. The discharge process of ground lightning using an indoor artificial arc was simulated by Zhu et al., in order to analyze the continuous discharge time and inflammable water content, along with the structures influencing the ignition during lightning-induced forest fires [11]. The conditions of lightning-induced forest fires were examined in accordance of the formation and development of lightning and its energy and power [12].

As for lightning and metal objects, Metwally used a long-duration current component after a lightning strike and a simulated lightning voltage with a waveform of 1.2/50 μs to analyze lightning-strike metal damage [13]. A simulated lightning current with a waveform of 10/350 μs was adopted to investigate the heating properties of lightning-strike round metal conductors by Paisios [14]. Considering that the damaged area largely depended on the lightning current amplitude and the damage depth mainly depended on the transferred charge, Liu et al. also conducted an experimental study on lightning damage to metal storage tanks using impact current with the waveform of 30/80 μs [15]. In addition, Mi et al. performed lightning current-induced round steel damage experiments, and the results showed that the high temperature effects of lightning arc discharges would cause damage to metal structures [16]. These studies have positive reference significance for the study of the lightning damage mechanism of ancient building timber.

2. Experimental method and equipment

The action mechanism of lightning damage to the ancient building timber is known to be complicated. In this study, according to the recommendation by the standard of IEC 62305-2010, an indoor lightning simulation device using a 10/350 μs first-lightning current waveform was adopted, along with the representative timber materials of ancient buildings. The lightning damage mode and influencing factors for the ancient building timber were examined. Based on the timber properties and lightning current parameters of the ancient buildings, the relationship between the lightning damage effects on the ancient building timber and the water content and thicknesses of the ancient buildings timber was analyzed, as well as the influence of lightning current on the lightning stroke. The thermal effect of lightning on ancient building components and the energy dissipation mode at lightning strike point were studied to reveal the lightning-induced timber damage mechanism and characteristics, which could provide guidance and reference for protection of ancient buildings from future damage caused by lightning.

Figure 3 shows the schematic diagram for the experiment of the lightning strike timber in this study. A waveform generator was firmly connected with Screw 1 and Screw 2, which were respectively inserted into the end of an ancient building timber board. The distance was about 100 mm for the two screws connected by 1.25 mm- diameter copper wire, which was placed into the 1.5 mm-deep groove and then fixed by insulating tape. One end of the copper wire was firmly connected with Screw 1, and the other end was kept at a certain distance from Screw 2, so as to generate arc discharge in the discharge process according to the action process of lightning effect. A larger space could be set with the increase of the impulse voltage. In order to ensure the safety of the experimental process, Screw 2 was well grounded and a grounding rod was used to release the residual current of the experimental device for each experiment.

Figure 4 shows the waveform generator (GTPS30-20kV, GrandTop Eletric, China) which is used to produce 10/350 μs of direct lightning current waveform with a maximum of 25 kA. The experimental current range was about 10 kA to 20 kA. Because the lightning hitting the timber was not generally the lightning induced wave, a 10/350 μs direct lightning current waveform was selected. Another reason is that there is no changes for the timber surfaces in the case of the selected 8/20 μs induced current waveform. The electrical generator mainly includes a charging device, a capacitor unit, a controllable trigger discharge device and a control system. The current voltage and charge–discharge state are displayed on the screen in real time. The digital fluorescent oscilloscope of a lightning current waveform (DPO3054, Tektronix, USA) can not only precisely display the lightning current peak, wave front time, transfer electric charge and other parameters, but also directly store the lightning current waveforms. In addition, a video camera was used to record the entire process of the lightning strike. For the experiment carried out in Beijing Lightning Protection Device Test Center, the temperature was 26 °C - 28°C and the relative humidity 42% - 45% in the laboratory with altitude of 32.5 m.

