Analysis of carbon fiber destruction by lighting current

I A Guschin and T N Erina
Chuvash State University, 15, Moscow ave., Cheboxary, 428015, Russia
E-mail: elpardon@gmail.com

Abstract. The paper considers the unique properties of conducting carbon fiber composite: specific resistivity at different directionality of layers and critical energy of layering and destruction on the basis of experimental data. High mechanical strength and low specific gravity are noted, allowing its use in aircraft engineering to improve aircraft tactical and technical data of aerial vehicles. Strong anisotropy of electrically-conductive properties affects current spreading through carbon fiber and leads to significant destruction of the material. Theoretical analysis of lightning current spreading along anisotropic-conducting material in the form of extended plate was carried out on the basis of two proposed models of carbon fiber destruction by lightning currents. For the first continuum model an exact analytical solution to the Laplace equation with Neumann boundary conditions via the Greenberg method was found. The criteria for composite destruction was found, and the radius and depth of destruction of a conductive material by lightning current were calculated. Layer-by-layer destruction is considered on the basis of carbon fiber equivalent circuit. The strong anisotropy of the material resulting in the release of full energy in the first layer is taken into account. It is shown that the destruction of the top layer changes the distribution of currents over the remaining layers. The results of numerical modeling of layer-by-layer destruction of carbon fiber for different number of layers are given. The conclusion on the application of criteria to forecast the lightning effects and optimize lightning at the stage of aircraft design is made.

1. Introduction
Carbon fiber as a conducting composite material is widely used in many industries, including aircraft engineering. It is caused by its unique properties – high mechanical strength and low specific weight considerably improving flight characteristics of aerial vehicles. The application of nanotechnologies allows influencing hardness and strength, thermal conductivity and electrical conductivity of materials. However, with increasing use of carbon fibers in aircraft engineering, they become more vulnerable to lightning than solid metal structures and suffer extensive damage [1–4].

In order to increase flight safety and lightning resistance of carbon fiber products there is a need to conduct experimental studies of their electrical conductivity affected by pulse currents simulating lightning discharge, analysis and assessment of material destruction, creation of models of lightning current spreading along conducting material and development of criteria for its destruction. The solution of these tasks will make it possible to forecast lightning effects at the stage of aircraft engineering and to choose lightning protection methods.

The electrical conductivity of carbon fiber and its destruction are sufficiently studied. A wide variety of carbon fibers resulted in a wide spread of electrophysical characteristics, but on average the main properties for the construction of destruction models and selection of structural material were
determined. Such characteristics include longitudinal and cross resistance of carbon fiber, critical energy of layering and destruction [5]. Table 1 shows the values of these parameters.

Table 1. Electrophysical characteristics of carbon fiber

| Characteristic                        | Value       |
|--------------------------------------|-------------|
| Longitudinal resistance              |             |
| Specific resistivity, Ohm·cm          |             |
| Unidirectional fibers, $\rho_0$       | (1–2)10^{-3}|
| at an angle of 45°, $\rho_{15}$       | (2–4)10^{-3}|
| at an angle of 90°, $\rho_{90}$       | (2–4)10^{-3}|
| cross, $\rho_{tr}$                    | 10–100      |
| Critical energy of layering, W_{er1}, J/cm³ | 1.2·10³   |
| Critical energy of layering, W_{er2}, J/cm³ | 2·10³     |

It was found that the greatest contribution to the destruction is made by the pulse component of the lightning current determined by the integral action of the current. Getting into carbon fiber the Joule heating destroys it. The aggressive heating of the binder forms gases with pressures capable of causing destruction of a material. On the basis of the available data on conductive properties of carbon fibers and energies leading to layering and destruction of a material it is possible to build models of lightning currents spreading along the conductive composite material, find criteria of material destruction, compare models and choose the most promising for further theoretical analysis of carbon fiber destruction and increase of lightning resistance of products from this material.

2. Methods and materials

For the analysis of lightning current spreading along carbon fiber two models are considered: continuum model and layered structure model. The first – continuum model – takes into account the current flow in longitudinal and cross direction in case of strong anisotropy of electrically-conductive properties of carbon fiber. The model of such a medium represents an extended plate of radius from carbon fiber with thickness $H$, which includes a lightning current of the channel radius $r_{ch}$ spreading along the plate to the outer ring electrode at a distance $R$ from the center of the plate. The distribution of current density within a circumference was considered as uniform.

