Kamil FILIK

Rzeszow University of Technology
ORCID: 0000-0002-6410-3573

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Study of new composite materials for aviation with the use of lightning current pulses

Abstract*. Composite materials used increasingly in the aerospace industry are required to have appropriate electrical properties to minimize the risk of negative effects of lightning strike to aircraft. The paper presents the results of experimental studies of carbon fiber reinforced composite materials with different concentrations of conductive additive using lightning-type current impulses. The proposed method enables to evaluate the influence of conductive additives in composite laminates on their properties with respect to their handling of lightning current.*

Streszczenie. *W artykule przedstawiono wyniki badań kompozytów wzmacnianych włóknem węglowym i o różnej zawartości dodatku przewodzącego z użyciem impulsów prądowych typu piorunowego. Zaproponowana metoda pozwala ocenić wpływ dodatków przewodzących w wypełniaczu paneli kompozytowych na właściwości kompozytów w odniesieniu do oddziaływania na nie prądu piorunowego. (**Badanie nowych materiałów kompozytowych dla lotnictwa z wykorzystaniem piorunowych udarów prądowych**).*

Keywords: polymer composites, aircraft, electrical conductivity, lightning current impulse.
Słowa kluczowe: kompozyty polimerowe, statek powietrzny, przewodność elektryczna, piorunowy udar prądowy.

Introduction

Nowadays, components made of lightweight and strong composite materials are increasingly used in the aerospace industry to replace metal structures [1]. They are required to have satisfactory electrical characteristics in addition to very good mechanical and chemical properties. First and foremost, they must be resistant to the effects of direct lightning [2], as well as minimize the formation and propagation of indirect effects [3]. This is mainly related to the ability to easily conduct current lightning current with significant specific energy without accompanying important changes or damage to the structure of the new materials [4]. The shape and level of surges induced in the internal installation also depend on the electrical conductivity and effectiveness of electromagnetic field shielding by the airframe structure [5].

A popular group of composites in aircraft engineering is Carbon Fiber Reinforced Polymer (CFRP). Despite the good electrical conductivity of the carbon reinforcement itself, the total conductivity of the complete composite filled with epoxy resin (usually with high resistivity) is not satisfactory. Hence, various methods are used to improve the behaviour of composite structures during the action of lightning current. Initially, metal meshes or films were implemented in their structure [6]. Advanced work is currently underway to improve the conductivity of composites by introducing conductive additives into the resin, usually as various forms of carbon, such as carbon dust, carbon black, graphite, carbon nanotubes or graphene, as described, for example, in the paper [7]. Assessments of the electrical performance of such materials are usually based on high-current or high-voltage surge tests [1] and computer simulations [9].

The article presents an experimental study of carbon fiber reinforced composite materials with different concentrations of conductive additive using current pulses with parameters corresponding to the lightning subsequent return strokes. The method proposed in the paper makes it possible to evaluate the influence of conductive additives in composite laminates on their properties , mainly electrical resistivity and surge resistance, responsible for the behavior of these materials in the presence of lightning current. The change of the mentioned parameters was observed both in the case of modification of the resin filler composition and the action of subsequent current pulses on the tested material. Based on the obtained results, a method was proposed for estimating the surge resistance of the tested materials using impulses produced by current generator. The method also complements low-voltage resistivity testing [10] as a non-invasive alternative to destructive testing of composite structures.

Composite sample preparation

The samples used for the study were made in the cooperation with the Department of Polymer Composites of Rzeszow University of Technology [11]. All of them were produced by vacuum infusion using five layers of 2/2 carbon fiber fabric with 200 g/m^2 gradation. The resin contained additives of various compositions and concentrations. Research results are presented for a selection of three, most representative panels, named respectively: P1, P2, and P3. The first panel P1 was based on an unmodified resin epoxy resin Epidian® 624 (EP), while the other two panels P2 and P3 had an additional 25% flame retardant (Me-thyl(5-methyl-2-methyl-1,3,2-dioxaphosphorinan-5-yl)ester,P,P'-dioxide. P2 also contained 0.25% and P3 contained 0.75% conductive carbon black AC-60. Samples were cut into square formats with sides of 30 × 30 cm. Due to the nature of the production uniform thicknesses of the panels were not obtained, which eventually amounted respectively to 1.51 mm (P1), 1.66 mm (P2) and 1.65 mm (P3). Also, the surface of the samples differed on both sides of the laminates. On the one adjacent to the glass during fabrication, it was smooth (this side was named BOTTOM), while the other had the characteristic texture of the fabric used in the infusion process (the side named TOP). No additional paint coating was applied to the tested laminates. After drilling holes at the edges, the samples could be screwed with the same torque of 9 Nm to the external electrodes, which were mounted on the test bed using clamps, as shown in Figs. 1 and 2.

