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Effect of hygrothermal aging on the damage characteristics of carbon woven fabric/epoxy laminates subjected to simulated lightning strike

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ABSTRACT

This paper investigates the effect of hygrothermal aging on the damage behavior of two stacking sequenced ($[45_2/0_2/\text{-}45_2/90_2]s$, $[30_2/0_2/\text{-}30_2/90_2]s$) carbon woven fabric/epoxy laminates subjected to simulated lightning strike. Damage characteristics are evaluated using visual inspection, ultrasonic scanning and scanning electron microscope. The mechanical properties of post-lightning specimens exposed to the dry and the moisture environments are then studied, respectively. Observations show that enlarged resin damage area and delamination region appear for both of the specimens under moisture condition. Compared to the dry conditioned specimens, the fiber damage shape of the moisture treated ones shows a less sensitivity to stacking sequence, which extends along the ply orientation. SEM results show that the fiber/matrix interfacial bonding is severely degraded by moisture and damaged by lightning strike infliction. Mechanical testing further shows that hygrothermal aging has a more significant influence on the residual strength than modulus for the two stacking sequenced specimens.

1. Introduction

In the last decades, low-cost carbon fiber reinforced polymer composites (CFRP) have been increasingly used in sports equipment, marine structure, civil infrastructures and electrical power construction [1–3]. Recently, this type of composites has attracted great attention on its potential replacement of traditional wooden or concrete fabricated electrical poles due to its excellent mechanical property and ease for transportation. As a type of outdoor working facility, electrical pole often exposes to local harsh environmental attacks such as moisture/watering and lightning strike or their combination. The resistance and endurance to such adversary surroundings are the most concerning issues for the design and widespread applications of composite poles in electrical power industry.

Composite structures are likely to be affected by hygrothermal aging under humid and rainy areas. Literature searching shows that there are various studies of hygrothermal effects on the mechanical and physical behavior of CFRP composites [4–8]. It is found that three major mechanisms activate the moisture absorption in the composite structures: diffusion of water molecules in the matrix, capillary transport into voids and microgaps at fiber/matrix interfaces, moisture or temperature induced swelling which propagates microcracks and further increases water diffusion in the composites [9–11]. For carbon reinforced composites, the swelling effect is mainly ascribed to matrix since the diffusion in the carbon fiber is negligible, which in turn, develops residual or hygrothermal stress in the composites [12]. Moisture can cause reduction of the glass-transition temperature by disrupting hydrogen bonds in the epoxy [2,13]. It can also induce matrix degradation and plasticization by breaking polymer chains [5], fiber/matrix interfacial deterioration [14] and chemical degradation of the matrix [15]. These degradations can be intensified by the exposure to high temperature which accelerates diffusion rate of moisture and increases aging, resulting in Fickian and non-Fickian behavior [4,5,9,16]. All of the above moisture induced effects are believed to have negative influence on the mechanical properties of the CFRP composites.

Lightning strike is another phenomenon which is prone to damage CFRP composites. It has been investigated in aerospace industry for decades due to its disastrous consequences inflict on the aircraft structures [17–23]. It shows that acoustic shock, joule heating and current discharge are the major sources for the damage in the composite structures subjected to lightning strike [24,25]. The acoustic shock is due to the fast deposit of energy during the ignition stage of the lightning arc [18] which degrades resin matrix and causes fiber breakage. Joule heating effect can generate high temperature and pyrolize matrix in the composites and lead to fiber/matrix interfacial breakdown [21,26]. The current discharge can pyrolize surface matrix to cause resin damage [27]. These damage forms have been found not only in the prepreg taped

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composites, but also in the woven fabric ones [28]. However, most of these studies ignore the moisture condition of the tested specimen during the lightning strike infliction. With long period exposure to harsh environments, composite poles are always attacked by hygrothermal aging and damaged by lightning strike. As such, the existence of moisture may govern the lightning strike damage characteristics to be completely different from whose inflicted under the dry condition, which as a result, significantly affects mechanical properties and service life of the composite pole structure. However, literature searching shows that limited attention has been focused on the study of lightning strike damage on the hygrothermally affected composite specimens.

The present work is part of a funded project which aims to design a series of composite poles in the remote central and western regions of China. Due to that the poles have to work in harsh environments like mountains, plateaus and wetland areas, the ease of transportation and the resistance to the typical local climatic conditions such as lightning strike, heavy rain and strong wind are major considerations for the choice of material and design process. Traditional material candidate for composite pole is fiberglass, which has good mechanical property and inexpensive cost. However, preliminary design shows that the deformation of the pole will beyond safety limit under strong external loads. Considering both of the lightweight and stiffness, carbon woven fabric is chosen as a new material candidate to fabricate component like the crossarm and to strengthen the column body of the pole. This paper is a prerequisite investigation to study the relationship between hygrothermal aging and lightning strike damage on the composite specimens, and the mechanism on how moisture influences the damage characteristics of carbon woven fabric laminates. Two stacking sequenced ($[45_2/0_2/\text{-}45_2/90_2]$s, $[30_2/0_2/\text{-}30_2/90_2]$s) carbon woven fabric/epoxy composite laminates have been fabricated and tested. The reason to choose $[45_2/0_2/\text{-}45_2/90_2]$s is due to its quasi-isotropic property which can be used to design the crossarm. The choice of $[30_2/0_2/\text{-}30_2/90_2]$s is due to its 0° direction-prone property which can be used to fabricate the support structure or attachments on the pole. Damage behavior is analyzed by visual inspection, ultrasonic testing and field emission scanning electron microscope. The effect of water absorption under different temperatures, as well as stacking sequence on the formation of various damage forms is discussed and mechanical properties of various preconditioned post-lightning specimens are subsequently studied. The damage mechanism in microscopic level is also explored.

