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Experimental and numerical study on residual strength of aircraft carbon/epoxy composite after lightning strike

F.S. Wang [a,*], X.S. Yu [b], S.Q. Jia [a], P. Li [a]

[a] School of Mechanics, Civil Engineering and Architecture, Northwestern Polytechnical University, Xi'an 710129, PR China
[b] Shanghai Naichao Aviation Technology Ltd, Shanghai 201100, PR China

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ABSTRACT

Mechanical properties of aircraft composite laminate after lightning strike are predicted and verified based on the combination of experiment and numerical simulation. Axial compression experiment of composite laminate containing lightning strike damage is carried out and failure modes of experimental samples under three kinds of electrical current waveforms are evaluated. The main failure modes include fiber fracture, matrix cracking and delamination. The final failure load decreases with the increase of actual integral action of lightning strike. Compression failure process of composite laminate is simulated using progressive damage analysis methods such as Hashin criterion, Maximum stress criterion and TSERPES criterion, respectively. Numerical simulation and experiment results are compared and coincided well. Percentage error of Hashin criterion is the minimum compared with those of TSERPES criterion and Maximum stress criterion. Stress concentration mainly appears in both angle sides on the fixed end and lightning damage regions of composite laminate.

1. Introduction

Aircraft carbon/epoxy composite materials have been widely used in fuselage, wing and tail structures because of their excellent mechanical properties and low specific weight. But Carbon/epoxy composite material is sensitive to lightning current and its conductive property is poor, which causes larger damage probability and serious threat to flight safety when suffered from lightning strike [1]. According to the relevant reports, a commercial aircraft may suffer one lightning strike about once a year [2]. Lightning strike damage mainly displays as thermal ablation and mechanical damage around attachment points, which will greatly reduce the bearing capacity of aircraft structures [3]. So, it has great engineering significance to study the mechanical properties of composite material such as residual strength after lightning strike damage.

At present, study on residual strength of composite laminate is mainly related with damage induced by the common low-velocity impact. For mechanical properties study on damage contained in composite laminate, the main methods include the softening inclusion method, sub-layer buckling method, opening equivalence method and progressive damage method [4]. At the same time, a variety of failure criteria have appeared gradually, which are suitable for failure analysis of composite laminate [5–8]. The common failure criteria suitable for composite laminate include three-dimensional Hashin failure criterion, Maximum stress failure criterion, Lee failure criterion and Chang–Chang failure criterion, etc. Feraboli P. et al. [9] carried out residual strength experiment of the damaged composite laminate after lightning strike. The results showed that tensile strength was not significantly reduced, but compression strength was weakened obviously. At the same time, Feraboli P. et al. [10] compared the lightning strike with low-velocity impact experiment of T700S/2510 composite laminates. The results showed that the damage caused by low-velocity impact was larger than that of lightning strike. But decrease progress of compression residual strength was so complex that the general impact dynamical theory cannot be adopted to analyze the lightning strike problem and the influence of thermal effect needs to be considered. Gou J.H. et al. [11] developed a kind of tissue paper made of nanometer fiber and nickel to pave on the composite surface used for lightning protection design. Lightning strike experiment results showed that this protection method can reduce the damage area and depth effectively. But the bending experiment after lightning strike showed that residual strength of composite structure was not reduced obviously. Hirano Y. et al. [12] also carried out the axial compression experiment of the damaged composite laminate after lightning strike and compared compression experiment results with those of low-velocity impact damage contained in composite laminate. Kawakami H. et al. [13] adopted four-point bending experiment to study the bending strength of metal mesh protected composite laminate with patch repair after lightning

* Corresponding author.
E-mail address: fswang@nwpu.edu.cn (F.S. Wang).

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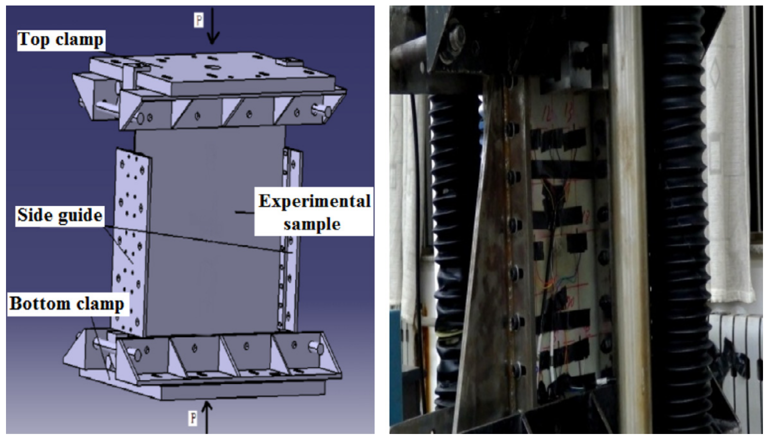
Table 1
Lightning electrical current waveforms and experimental data.

