Dynamics and criteria of CFRP destruction by lightning currents

I A Gushchin

1Ulyanov Chuvash State University, Moscovski ave., 15, Cheboksary, 428015, Russia

E-mail: elpardo@list.ru

Abstract. The article discusses a promising conductive composite material such as carbon-plastic. This material has significant strength, not inferior to metal, has a low specific weight and has interesting electrophysical characteristics. For a wider use of the material in various structural products, it is necessary to consider its unique characteristics. The work is devoted to the study of the conductive properties of carbon fiber under the influence of lightning currents and the development of criteria for its destruction. Based on two models of destruction of CFRP by lightning currents, a theoretical analysis of its destruction has been carried out. The first model considered the composite material as a continuous medium with anisotropic conducting properties. The solution of the Laplace equation with the Neumann boundary conditions made it possible to find the distribution of current densities over the material and theoretically determine the radius and depth of damage. The second model, the layered structure model, took into account the structure of real CFRP. The dynamics of layer-by-layer destruction is considered on the basis of the equivalent circuit of carbon fiber reinforced plastic, which takes into account the longitudinal and transverse resistivity of the composite. The distributions of the radial current density along the radius and depth of the material are constructed and the analysis of the spreading of currents at various degrees of material anisotropy is carried out. Strong anisotropy, leading to the release of total energy in the first layer. Destruction of the upper layer changes the distribution of currents in the rest of the layers. The results of numerical modeling of layer-by-layer destruction of CFRP for five layers are presented. The process of destruction under the action of large current pulses is considered. The fracture criteria for various degrees of material anisotropy are obtained and refined. The resulting formulas contain values that are reproduced in the experiment. The calculation results are in good agreement with experiment. In conclusion, it is concluded that the criteria are applied to predict the effects of lightning and optimize lightning protection at the design stage of an aircraft.

1. Introduction
The creation of a new generation of materials with predictable characteristics is a priority task. Such materials include conductive composites such as carbon fiber, which have long been used in various industries: space, aviation, and automotive. The use of composites is constantly increasing due to their unique strength, weight and electrophysical characteristics. This work is devoted to the influence of the electrically conductive properties of the material on the degree of their destruction during the flow of currents. Studies of the behavior of conducting composite materials when large pulsed currents flow through them have not lost their relevance to the present time [2, 6, 7, 8]. Aircraft designers are attracted by the high strength and low specific gravity of these materials, but their high vulnerability to lightning currents significantly reduces flight safety compared to solid-metal structures [1, 5].
requirement of increased lightning resistance of products made of conductive composites such as carbon fiber makes it extremely necessary to study the flow of currents through the material and its destruction.

2. Materials and methods
In papers [3, 4], models of the spreading of lightning currents through a conductive composite material are considered. If in the model of a continuous medium with anisotropic conducting properties, the current distributions were determined from the Laplace equation, then in the model of a layered structure, a carbon fiber replacement scheme with discrete conductivity was used to find the currents (Fig.1).

![Carbon fiber equivalent circuit with discrete conductivity.](image)

Both models allowed us to obtain results that coincide well with the experiment with the same initial data, but did not allow us to study the dynamics of destruction.

The purpose of this work is to analyze the dynamics of destruction of a conductive composite material and to develop criteria for destruction at various stages of destruction of the material.

Only after determining the electrophysical characteristics of the carbon fiber (conducting properties and specific energy of destruction) [3] and analyzing the processes of spreading lightning currents in the radial and transverse directions, it becomes possible to analyze the destruction of the material itself under the action of lightning currents.

Strong anisotropy leads to the fact that almost all the energy is released only in the first layer until its destruction. After the destruction of the first layer, the distribution of currents across the layers changes, so that a significant part of the current branches off into the destroyed layer, and the rest is distributed over the remaining undisturbed layers.

The process of layer-by-layer destruction is modeled using the carbon fiber substitution scheme, if we assume that the component modeled by the resistance under the channel $\Delta R_z$ is destroyed first of all.