Setup for current pulse tests

The tests were carried out on a prepared stand, described in more detail in [10,12], which was shown in Fig. 1. However, the schematic diagram of the measurement system in simplified form is presented in Fig. 2a. The GUP-80/10 generator, with a charging voltage of 10 kV to 80 kV and a maximum energy of 10 kJ, was used to generate current surges similar to subsequent return strokes occurring during the lightning discharge after the first return stroke. The shape of the generated current strokes in the generator's output circuit strongly depended on the load connected to it. The maximum value of the obtained current was 50 kA in the short-circuit condition of its output. During the tests described in this article, the generator was charged up to 40 kV, and the current pulses reached about 15 kA of maximum value.

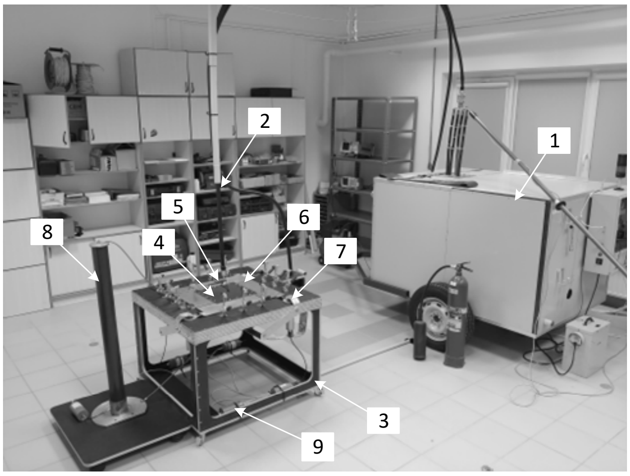

Fig.1. The view of the test setup: 1 – surge current generator, 2 – high voltage insulated conductors, 3 – test bed, 4 – composite laminate sample, 5 – high voltage injection ball electrode, 6 – return circuit electrode, 7 – current shunt, 8 high voltage divider, 9 – fiber-optic measurement system