Waveform number	Sample number	Integral action/A^2/S	Lightning zone	Current peak/kA	Compression failure load/kN
1	1–0–1	2×10^6 (A wave)	IA	88.4	29.7
2	1–0–2	2.25×10^6 (A wave + D wave)	IB	93.7	29.6
3	1–0–3	0.25×10^6 (D wave)	IIB	31.3	30.6



(a) Fixture model (b) Real fixture assembly

Fig. 1. Experiment fixture and assembly pattern.

strike. The results showed that a good repair performed as well as the pristine protected specimen, while a poor repair performed equally or worse than a fully unprotected specimen. Klaus M. et al. [14] adopted three-dimensional progressive damage theory to predict residual strength of sandwich panels by four-point bending experiment after low velocity impact, which can also be employed to predict residual strength in compression after impact. Cestino E. [15] adopted numerical and experiment methods to evaluate the buckling behavior and residual tensile strength of aerospace composite structure after low velocity impact. Tensile and buckling experiments were used to validate the present methodology and a good correlation is obtained for all the cases under investigation. The authors also studied the lightning strike damage and residual strength of composite laminates [16–18]. But it only adopted numerical simulation method to predict residual tensile strength of composite laminates and lack of necessary experiment verification [16].

In this paper, lightning strike experiments of composite samples under three kinds of lightning current waveforms are carried out and evaluated. Residual compression strength and failure modes of the damaged composite laminates after lightning strike are studied through experiment and numerical simulation. For each lightning current waveform, residual strength is also compared by different failure criteria such as three-dimensional Hashin criterion, Maximum stress criterion and TSERPES criterion, respectively.

2. Experiment

Experimental sample is T700/3234 carbon fiber/epoxy resin matrix composite laminate. Its size is 500 mm × 250 mm × 2 mm and ply number is 16. The stacking sequence is $[45/-45/0_2/45/90/-45/0]_s$ and thickness of each ply is 0.125 mm. Current peak values are 88.4 kA, 93.7 kA and 31.3 kA and their serial numbers are denoted as 1, 2 and 3, respectively. The detail description is given in Table 1. Three experimental samples are used and their serial numbers are 1–0–1, 1–0–2 and 1–0–3, respectively. It needs to be illustrated specially that the stacking sequence is changed to $[-45/45/0_2/-45/90/45/0]_s$ here because composite samples are all upside down on both sides by operator in lightning current strike experiment. But this change does not affect the method correctness to evaluate ablation damage and residual strength.

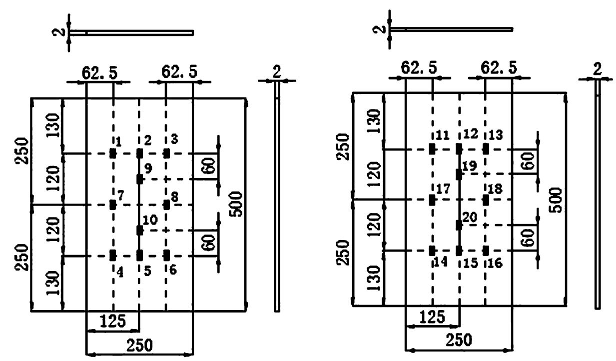


Fig. 2. Paste scheme of strain gauges (unit: mm).

CSS-WAW600 hydraulic testing machine is used and DH-3815 static strain collection device is adopted to collect strain data. Test fixture and assembly pattern is shown in Fig. 1. The FRP strengthening pieces with 3 mm thickness are pasted on both up and down ends of experimental sample in order to protect the clamped ends. The fixed constraint is adopted on the bottom end and displacement load with 1 mm/min is applied. Simply supported constraint is adopted by active blades on both sides. Displacement load is applied until composite samples loss the bearing capacity completely. The BE120-4 strain gauges with one-way resistance are pasted on the given positions of experimental sample and paste scheme of strain gauges is shown in Fig. 2. Strain gages are pasted on the face and back of experimental sample, respectively. There will have no strain gages pasted in the places where lightning damage appears.

The damaged experimental sample after axial compression is shown in Fig. 3. The typical failure modes are shown in Fig. 4, which include fiber fracture, matrix cracking and delamination. Experimental results show that failure modes are almost the same for different experimental samples. Delamination damage is caused by the excessive stress between the layers as shown in Fig. 4(a).