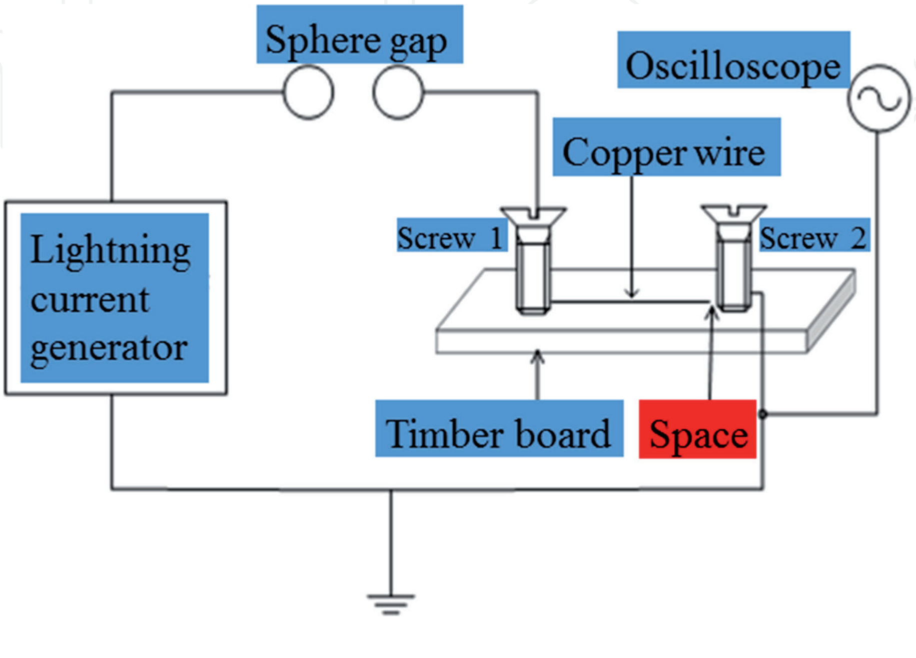

Figure 3.
The schematic diagram for the experiment of the lightning strike timber.

Figure 4.
The multi-waveform lightning generator with the voltage of 20 kV.

Just as shown in **Figure 5**, a voltage divider (PSURGE6.1, HAEFELY, Switzerland) with a 1.2/50 μs voltage wave was connected with timber, which was used to obtain firstly the specific value of the breakdown voltage of the timber as well as the spacing between the copper wire and Screw 2. In this experiment, ancient building rafters and sheathing components (white pine and yellow-flowered pine) were selected as the specimen and the moisture content of timber ranged from 30% to 55% changed by spraying. The timber surfaces were relatively rough with burrs because of the natural aging caused by long-term exposure to sun, wind, and rain. In the test of different water content and different current intensities, the thicknesses of the timber boards with the same material was kept at 20 mm. When assessing the damage to the board with the same material of yellow-flowered pine, the boards with thicknesses of 10 mm, 20 mm, 30 mm, and 40 mm were selected, just as shown in **Figure 6**, which were removed from the ancient building for maintenance. Each board had only one discharge position which was the same for each experiment.

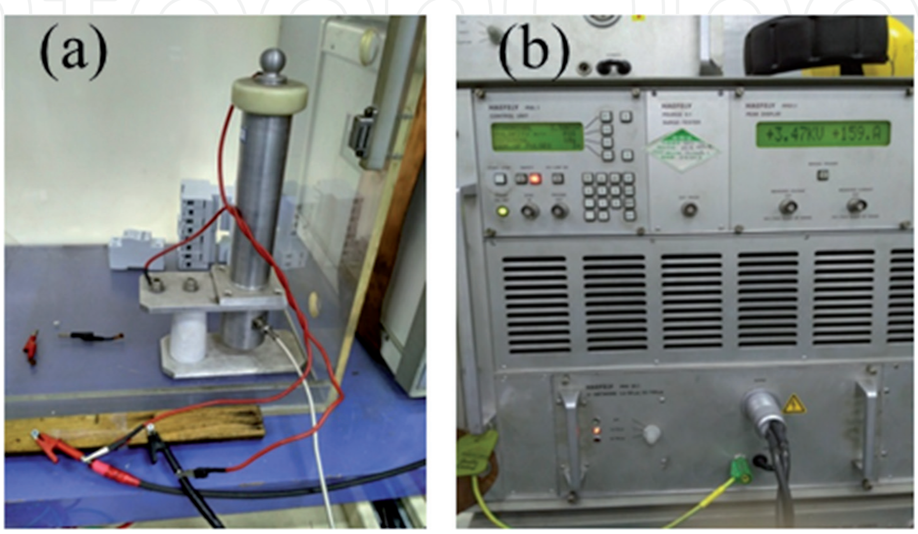

Figure 5.
(a) The diagram for the connection of the voltage divider with timber. (b) The operation interface of the voltage divider.

