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An experimental study of the damage degrees to ancient building timber caused by lightning strikes

Jingxiao Li [a], Xiaoqing Zhang [b], Jing Li [c, *], Rujian Li [a], Muhui Qian [a], Pingjian Song [a]

[a] Disaster Prevention Center, Beijing Meteorological Bureau, Beijing 100089, China
[b] School of Electrical Engineering, Beijing Jiaotong University, Beijing 100044, China
[c] Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China

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ABSTRACT

Lightning strikes are one of the main natural causes of damages to ancient buildings, and have attracted a great deal of attention to the problem of lightning strike disasters. In this study, the lightning strike damage mechanism of ancient building timber and the related damage degrees are investigated, based on the representative timber materials. A lightning-strike simulation device with a 10/350 μs lightning current waveform was adopted for the experiments. The experimental results showed that the lightning strike damages to ancient building timber mainly included timber heating caused by lightning arc heat and current, as well as the air shock wave effects of the lightning, which led to various effect modes under different conditions. The correlations between the damage degree of timber and the water content of timber, timber thickness, as well as the lightning current intensity, are obtained. The current peaks of lightning and the timber water content are the main external and internal causes which influence the damage degrees of ancient timber.

1. Introduction

Ancient Chinese buildings are unique in the eastern regions of the world, and are part of the three largest global building systems, along with European and Islamic architecture [1]. In China, a great number of ancient building relics have been preserved. In 2013, there were a total of 4295 national key cultural relics protection units, which included 1882 ancient building relics which made up a proportion of 43.82%, or close to half of the total. Most ancient buildings are nationally important cultural tourism resources, as well as precious cultural heritage sites with irrecoverable properties. Therefore, the safe protection of these ancient buildings is of particular importance. It is an important task of ancient building protection to prevent their destruction by natural disasters, including protecting them from lightning damage [2]. Most of the ancient Chinese buildings have been constructed using timber as the main building material. With the exceptions of stone lanes and brick towers, the roof trusses are mainly timberwork, including beams, columns, buckets, arches, purlins, rafters, windows, and other components which are composed of timber. Generally speaking, ancient buildings show 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). Due to the structures, locations, and other characteristics of ancient buildings, events such as lightning-induced fires or lightning strike damages occasionally occur [3,4]. The timber of ancient buildings have experienced long histories of possibly hundreds of years, and have become old and soft. Therefore, they are prone to burning following lightning strikes [5], which has resulted in a large number of specimen components with historical information quickly and completely vanishing. Also, after lightning strike damages, the timber's mechanical support performance becomes reduced, which brings hazards to safety of the overall structure of the ancient buildings. Therefore, it is significant to study the causes and ways lightning strikes may damage the timber of ancient buildings.

At the present time, only limited research results are available regarding the global damages to ancient building timber caused by lightning. Also, the previous research studies regarding lightning damage and destruction have mainly concentrated on the artificial composite materials, lightning forest fires, or the effects of lightning on metal bodies. The direct damage effects of lightning currents on graphite and epoxy composite laminates were simulated

* Corresponding author.
E-mail address: lijingsp@mail.ipc.ac.cn (J. Li).