2. Experimental procedure

2.1. Materials

In this work, TORAY T700SC-12K UD woven fabric [29] with single layer density of 300 g/m^2 in the warp direction is used as reinforcing material for the production of composite samples. Thread yarns with single layer density of 30 g/m^2 in the weft direction hold the warp yarns from apart. AIRSTONE 760E/766H with a mixture ratio of 3:1 by weight from Dow Chemical Company is chosen as epoxy resin/hardener. The resin mixture has been cured for 24 h at room temperature and then post-cured for 8 h at 80 °C before final use. Properties of the UD carbon woven fabric and the matrix material can be found in [28].

2.2. Sample preparation

Vacuum assisted resin transfer molding (VARTM) method [30] is used to fabricate UD carbon woven fabric/epoxy laminates. It is an efficient and cost-effective composite molding technique which is widely used in civil applications, such as wind turbine blades and marine structures [31,32]. A schematic layout is shown in Fig. 1(a) and the practical preparation of the specimen is presented in Fig. 1(b). Dry carbon woven fabrics are placed on a 500 mm × 500 mm sized mold with the stacking sequence of $[45_2/0_2/\text{-}45_2/90_2]$s and $[30_2/0_2/\text{-}30_2/90_2]$s. Two layers of release fabric are placed on both sides of the fabric reinforcement to facilitate detachment of specimen from the mold. A vacuum bag is covered and sealed on the mold to allow the input of epoxy resin/hardener under a pressure of −1 bar and then, to impregnate carbon fabrics fully with the help of a well-permeated resin distribution medium (bleeder). Meanwhile, the extra air is evacuated from the vacuum outlet port.

The laminate is pre-cured for 24 h at a temperature of 30 °C and then taken to an autoclave for 8 h post-curing with a temperature of 70 °C. After that, it is cooled down to room temperature before being released from the mold. For each molding, a 400 mm × 400 mm sized laminate with a total of 16 plies carbon woven fabrics is fabricated. The weight fraction of fiber constituent is about 75%. The laminate is then cut with a diamond-coated saw to the dimension of 150 mm × 100 mm × 4.0 mm and 250 mm × 25 mm × 4.0 mm for lightning strike experiment and mechanical testing, respectively.

2.3. Porosity and water absorption test

The porosity of the two stacking sequenced specimens $[45_2/0_2/\text{-}45_2/90_2]$s (45° specimen for short) and $[30_2/0_2/\text{-}30_2/90_2]$s (30° specimen for short), is measured to study the void content in the corresponding resin matrix. ASTM D2734 is used to calculate the porosity with the following equation:

$$V = 100 - M_d\left(\frac{r}{d_r} + \frac{f}{d_f}\right) \tag{1}$$

where V is the void content in volume percentage, M_d is the measured specimen density, r is the resin in weight percentage, f is reinforcement in weight percentage, d_r and d_f are density of the resin and fiber, respectively.

The water absorption test proposed here is to simulate the moisture environment originally created by rainy attack, which is conducted according to ASTM D570. After being dried in an oven at 50 °C for 24 h, the samples are immersed in a thermostatic distilled water bath with a temperature of 23 °C and 60 °C, respectively. Here, the 23 °C water is to simulate water absorption of the composite pole from short period of rainy attack, while the 60 °C water is to increase the amount of water absorption to simulate a long duration of rainy attack. The four edges of the specimen are not sealed to permit water sorption. At periodical intervals, the specimens are taken out from the water bath and wiped free of surface water with a dry cloth, then weighted on a digital balance with a precision of 0.001 g. The whole process is finished within 10 min before replacing the samples in the bath to avoid possible error due to water evaporation. Saturation time is reached after 152 days and 104 days for 23 °C and 60 °C water bath, respectively. The water content percentage increased in the specimen is calculated as follows:

$$M(\%) = \frac{M_t - M_0}{M_0} \times 100 \tag{2}$$

where M_t is the weight at periodical intervals and M_0 is the initial sample weight.

2.4. Lightning strike generator and experimental setup

A lightning impact high-current generator device (HRHG(A)-100 kA) produced by WuGao HuaRui Voltage Technology Co. Ltd. is used to simulate lightning strike infliction. As shown in Fig. 2(a), it has 24 high voltage capacitors (100 kV and 4 μF), an adjustable resistor, a charge supply (100 kV and 80 kJ), a protection system and a test platform. Capacitors can be charged on the control board to generate lightning strike with current amplitude ranges from 1 kA to 100 kA. The current waveform is obtained by choosing resistors with specific types. In the present work, a 0.2 Ω resistor is used to generate component A [33] typed lightning strike.