3. Results and discussions
It is of interest to see the distribution of currents over the material before the destruction of the layers. The equivalent circuit for carbon fiber reinforced plastic makes it possible to numerically analyze the distribution of currents over thickness and radius, depending on the degree of anisotropy of the material. The distribution of the current density on the number of layers depends weakly, which is explained by the strong anisotropy of the conductive properties of CFRP, namely, at $\rho_z / \rho_r >> 1$. Figure 2 shows the distributions of the radial current density over depth (layers) $j_r (z)$ at various ratios $\rho_z / \rho_r$ and at a radius $r = r_{ch}$. Figure 3 shows the distributions along the radius $j_r (r)$ in the upper layer at different ratios $\rho_z / \rho_r$.
Figure 2. Distribution of $j_r/j_0$ over depth $z/d$ for $r = r_{ch}$ at various ratios $\rho_z/\rho_r$.

Figure 3. Distribution of $j_r/j_0$ along the radius for $r = r_{ch}$ in the upper layer at different ratios $\rho_z/\rho_r$.

From the analysis of the distribution of the radial current density it follows that the uniform spreading of the current over the layers is achieved in the range $\rho_z/\rho_r = 1 - 10$.

Let us analyze the calculations of the fracture of the layered material depending on various parameters. Let the destruction of the first layer occur as a result of the impact of lightning currents. In this case, the distribution of currents in the longitudinal direction should change. Fig. 4 shows the results of numerical modeling of layer-by-layer fracture of carbon fiber at $n_l=5$ and $\rho_z/\rho_r = 10^4$. 

The analysis of the results allowed us to construct the following scheme of material destruction. After the destruction of the first layer caused by a significant energy release at the contact point of the discharge channel with the carbon fiber, the current in the main spreads over two layers. As follows from Fig. 1, the current density is halved. If the specific energy of destruction reaches a critical value, the destruction of the second layer occurs and the current spreads over three layers. When all layers are destroyed, the current density is the same in each layer (Fig. 5). This can also be seen from the substitution scheme in Fig. 1, which becomes symmetric with through-breaking.

**Figure 4.** Distribution of the radial current density along the radius $r/r_{ch}$ during the destruction of the first layer.

The process of layer-by-layer fracture in dynamics can be specified by time intervals $t_i$, provides the flow of current through layers $n_i$ with layer thickness $\Delta$.

The presented scheme of layer-by-layer destruction allows us to conduct a theoretical analysis of the process of destruction of carbon fiber. This analysis included the following provisions:

- strong anisotropy leads to current spreading through the first layer;
the discharge channel has the greatest energy release:

\[ W_i = \int_{0}^{t_1} \rho_r \cdot \hat{F} \cdot dr / (2\pi r_{ch} \Delta)^2, \]

where \( \rho_r \) is the resistivity of the material in the radial direction; \( I \) is the discharge current at any time; \( \Delta \) is the layer thickness; \( r_{ch} \) - radius of the lightning discharge channel.

the approximation of \( \rho_r \) from the current and the dependence of \( I \) on time is represented as:

\[ \rho_r = \rho_m I_m n_d / I, \quad I = I_m \exp(-t/\tau), \]

where \( \rho_m \) is the resistivity of carbon fiber at the maximum current \( I_m \); \( n_d \) is the number of destroyed layers.

After reaching the critical value of the released energy

\[ W_1 = W_{cr2} \]

the first layer is destroyed. The channel begins to contact the two layers, and the current density decreases by 2 times. After the destruction of the second layer, the current density is reduced 3 times, etc.

It is easy to show that the destruction of any of the \( n \)-th layer in the time interval \( t_{n-1} - t_n \) is true for the equality of the energy release in a layer with a thickness of \( \Delta \) and in a layer with a thickness of \( A \rho_m / (W_{cr2} (\pi r_{ch})^2) \) (1 + 2 + ... + \( n \)) / (2 \( \Delta \)).