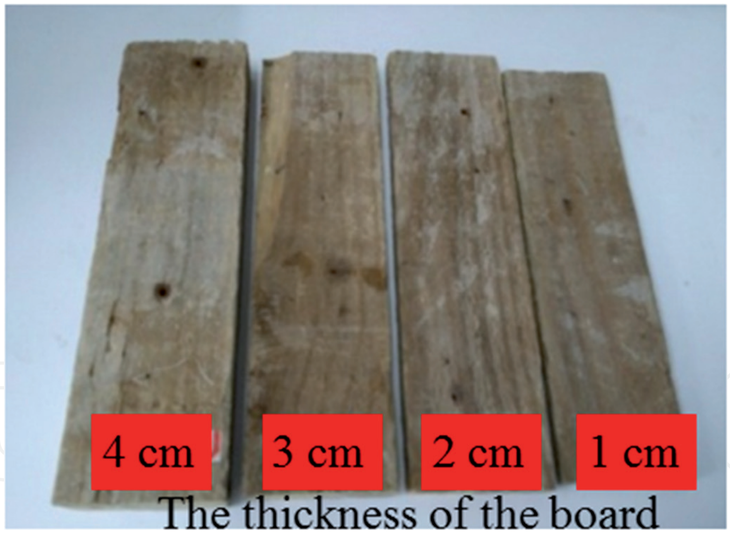

Figure 6.
The timber board of ancient building with different thicknesses.

3. Experimental results and analyses

Lightning may directly strike the timber artifacts of ancient buildings (architraves, beams, windows, brackets, and so on) if there is no lightning protection systems for the ancient buildings. In the cases there is lightning protection systems but the protection is not perfect, lightning may strike the parts beyond the scope of the protection [3]. Especially when the eaves or sheathing have become wet due to thunderstorm conditions, lightning may directly strike the eave rafters or sheathing of ancient buildings, which is shown in **Figure 7**. In this study, the damage of lightning strike to ancient building timber were studied.

3.1 The experimental phenomena for the process

Figure 8 shows the process for the timber after the lightning strike within several tens of milliseconds. For the experiment, capacitance charging was first conducted on lightning impulse equipment, and then an automatic triggering of the switch produced, which simulated a thunder-release lightning current. At that moment, as shown in **Figure 8(a)**, a strong white light instantly appeared and then disappeared, along with the sound of a loud explosion ("pow!"). And even the door of test bench where experimental specimens were placed was burst through. The white light instantly appeared and then disappeared quickly, which was the simulated lightning. Followed by the white light, there were a large amount of dazzling scattered sparks near the surface of the timber, which is shown in **Figure 8(b)**. After that, the combination of **Figure 8(c)** and **Figure 8(d)** shows that the brightness of sparks slowly weakened and its number slowly decreased. Based on the preliminary analysis, after lightning struck the timber, the timber skin would first be shattered into many tiny timber chips, which was followed by the lightning arc igniting the timber chips or the timber surface burrs. So, as shown in **Figure 8(b)**, a lot of sparks were induced. From the surface of the copper wire between the two screws, it could be seen that the surface of the copper wire was blackened, and there were black substances attached to it, which were the components decomposed by high temperature of the timber and the adhesion of carbonized substances. At the same time, the end of the copper wire near the screw 2 is etched with a sharp tip. Meanwhile, if the space (seeing the red mark in **Figure 3**) was zero, which meant that the copper wire was connected with to Screw 2, the copper wire would melt