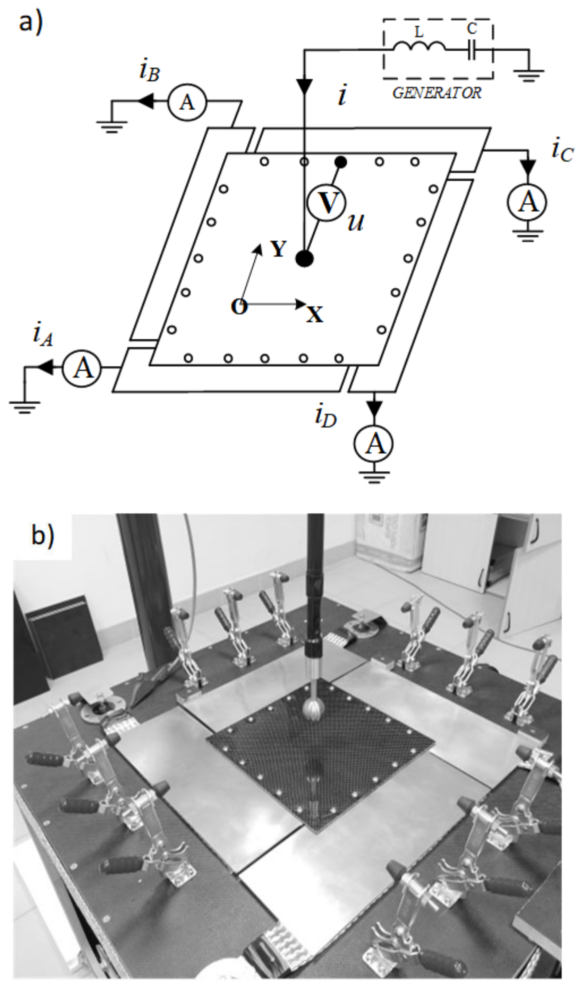

Fig.2. Measurement of current distribution in the sample and voltage drop: a) simplified diagram adopted from [10], b) view of the table with the assembled composite

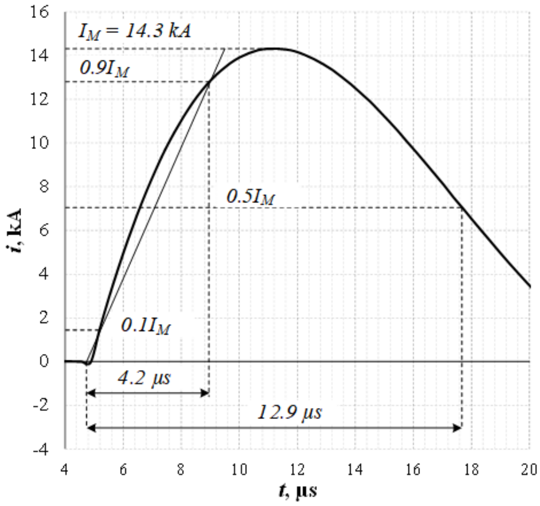

Fig.3. Parameters of first current pulse exciting the P1 sample

Each sample was excited with successive five pulses. The interval between these pulses of the order of single minutes was due to the procedure of recording measurement data and preparing the system for the next excitation. Figure 3 shows, as an example, the shape of the injected current obtained when sample P1 was tested with the first pulse. In this case, the front time T_1 was just over 4 μs and the time to half value T_2 was almost 13 μs. T_1 and T_2 times for other recorded surges were of similar order to those shown in the Fig. 3.

During the tests, the component currents were also recorded simultaneously as the effect of the distribution of the main surge injected by the ball electrode into the centre of the specimen on the laminate side previously defined as BOTTOM. Current shunts via a measurement system based on fiber optic links and analog-to-digital converters measured the time waveforms of currents i_A, i_B, i_C and i_D flowing to each edge of the laminate (see Fig. 2a). In this way, it was possible to assess whether the samples exhibit better electrical conductivity in any of the selected directions in the OXY plane.

Result of experimental research

In response to the forcing current i for each measurement case, the component currents at points A, B, C and D were recorded, as well as the voltage drop u between the centre of the laminate and one of its edges, as shown in Figure 2.

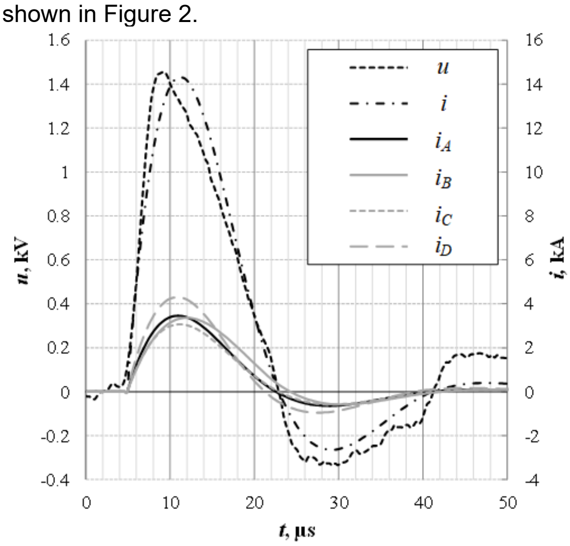

Fig.4. Current and voltage waveforms recorded during the test of sample P1 with the first stroke

Fig. 4 shows a representative example of the recorded time waveforms of currents and voltage during the conducted tests. Table 1 summarizes the peak values of currents and voltage for each test step.