For this medium, it is valid to consider the Laplace equation with Neumann boundary conditions, which has an exact analytical solution. It was found via the Greenberg method and included the Bessel functions [6]. Similar problem is solved for coaxial arrangement of elements opposite to each other. The case of $R\to\infty$ considers infinitely extended plate with thickness $H$. The densities of cross and longitudinal currents $j_{z}=-\varphi_{z}/\rho_{z}$ and $j_{r}=-\varphi/r_{r}$, allowing analyzing the distribution of currents in the anisotropic conductive medium, are found from potential distribution $\varphi(r, z)$. The correlation with the experiment is achieved by defining the longitudinal $R_{r} = [\varphi(r_{ch},0) - \varphi(R, 0)]/I_{l}$ and cross resistance $R_{z} = [\varphi(r_{ch},0) - \varphi(r_{ch}, H)]/I_{l}$ of passing lightning current $I_{l}$.

In order to understand the complete picture of destruction, it is necessary to consider the model taking into account the layered structure of the real carbon fiber [7]. This can be done using a series-parallel composite equivalent circuit (Figure 1).

The resulting system of equations was solved by the Gauss method. At the same time the quantity of elementary longitudinal $\Delta R_{r}$ and cross resistance $\Delta R_{z}$ was chosen final and equal accordingly to $N$ and $n = n_{lay} - 1$ with the number of layers of the material. From $nN$ equations longitudinal and cross currents were found, from which the analysis of lightning current spreading was carried out. At $\Delta R_{r}$, $\Delta R_{z}$ tend to zero, the results of calculations for both models coincided and are given in Section III.

For practical calculations, the concept of equivalent fracture depth $Ze$ (similar to the depth of electromagnetic radiation penetration into the conductive medium) is introduced to determine the degree of material destruction. It is found from the equality of the energy released in the equivalent layer of thickness $Ze$ at the maximum current density in the first layer and the total energy released in all layers through which the unevenly distributed current flows:
Then we face the matter of choosing a particular model for specific calculations and ways to increase the lightning resistance of a composite material at the stage of aeronautical design engineering. The necessary comparative analysis of calculations for the two proposed models is carried out in the next section.

For experimental confirmation of the chosen models of destruction the carbon fiber samples were produced and longitudinal and cross resistance at lightning current transmission were defined. Cylindrical electrodes were brought in contact in the middle part of a sample transversely to the layers on both sides. The simulation of discharge channel of rch radius took into account one electrode, and the second – structural conducting object under carbon fiber skin. The experiment used cylindrical electrodes of diameter D from 4 to 50 mm. The general parameters for the two models (radius of the lighting channel rch, thickness (number of layers) H (nlay), specific resistance ratio \( \rho_r/\rho_z \)) fully corresponded to the experiment. At the same time, the error of calculation with the experiment did not exceed 15 % (Table 2).

### Table 2. Experimental validation of calculations

| D, mm | R, Ohm | Longitudinal resistance | Cross resistance |
|------|-------|-------------------------|------------------|
|      |       | Experiment, Rav, Ohm    | Number of samples | Variation, % |
| 4    | 0.052 | 0.050                   | 4                | 15           |
| 20   | 0.024 | 0.023                   | 4                | 12           |
| 4    | 0.202 | 0.185                   | 4                | 10           |
| 50   | 0.173 | 0.178                   | 4                | 10           |

### 3. Results

Calculations of current density distributions make it possible to draw the conclusion on the nature of current spreading in a plate with anisotropy of conductivity. Thus, with a large relationship between cross and longitudinal specific resistivity \( \rho_z/\rho_r \), the current will mainly flow in the narrow surface layer, and the resulting current density in the vicinity of the channel radius will be determined by the radial component of the current density \( j_r \). Figure 2 shows dependencies of reduced current density \( j_r/jm \) from parameter \( r/R \) at different ratios \( z/H \) (\( H/R = 0.01 \)). The data clearly show that the maximum
current densities are located near the radius of the channel. With the increase of \( r/R \) and \( z/H \), the distribution of the radial component of the current density is equalized.

Figure 3 shows the dependence of \( jz/jm \) on \( z/H \) at different \( r/R \). It follows from the comparison of the figures that in calculating the resulting current density, the cross component \( jz \) can be neglected. The current density \( jz \) decreases rapidly with increasing thickness of a composite, resulting in highly uneven current distribution across the material near the discharge channel.