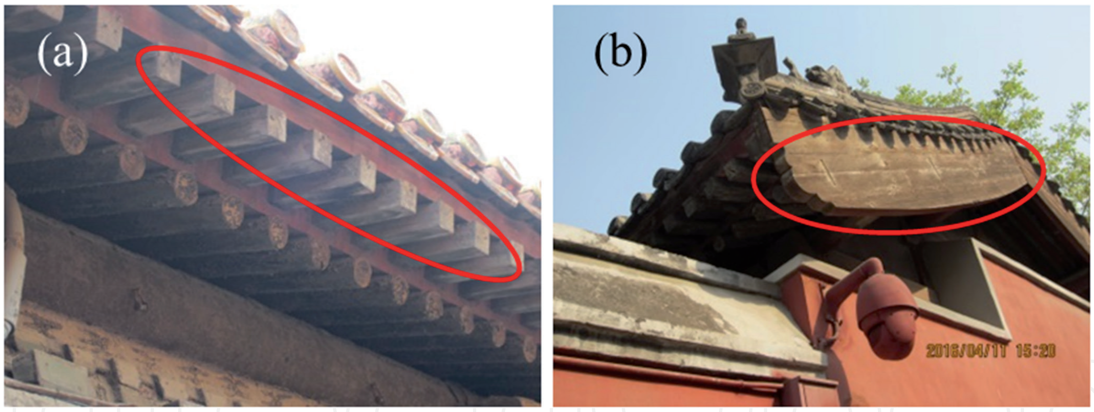

Figure 7.
The components prone to lightning strike for the ancient building timber. (a) the rafters and (b) the sheathing of Yangxin Hall in the Palace Museum in Beijing (the red ellipse locations highlighted in the figure).

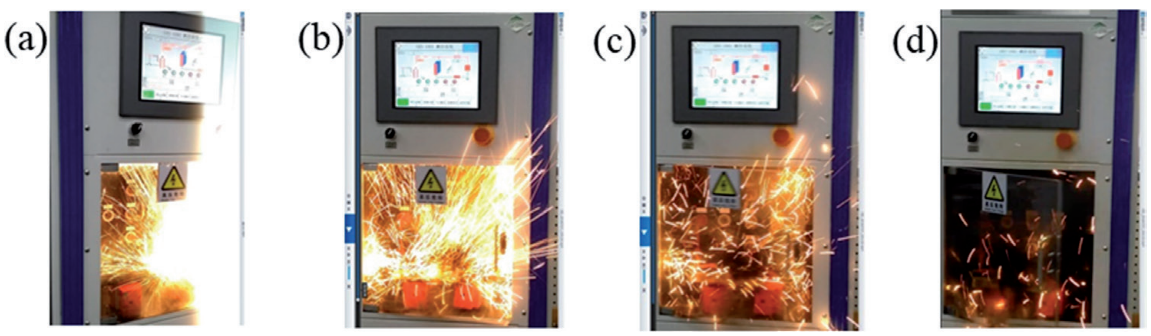

Figure 8.
The process for the timber being struck by lightning. (a) A strong white light instantly appeared and then disappeared quickly. (b) Then a large amount of dazzling scattered sparks near the surface of the timber. After that, the sparks slowly weakened and its number slowly decreased in (c) and (d). Each picture was separated by 10-20 milliseconds.

and crack into multi-segments. There were some burning spots on the surfaces of the timber after struck lightning. And even there were some cracks which affected the support strength of ancient building timber, or it was easy to get rotten or attract insects.

3.2 Effect of the water content on the timber after lightning strike

As the water content in the transverse direction is generally smaller than that in the longitudinal direction, the longitudinal direction is selected and the insertion depth of the water content tester (GM610, BENETECH, China) was kept at 2 mm in this experiment. During the measurement process, it was found that the water content of the same timber at different locations was not completely consistent, which was consistent with the actual situation of the ancient building timber. In thunderstorm weather, rain will pour on the rafters of the ancient building, and the timber water content may be uneven and variable. In order to solve this problem, the water content of the same timber at the lightning impulse position was measured three times and then the calculated average value was adopted. The water content of the ancient building timber was successively increased (about 5% each time) with the same thickness and material of timber. The lightning impulse results for the different water content are shown in **Table 1** and **Figure 9**. After the lightning strike, the position of the timber that was directly hit turned black and the water content obviously decreased with the evaporation of water. In addition, the tape used for