For the destruction of \( n \) layers under the action of a full current pulse, it is necessary that the integral of the action is equal to

\[ A = n_d (n_r + 1) (\pi r_{ch} \Delta)^2 W_{cr2} / \rho_m \]

With a sufficiently large number of layers, the depth of destruction takes the form

\[ z_d = n_d \Delta = [A \rho_m / (W_{cr2} (\pi r_{ch})^2)]^{0.5} \]

Expressions (1) and (2) are the criteria for end-to-end destruction, if we equate the number of destroyed \( n_d \) layers to the number of material layers. The radius of the bundle of the upper layer of carbon fiber \( r_d \) is determined from the condition that the energy \( W_r \) is reached at the end of the pulse at any value of the radius \( W_{cr1} \) and taking into account that when each layer in the first layer is destroyed, one and the same energy \( W_{cr2} \) is released at the channel radius

\[ W_r = \int_{0}^{\infty} \rho_r \cdot \hat{F} \cdot dr / (2\pi r \Delta)^2 \quad r_d = r_{ch} [W_{cr2} n_d / W_{cr1}]^{0.5} \]

Expression (3) is obtained under the assumption that when lightning contacts the surface, the current spreads only over one upper layer. It should be noted that in the presence of transverse conductivity, the current can also flow in the depth of the material (along the following layers).

The equivalent depth of destruction determined in [3] allows us to refine the calculated expressions (1), (2) and (3) for finding the degree of destruction of carbon fiber. If \( z_{eq} > \Delta \), then in these expressions, instead of \( \Delta \), the value \( z_{eq} \) should be substituted. In fact, at the radius of the channel \( r_{ch} \) at \( \rho_r / \rho_c = 10^5 \), the relative depth of energy release is \( z_{eq} / \Delta \rightarrow 1 \). In the model of a continuous electrically conducting anisotropic medium for practical calculations, an equivalent depth of destruction \( z_e \) was found from the equality of the release energy in a layer with a thickness of \( z_{eq} \) at the maximum current density in the upper layer and the total release energy in all layers. The degree of destruction is expressed by formulas (1) and (2). However, the expression (3) turns out to be very approximate and requires clarification. The energy release at a radius \( r > 1.5 r_{ch} \) occurs no longer in one layer, and the expression (3) takes the form:

\[ (r_d / r_{ch})^3 + (r_d / r_{ch})^2 = 2 W_{cr2} n_{layer} / W_{ch1} \]

With a relatively small degree of anisotropy \( \rho_c / \rho_r \leq 10^3 \), the criterion of through destruction of the material (1) takes the form:
\[ A = N_d (N_p + 1) \left( \pi r_{ch} z_{eq} \right)^2 \frac{W_{cr2}}{\rho_m}, \]  

where \( N_d = \frac{z_d}{z_{eq}} \).

The presented refinements play a significant role with a low degree of anisotropy. For example, with \( \rho_z/\rho_r \leq 10^3 \), expression (1) differs from expression (5) by no more than 10 \%. With the ratio \( \rho_z/\rho_r \geq 10^4 \), this difference is insignificant.

The resulting formulas contain values that are reproduced in the experiment. As shown in [3], the calculation results are in good agreement with the experiment. For example, Table 1 shows the resistivity and critical energies of delamination of various types of carbon fiber reinforced plastics.

### Table 1. Characteristics of promising CFRPs.

| Focus fibers, degree | Longitudinal resistivity, m\(\Omega\) cm | Transverse resistivity, m\(\Omega\) cm | \( W_{cr1} \), kJ / cm\(^3\) | \( W_{cr2} \), kJ / cm\(^3\) |
|---------------------|------------------------------------------|------------------------------------|------------------------|------------------------|
| 0                   | 1-2                                      | 10-100                             | 1,2                    | 2,0                    |
| 45                  | 2-4                                      |                                    |                        |                        |
| 90                  | 2-4                                      |                                    |                        |                        |

4. Summary

Thus, based on two models of current spreading through a conductive composite material, it was possible to consider the dynamics of layer-by-layer destruction in time and find the criteria for destruction. The obtained expressions allow us to predict the consequences of the impact of lightning on carbon fiber products and optimize lightning protection at the design stage of the aircraft. The validity of the application of the obtained criteria for assessing the destruction of conductive materials will be considered in subsequent works.

5. References

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