Table 1. Comparison of currents and voltage peaks recorded during testing of all three laminates with five strokes. For the component currents at points A - D, the percentage relation to the main current i is given

Sample name	Impulse number	Maximum values					
		I_{AM}/I_M, %	I_{BM}/I_M, %	I_{CM}/I_M, %	I_{DM}/I_M, %	I_M, kA	U_M, kV
P1	1	24.0	23.5	21.4	31.2	14.32	1.46
	2	24.3	23.6	21.5	30.9	14.51	1.16
	3	24.3	23.7	21.6	30.7	14.60	1.13
	4	24.2	23.7	21.8	30.6	14.56	1.04
	5	24.1	23.6	21.6	31.0	14.56	1.04
P2	1	25.7	20.2	23.3	31.0	14.45	1.29
	2	25.7	20.0	23.6	30.9	14.45	1.11
	3	25.6	20.1	23.7	30.7	14.48	1.03
	4	25.6	20.1	23.7	30.8	14.48	1.01
	5	25.6	20.1	23.7	30.8	14.46	1.00
P3	1	25.1	21.7	23.9	29.4	14.64	1.03
	2	24.9	21.9	23.8	29.5	14.63	0.96
	3	25.1	21.8	23.8	29.6	14.65	0.90
	4	25.1	21.8	23.7	29.5	14.64	0.91
	5	25.2	21.7	23.8	29.7	14.63	0.89

The measured current components differed slightly in peak value and shape. Very similar behaviour was observed for the other samples. In most cases, the highest current values were recorded at point D, followed by A, then C and B. The voltage time waveform contained strong oscillation noise on the rising edge, which was filtered out for further analysis. The time difference between the moments of occurrence of the maximum of voltage u and of the main current i seen in Fig. 4 equal to 2 μs indicates the resistive-inductive nature of the object under study.

Based on the relative peak values of the component currents (see Table 1), it was found that the specimens did not show a clear tendency towards higher electrical conductivity in any of the four directions. Only the current flow increased by a few percent in the YO direction for all specimens was observed.

Based on the recorded peak values of voltage U_M and of current I_M, the surge resistance R_S of the samples was defined:

$$R_S = \frac{U_M}{I_M} \qquad (1)$$

where: U_M – maximum value of voltage, I_M – maximum value of current.

The concept of surge impedance is not used in formula (1), assuming that impedance is generally defined in the frequency domain and as such it should be defined as a function of frequency. Additionally, the maximum voltage value U_M does not occur at the same time as the maximum current value I_M. Taking into account the above limitations, Fig. 5 shows the results of impact resistance calculations for three tested samples.

A change in the R_S resistance value was observed with the impact of subsequent strokes. There was usually a decline. The reason was the impact of the current on the structure of the tested material, but it should be noted that in general the resistance was the highest for all panels during the first impact. However, in the case of samples P2 and P3, a slight increase was observed during the fifth (P2) and fourth stroke (P3), respectively, compared to the value estimated for the previous strokes, which proves the complexity of the phenomena related to electrical breakdown and the formation of local bridges between the reinforcement and resin layers, changing the electrical conductivity of the entire composite. The largest changes in these parameters were observed for sample P1, while the P3 composite containing the highest concentration of conductive carbon black in the resin filler was the least sensitive to the effects of current. Also, the introduction and increase in the concentration of a conductive additive in the resin mixture resulted in a decrease in the resistance R_S.

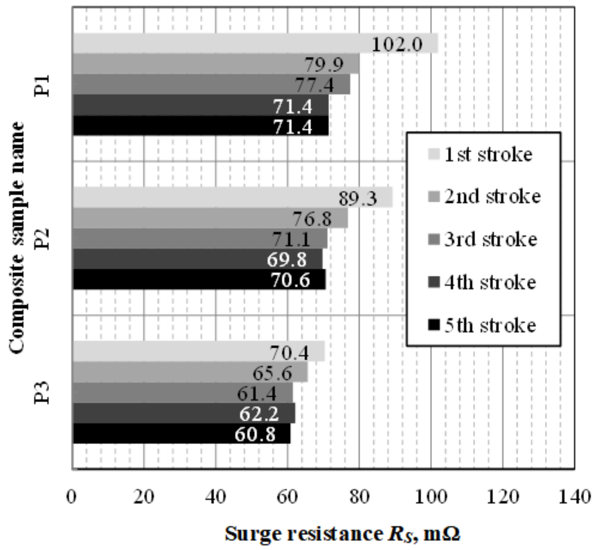

Fig.5. Comparison of the R_S surge resistance of the tested laminates for five following current surges applied from the generator