No.	Water content of the timber prior to impulse	Water content of the timber posterior to impulse	Timber state
1	32.3%	26.2%	Blackened burn marks; a square damage pit posterior to the impulse with a depth of approximately 3 mm, length of 8 mm, and width of 3 mm
2	37.8%	34.4%	Blackened burn marks; a quasi-square damage pit posterior to the impulse with a depth of 5 mm, length of approximately 12 mm, and width of 6 mm
3	42.2%	36.7%	Blackened burn marks; an elliptical damage pit posterior to the impulse with a depth of approximately 6 mm, length of 28 mm, and width of 8 mm
4	47.6%	38.1%	Timber surface is hit to an oblique cleavage (a length of approximately 55 mm); a strip damage pit occurred with a depth of 4 mm, maximum width of 10 mm, minimum width of 2 mm; and with obvious water evaporation in surrounding area
5	52.7%	38.8%	A long crack occurred along the timber fiber direction, with a depth of 20 mm (for example, an impulse crack), length of approximately 120 mm, and width of 3 mm

Table 1.
Timber state changes in the cases of different water content posterior to impulse (the thickness of 20 mm, the current of 20 kA).

Figure 9.
Impulse damage map of the timber with the water content of (a) 42.2%, (b) 47.6%, (c) 52.7%. (The red ovals represent the damage locations, and the red arrow faces toward Screw 2).

fixing the copper wire turned black due to high temperature. The instantaneous high current hits resulted in the elliptical damage pits or crack at its outflow position (i.e. at screw 2), of which the damage pits were commonly elliptical or square. With the increase of the water content, the hit damage pit or crack became deeper and the depth for the lightning current entering into the timber increased.

The timber board morphology after the lightning strike was used to observe the lightning damage. As shown in **Figure 9**, for the dry timber with low water content, it was easily burnt when encountering the lightning arc. And it was more likely to show damage pits or splitting for the timber with high water content. With the increase of the water content, the hit damage pit or crack became deeper and the depth for the lightning current entering into the timber increased. The reason might be that the energy conversion process at the contact between the lightning channel and the timber could be similar to the phenomenon of spark-gap arc heating, and the temperature of the lightning arc was very high, resulting in the burn marks on timber. However, due to the short action time, the energy was limited and the instantaneous high temperature might not ignite the timber. In the cases of low water content, the heating of the lightning struck timber was mainly decided by the arc heat based on the burning effect of lightning arc spark. Because of the poor electrical conductivity, the lightning current into timber with low water content was found to be small, and the heat was also very small. Although it is easy to ignite when the moisture content of combustible materials is low, it is difficult to ignite only by the arc temperature at the moment of lightning. However, when the water content was high, the surface resistivity of timber decreased, and the lightning current entering the lighting point of timber also increased, producing more heat energy. These situations are basically referred to as resistance heating. Lightning currents travelling through timber induced the generation of heat which produced interior gases. The impact force formed by the instantaneous expansion of gas would knock the timber out of the damage pit or crack. The generated gas was not only from the instantaneous evaporation of timber moisture at high temperatures, but also from the decomposition of timber material at high temperatures. And then the gas expanded rapidly at high temperatures, producing a great mechanical force. Under this section, the timber fiber peeled, split and decomposed instantaneously, and finally form pits or bursts. In the cases of high water content, the heat generated by the lightning generally caused more water to evaporate. Therefore, in the cases of high water content, splitting or damage pits were more likely to occur.

Figure 10 shows that the impulse damage pit depth and area for the timber with different water content. It could be found that the depth and area of the impulse damage pit became large when the timber water content increased. And the change of the damage pit area was more significant with the increase of water content. There was a sudden increase of the damage depth at the water content of 52.7% (just as shown in No. 5 in **Table 1**), and the complete longitudinal split of the timber was observed. The conductivity of timber increased rapidly with the increases of water content. Even a small amount of moisture would lead to a significant increase in conductivity. The conductivity of timber with 30% water content was about 10 million times that of completely dried timber [17]. Lightning experiments for the carbon fiber composite materials show that the conductivity has a maximum influence on composite material damage [18], and there are more similarities for the timber and carbon fiber composite materials. The most important factor affecting the conductivity of timber may be the water content. It is believed that the water content is the biggest internal cause of timber damage by lightning. What's more, the conductivity in the timber fiber direction (longitudinal) is greater than that in the transverse direction or thickness direction, due to the pore structure of timber