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for massive experimental research by Hirano et al. [6], in order to analyze the change laws of the fiber damaged areas, and the maximum damage thicknesses over the electric charge quantity, current peak value, and action integral. The theoretical analysis and numerical simulation were carried out on the burning damage of carbon fiber composites caused by the lightning and the residual strength after a lightning strike by Wang et al. [7]. Also, a lightning shock test was conducted on the composite materials by Wang et al. [8]. The results showed that the high potential, temperature, and thermal stress generated at the moment of a lightning strike mainly extended along the maximum direction of the composite top conductivity in symmetry. In terms of the research regarding lightning-induced forest fires, Latham et al. [9] first developed a small-scale lightning fire simulation experiment platform using the local forest inflammables as the experiment material, in order to obtain the ignition probability logistical equation of the different inflammables. Darveniza et al. [10] also created a lightning test bench to calculate the energy for lightning-induced inflammable ignition. An indoor artificial arc was used to simulate the discharge process of ground lightning by Zhu et al. [11], for the purpose of analyzing the continuous discharge time and inflammable water content, along with the structures influencing the ignition during lightning-induced forest fires. In terms of the formation and development of lightning and its energy and power, the conditions of lightning-induced forest fires were examined by Lin et al. [12]. As can be seen from previous research results regarding lightning and metal objects, a long-duration current component following a lightning strike and a simulated lightning voltage with a waveform of 1.2/50 μs were adopted to analyze lightning-strike metal damages to properties by Metwally [13]. A simulated lightning current with a waveform of 10/350 μs was applied to study the heating properties of lightning-strike round metal conductors by Paisios [14]. Also, an impact current with a waveform of 30/80 μs was used for an experimental study regarding lightning damages to metal tanks by Liu et al. [15], with consideration given to the fact that the damaged metal areas was largely dependent on the lightning current amplitude, and the damage depth was mainly dependent on the transfer charge. Mi et al. performed lightning current-induced round steel damage experiments [16]. The results of the experiments confirmed that the high temperature effects of lightning arc discharges will cause damages to structures made of metal materials. These studies have provided positive reference significance to the research regarding the lightning damage mechanism involving ancient building timber.

The action mechanism of lightning damage to ancient building timber is known to be complicated. It has been found that the use of simulated lightning current experiments is an effective method to examine this action mechanism. In this study, an indoor lightning simulation device was adopted, with a 10/350 μs first-lightning current waveform recommended by IEC62305-2010, along with the representative timber materials of ancient buildings. The lightning damage mode and influencing factors of ancient building timber were examined. The timber properties and lightning current parameters of the ancient buildings were changed in order to analyze the relationship between lightning damage effects on the ancient building timber and the water content and thicknesses of the ancient buildings timber, as well as the size of lightning current. The goals of this examination were as follows: to determine the thermal effect mechanism of lightning on ancient building components; establish an energy dissipation method at the point of a lightning strike; reveal the lightning-induced timber damage mechanism and characteristics; and provide guidance and reference for protection of ancient buildings from future damages caused by lightning.

2. Experimental device and method

This experiment was carried out in Beijing Lightning Protection Device Test Center. The equipment included a Chinese GTPS30-20 kV waveform generator (Fig. 1), which was able to produce 10/350 μs of direct lightning current waveform for a maximum of 25 kA. Due to the fact that the lightning which hits timber is not generally the lightning induced wave (in the case of the selected 8/20 μs induced current waveform, the timber surfaces displayed no changes), a 10/350 μs direct lightning current waveform was selected. The electrical generator mainly included a charging device, capacitor unit, controllable trigger discharge device, and control system, of which the control system was primarily composed of a man-machine interface, parameter setting, security protection function, and so on. The screen was able to show the current voltage and charge-discharge state in real time. The digital fluorescent oscilloscope of a lightning current waveform (US Tektronix DPO3054) cannot only precisely display the lightning current peak, wave front time, transfer electric charge, unit energy, and other parameters, but also has the ability to directly store lightning current waveforms. In addition, a video camera was used to record the entire process of the lightning strike, and the camera was adapted to the photographic experimental results. During the experiment, the laboratory altitude was 32.5 m; laboratory temperature was between 26 °C and 28 °C; and the relative humidity was between 42% and 45%.

The lightning impulse experimental device is shown in Fig. 2. Screws were set up on both ends of an ancient building timber board in order to insert the timber inside the device. Also, the current line of the lightning surge generator was firmly connected with two screws. The screw spacing was 10 cm, and the two screws were connected by copper wire with a diameter of 1.25 mm. The copper wire was placed into the deep groove with the depth of 1.5 mm beneath the timber surface, which was then fixed by winded tape. The end of the copper wire was firmly connected to Screw 1, and the other end was kept at certain spacing with Screw 2, which led to an arc discharge for the discharge process, in accordance with the action process of the direct lightning effect. When the impulse voltage increased, a larger distance could be set. Screw 2 was well grounded, and a grounding rod was used to release the residual current of the device in each experiment, in order to ensure the safety of the experimental process.

In this study's experiment, a voltage divider provided by the HAEFELY Co. of Switzerland (Fig. 3) was used, which had a 1.2/50 μs

Fig. 1. 20 kV multi-waveform lightning generator.