**Figure 2.** Distribution of \( jr/jm \) along radius \( r/R \) at different ratios \( z/H \).

**Figure 3.** Distribution \( jz/jm \) along thickness \( z/H \) at different \( r/R \) (\( r_{ch}/R = 0.1 \)).

Based on the calculation of current densities in solid anisotropic-conducting medium with thickness \( H \), it is possible to calculate the radius and depth of material destruction. The destruction criterion is the specific energy input per unit of time, for which the following expression is true:

\[
W_{rel} = \left( j_r^2 \rho_z + j_z^2 \rho_r \right) \cdot A/(2I_m^2),
\]

where \( A \) – integral of lightning current action; \( I_m \) – maximum current in a pulse.

Hence, the current densities resulting in the release of a given specific energy \( W_{rel} \) lie on the ellipse. Let us estimate the depth and radius of composite destruction by constructing isoenergetic curves in coordinates \((r, z)\) at preset values of lightning channel radius \( r_{ch}, A, \rho_z/\rho_r \) (Figure 4).

Figure 4 shows the results of calculation of isoenergetic curves for carbon fiber at \( r_{ch} = 1 \) cm, \( A = 0.6 \cdot 10^6 \) A\(^2\)c and two values \( \rho_z/\rho_r \). At \( \rho_z/\rho_r = 10^4 \), the destruction radius and depth will make respectively \( r_p = 2.5 \) \( r_{ch} \) and \( z_p = H/3 \), and at \( \rho_z/\rho_r = 10^4 \) \( r_p = 3 \) \( r_{ch} \) and \( z_p = H/4 \). Hence, the non-uniformity of current spreading due to severe anisotropy results in painful destruction of the outer layers.

The calculations taking into account the layered structure of carbon fiber showed that the distribution of current density weakly depends on the number of layers, which is caused by the strong anisotropy of the conductive properties of carbon fiber, namely at \( \rho_z/\rho_r >> 1 \). For the case of strong anisotropy \( \rho_z/\rho_r >> 10^4 \) it can be considered that the energy release near the channel occurs only in the
first layer and there is a layer-by-layer breakdown of the material. The distribution of equivalent depth of destruction at various $\rho_z/\rho_r$ is shown in Figure 5 and 6.

**Figure 4.** Isoenergetic curves at $A = 0.6 \cdot 10^6 A^2 c$ and $\rho_z/\rho_r = 10^3(a)$ and $\rho_z/\rho_r = 10^4(b)$

**Figure 5.** Distribution of relative depth of energy density $z_e/d$ along radius $r/r_{ch}$ for different number of layers at $\rho_z/\rho_r = 10^3$

**Figure 6.** Distribution of relative depth of energy density $z_e/d$ along radius $r/r_{ch}$ for different number of layers at $\rho_z/\rho_r = 10^4$
For example, Figure 5 shows that the relative radius at which the current density is aligned with the layers, i.e. $z_c = n_{lay} d$, can be expressed as follows:

$$r_e/r_{ch} = n_{lay} - 1$$

It follows from the continuum model that in the real material the current density across the layer thickness is uneven. In other words, each individual layer has anisotropy properties typical for the entire material.

In a model taking into account the layered structure of the material, the current density was considered to be uniformly distributed within each layer. At a small layer thickness (0.01 cm) this assumption is quite justified. Figure 6 shows the comparison of calculation results regarding both models, in particular for $j_r(r)$ and $j_z(r)$ at $n_{lay}=10$, $\rho_z/\rho=10^4$, $r_{ch}=1$ cm, $R=10$ cm. The solid line shows the graphs for the continuum, and the dash-and-dot line is used for the layered medium.

**Figure 7.** Distribution of radial current density $j_r/j_m$ by radius $r/r_{ch}$ at different ratios $z/H$

4. Conclusion

Thus, both models made it possible to construct the destruction curves and forecast the degree of destruction, to obtain expressions for destruction characteristics (radius, depth, and integral of destructive current action), but the layered model proved to be more consistent with the layer-by-layer destruction mechanism. Thus, it becomes possible to consider the dynamics of destruction over time, which does not allow making the static models. The proposed model of current spreading through the conducting composite material taking into account its layered structure makes it possible to forecast the degree of destruction of the real layered carbon fiber material without the experiment and reasonable selection of the necessary structural material.

Thus, the results of the calculations for two independent models of current spreading along carbon fiber fully coincided with the experiment with the same initial data. This confirms the correctness of theoretical conclusions and the possibility of its application to forecast the consequences of carbon fiber destruction by lightning currents. The simplicity of analysis of the numerical method for the layered structure of the material compared to the continuum makes this model more cost-efficient and suitable for the analysis of material destruction. Of all tested models, the layer-by-layer destruction mechanism most reflects the real processes that occur in carbon fiber when it is exposed to lightning channel. The dynamics of layer-by-layer destruction over time will be considered in the following works.

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