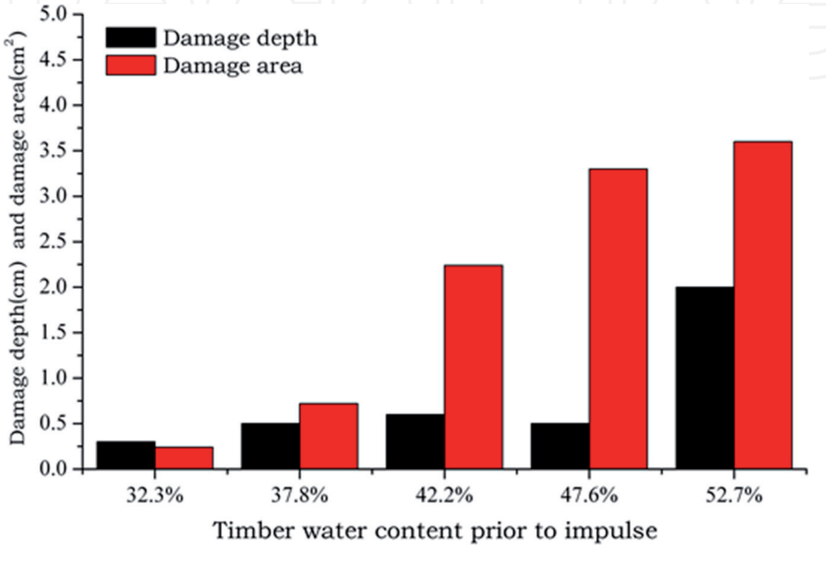

Figure 10.
The impulse damage pit depth and area of timber with different water content.

with more water. For example, the conductivity in the longitudinal direction is about twice that in the transverse direction. Lightning current propagates rapidly along the longitudinal direction and is blocked along the transverse and thickness directions. Therefore, in the case of lightning, the timber is more likely to crack along the longitudinal direction.

Timber with high water content is equivalent to the semi-insulator material with a large electrical resistivity and small conductivity. For example, the resistivity of fully-wet timber at room temperature is about 10^2 Ω•m to 10^3 Ω•m, which belongs to semi-insulator material. The lightning current into the timber causes heating, resulting in the splitting or damage pits of timber, which is different from the metal body. The metal tank lightning experiment shows that the arc temperature is the main factor of lightning-induced metal body damage [15]. The resistance of the metal body is small, and the temperature rise caused by lightning current is low. However, because of the poor electrical and thermal conductivities of timber, the current density near the lightning strike points (lightning attachment points) will be the maximum, along with the fastest heating and the highest temperatures. In these regions, heat accumulates with internal pyrolysis, resulting in gas pressure, which leads to splitting.

Figure 11 shows the damage state of fresh willow branch after lightning strike in order to further study the relationship between lightning and timber water content. Because willow material with high flexibility was also used in the ancient building timber, fresh willow branches were selected for the experiment of high water content timber. Prior to the experiment, the surface resistivity of the willow branch with the measured water content of 62.4% (higher than those shown in **Table 1**) was about 150 Ω•m, because the free ion concentration (the quantity of charge carrier) was high for timber with high water content. Just as shown in **Figure 11**, the fresh willow branches presented a bark peeling effect when exposed to the lightning strike conditions. The peeling region was approximately a rectangular shape, with a maximum length of approximately 25 mm and a maximum width of approximately 18 mm, and there are black burnt marks in this area. Under the condition of lightning current, willow twig bark produced high-temperature evaporation, and the released gas had great mechanical force, resulting in willow bark peeling. It was found that fresh trees (living trees) with high water content were more likely to experience splitting when struck by lightning. However, as for the dead trees with low water content, they were more prone to fire under lightning strike.

According to the above analysis, the damage of timber caused by lightning was mainly determined by the heat generated by lightning channel arc and the heat generated by lightning current injected into timber with a certain moisture content. The potential difference U between the lightning channel top and the ground can be approximately 10^7 V to 10^9 V [19]. If U is set as 10^8 V, the transmission charge is set as