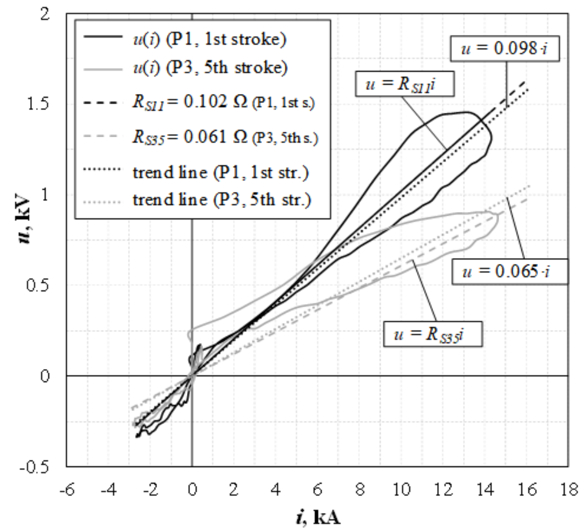

Fig.6. Comparison of the R_S surge resistance of the tested laminates for following current surges applied from the generator

In the paper [13] the correlation between the change in resistance and the degree of damage of CFRP composites by gradually increasing the peak current value of the applied strokes was investigated. Initially, with increasing the level of the peak value of the strokes, a gradual decrease in resistance was observed , but after exceeding a certain threshold of the peak value of the forcing current, the trend reversed. For different shapes of the surge current, a different value of the current threshold was observed at which the characteristics had a point of change in monotonicity. Thus , it seems possible that, despite the initial downward trend of the surge resistance examined in this paper, after applying strokes with a higher peak value, the nature of the changes may reverse.

Based on the measured time waveforms of the major current i and voltage u, voltage-current characteristics $u(i)$ were prepared.

Fig. 6 compares these characteristics for samples P1 (for first stroke) and P3 (for the fifth) that differ most in conductive additive content. Trend lines (dotted) were drawn for them. The slope of these lines went hand in hand with the expected change in electrical conductivity of the samples due to the addition of conductive carbon black. It was noted that the dashed lines plotted based on the values of the selected surge resistances R_{S11} and R_{S35} were close to the trend lines.

In view of this, the surge resistance was proposed as a useful indicator in quickly estimating the electrical properties of the samples under test.

Conclusions

Experimental studies indicated that it is possible to evaluate electrical properties of composite materials dedicated to aerospace industry using the developed laboratory stand for lightning-type current surge testing.

The proposed parameter of surge resistance R_S can act as an indicator to quickly evaluate the electrical properties of laminates without the need to prepare full voltage-current characteristics. The author agrees that this may not be enough to fully assess the quality of the material and believes that another determinant could be the effectiveness of electromagnetic field shielding. While the surge resistance of a material may be a reliable indicator to assess susceptibility to the direct effects of lightning, for the purpose of fully determining the induced transients in the circuits inside an airframe made of such a material may be insufficient. Resistance R_S determined during the first-impact of current allows to compare with each other materials that differ in construction, for example, the content of conductive carbon black additives.

The study did not fully analyze the mechanical and thermal effects of the surge currents impact on the tested samples. In the future however, studies are planned that will take into account the use of appropriate measurement techniques allowing precise definition of damage and structural changes of the laminates.

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***Author**: dr inż. Kamil Filik, Rzeszow University of Technology, Department of Electrical and Computer Engineering Fundamentals, ul. W. Pola 2, 35-959 Rzeszów, E-mail: kfilik@prz.edu.pl*

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