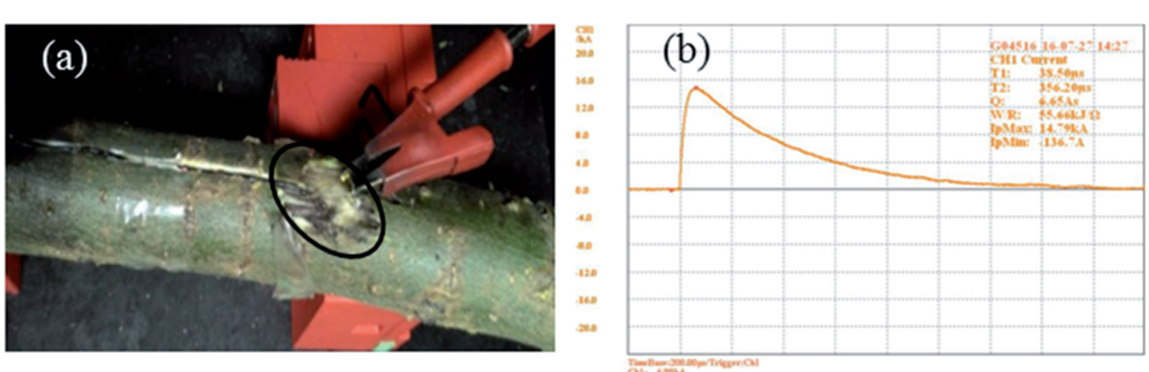

Figure 11.
(a) The damage state of fresh willow branch after lightning strike (the black oval represents the peeling region), (b) the corresponding lightning current waveform.

the typical value Q of 20 C, and then the lightning energy W of 2.0×10^9 J is obtained according to the formula $W = Q \cdot U$. If the lightning discharges to the ground at an altitude of 5 km, the energy per unit length of the discharge channel is about 0.4 KJ/mm, which is the energy generated by the lightning arc. If the resistivity of timber R is 0.1 Ω•mm at the lightning strike point and the lightning current i is set as 20 kA, the energy per unit length of timber with lightning current is approximated as 14 kJ/mm according to the formula $W = R \int i^2 dt$. Therefore, it can be seen from the approximated estimation that the energy per unit length of timber with lightning current is somewhat greater than the energy produced by the lightning arc.

3.3 Effect of the thickness on the timber after lightning strike

Table 2 shows the experimental results for the timbers with different thicknesses under equal current strength, and the water content of timber was fixed at 42.5%. It was found that there was bursting for thin timber, which was related to the lightning air shock wave and the rising temperatures from joule heat generated by the lightning current through the timber with certain water content. During the lightning discharge process, the temperature for the lightning channels increased abruptly and the air volume rapid swelled, which diffused around at the speed of ultrasonic waves to form shock waves. The generated pressure could be as high as dozens of atmospheric pressures, which led to the timber damage. The glass door of the test bench where the experimental samples were placed was observed to vibrate because of the lightning shock wave effects. And even, the vibrations or collapses of the door, window and wall for building in the cases of large lightning current strength very close to impulse points [20]. The thinner the timber board was, the smaller the withstanding impact strength would be, and the more easily cracking would occur under the action of the lightning surges. Meanwhile, it was prone to blackening and burning when the timber was thick. The thicker the timber board was, the larger the withstanding impact strength would be. And the large thicknesses resulted in the boards being more difficult to burst under impact pressures. Therefore, under the same heat conditions, the thicker boards were found to be more difficult to light on fire, and the fire burn rate was also slower.

Figure 12 shows that it's more easily for the broadsides of the timber to be caught on fire after the lightning strikebecause there was more contact with oxygen. Similarly, just as shown in **Figure 7(a)**, the timber with fissures, cracks, or decaying were prone to fire. Over long periods of time, the exposed portions of eave rafters become decayed with cracks, which leads to larger oxygen contact, making them more prone to burning during lightning strikes.

No.	Timber thickness	Current peak	Timber state
1	10 mm	20 kA	Blasting occurs at the lightning strike point of the timber, which leads to the timber cracking into two parts
2	20 mm	20 kA	Approximated square damage pit occurs on the timber surface, with a pit depth of approximately 3 mm
3	30 mm	20 kA	Square damage pit occurs on the timber surface with a pit depth of approximately 4 mm, and some parts display blackened burnt marks
4	40 mm	20 kA	Timber is burnt black and shows carbide markings

Table 2.
State changes of timber with different thicknesses after lightning strikes (water content of 42.5%).

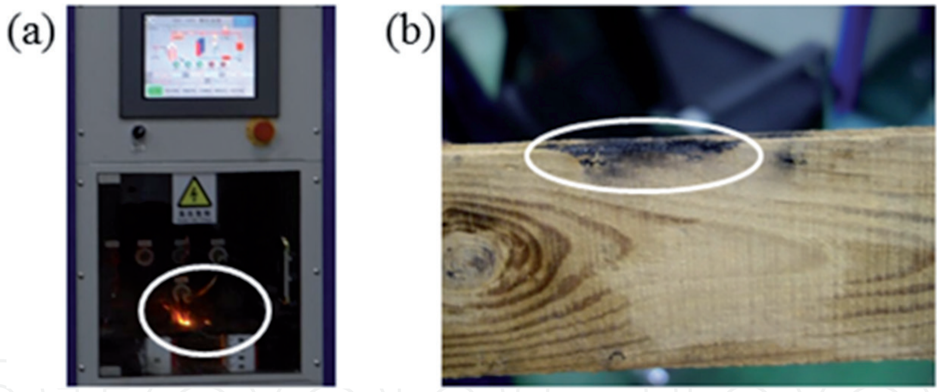

Figure 12.
(a) Experimental onsite for the fire of timber with the water content of about 52.3% and the thickness of 20 mm after lightning with lightning current of 20 kA (the white oval represents the location of timber). (b) The timber after fire (the white oval represents the location of fire).

No.	Wave-head time (μs)	Half-peak time (μs)	Charge (As)	Ip_{max} (kA)	Ip_{min} (A)	Unit energy (kJ/Ω)
1	40.5	361.2	4.71	10.25	125.0	26.93
2	38.0	342.4	5.08	12.45	181.2	36.87
3	38.8	364.8	6.70	14.85	133.8	56.74
4	38.8	348.4	7.44	16.32	128.7	67.52
5	38.5	349.2	8.00	17.91	131.9	78.49
6	38.9	349.5	9.10	20.15	140.6	91.32

Table 3.
Energy parameters of the different lightning currents.

3.4 Effect of the lightning current on the timber after lightning strike

In order to study the influence of lightning current on the lightning stroke for timber, the lightning current value was successively increased (about 2.2 kA each time) and the lightning current parameters in this experiment were shown in **Table 3**. With the increase of the peak current which was an important parameter of lightning current, the sound of explosion increased when lightning strikes, and the damage area and the damage depth for the timber also increased. This is consistent with the fact that the higher the water content of timber, the more serious the lightning damage. When the peak current increased, the impact energy of lightning current increased, so the damage for the timber was more serious. **Table 3** also shows that, when the peak value of lightning current increased in turn, the transferred charge and unit energy increased accordingly. From the perspective of lightning parameters, the main factors affecting the degree of timber damage are current peak, transferred charge, unit energy and waveform, of which peak current is the most important factor.

4. Conclusions

In this paper, a lightning simulation experiment was mainly used to study the lightning strike damage characteristics of ancient building timber, including the effect of the water content and thickness of the timber for the timber after lightning strike. The results show that the main ways of timber damage caused by lightning were lightning arc heat, gasification impact caused by lightning current on timber heating and lightning air shock wave effect, which played different roles under different conditions.

For the timber with low water content, the timber was easier to blacken or burnt after lightning strike, and the burning loss of lightning arc was the main reason. For the timber with high water content, the timber was more prone to pit crack damage, in which lightning mechanical energy was the main factor causing timber splitting damage. In essence, lightning current entered the timber, resulting in the increased heating and the rapid expansion of gas produced by high temperature. This effect produced a mechanical force similar to an explosion. The higher the water content, the greater the damage depth and the larger the damage area. In cases of timber with different thickness, the thicker the timber, the more difficult it was to ignite after lightning strike. When the timber was too thin, lightning shock waves would also cause damage. With the increase of the lightning current intensity, the timber damage will be more significant after lightning strike with the larger timber damage area and the greater damage depths. Therefore, it was concluded that the peak value of lightning current and the water content of timber were the main external and internal causes which influenced the damage degree of timber.

Generally speaking, these is always a series of complicated process within the timber after lightning strike. It is hoped that this study can provide some guidance and reference for the protection of ancient timber buildings from the possible damage caused by lightning.

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