Investigation of composite material destruction under lightning stroke effect

V N Boronin¹, T G Minevich¹ *, E Y Kochetkova¹, A V Smorgonskiy² and I S Kolodkin¹

¹Institute of Energy and Transport Systems, Peter the Great Saint-Petersburg Polytechnic University, Saint-Petersburg, 195251, Russia
²HEIG-VD Haute Ecole d'IngEnierie et de Gestion du Canton de Vaud Yverdon-les-Bains, Switzerland

* E-mail: minevich_tg@spbstu.ru

Abstract. Destruction processes of composite materials under lightning stroke effect have been studied. The results of characteristic damages of samples have been presented upon a series of tests conducted with standard lightning currents and those ones whose shape is close to actual lightning stroke. There have been exhibited distinctions between the levels of sample damages: in the second case significant damages of composite matrix external layers have been shown, among which multiple destructions of bundles of carbon fibers at a depth of several layers, layer delamination and cavities formed inside sample. There have been described the results of generalized analysis of damages obtained by applying nondestructive inspection methods: stereoscopic microscope investigation and X-ray microtomography. The mechanism of damages has been presented on the basis of obtained data. The results of testing electrical, mechanical, thermal properties of composite samples have been given upon a set of experiments for lightning current resistance.

1. Introduction

Composite materials are widely used for manufacturing details and components in electric power engineering, automotive and aircraft industry, in space-based technology, bridge and high-rise construction. The use of composite materials is associated with the combination of their useful properties, i.e. lightness, elasticity, strength, environmental resistance. In electrical engineering industry composite materials are used to manufacture towers for overhead transmission lines, blades for wind-driven power plants of various capacities etc. [1]-[3]. The use of composite materials instead of traditional ones enables us to create environmentally compatible plants while reducing the weight of equipment and increasing the output of power-producing plants.

In the process of operation performance violations of wind-driven power plants have been detected up to total fading of their service characteristics which may be due to the action of lightning currents on composite-based blades. Blades of wind-driven plants have been partially or completely destroyed as a result of fire initiated by lightning stroke. Similar damages have been detected in composite materials whose component structure was different when using types of composite base and different reinforcing carbon or glass fibers. Conventionally, a standard lightning pulse is used to describe the process of object destruction under lightning impact [4]-[9]. In papers [10], [11] it has been shown that the application of standard lightning pulse for calculations or tests prevents from reproducing a
comprehensive lightning effect on composite samples. Statistical analysis of experiments conducted on Saintis tower (Switzerland) has shown that actual forms of lightning currents differ from standard pulse waveforms. A standard lightning pulse simulates a fast current rise and fall to zero values within tens of microseconds [12]-[14]. The energy of such a pulse is small and does not result in heating the point of lightning stroke impact. Actual pulse does not show the fall of current to zero values after its quick rise. The current may reach the value of kiloampere in final stage of pulse during a long time (milliseconds). This current transfers the main charge and causes high-temperature breakdown of composite materials [15], [16].

2. Model description
Dimensional data and physical properties of composite materials have been chosen on the basis of values got for manufactured samples. Major parameters used for simulation are given in Table 1.

| Parameter              | Value | Parameter              | Value |
|------------------------|-------|------------------------|-------|
| Width, mm              | 250   | Heat conduction K, W/m°C | 11.8  |
| Length, mm             | 250   | Heat conduction K, W/m°C | 0.609 |
| Thickness, mm          | 1.1   | Heat conduction K, W/m°C | 0.609 |
| Layer depth, mm        | 0.1375| Thermal-expansion factor αx | 5e-6  |
| Number of layers       | 8     | Thermal-expansion factor αy | 4e-6  |
| Layer orientation      | 45/0/-45/90 | Thermal-expansion factor αz | 4e-6  |
| Density, kg/m³         | 1520  | Specific heat capacity, J/kg°C | 1070  |

3. Method of analysis
To analyze lightning resistance properties of composite materials there has been designed in Peter the Great St. Petersburg Polytechnic University (SPbPU) a bench simulating the impact of either standard or actual lightning current pulse [15]-[17]. Surge-current generator designed on the basis of two capacitor storages with distinct time and energy responses and interface developed on the basis of switching unit with exploding conductor make the base of test facility. The task of the optimal selection of the impulse source parameters is the task of the parametrical synthesis [18]-[20]. Standard pulse contains only “fast” component while actual pulse is simulated through combination of “fast” and “slow” components. Representative results of composite sample damages after test runs under standard lightning pulse impact as well as under the action of pulse whose shape is close to actual one are given in Table 2.
Table 2. Representative results of composite sample damages and lightning current parameters recorded while testing.

| Sample number | Type of lightning current pulse | Current amplitude in «fast» stage kA | Current amplitude in «slow» stage kA | Charge (cl) | Damage level | Photo of sample central part |
|---------------|---------------------------------|--------------------------------------|--------------------------------------|-------------|--------------|-----------------------------|
| 1             | Standard lightning pulse        | 18                                   | -                                    | 0.36        | Weak, there are signs of breakdown along carbon fibres | ![Photo](image1) |
| 2             | Actual lightning pulse          | 18                                   | 1                                    | 10.4        | Heavy, there are damages of sample volume with egressing | ![Photo](image2) |

As for samples 1 and 2 whose test results are given in Table 1, the analysis of damages has been conducted by applying nondestructive inspection technique. External damages observed on samples differ greatly. As a result of current pulse passing of greater duration and consequently of greater charge composite samples get more marked damages.

At performing surface analysis with stereoscopic microscope insignificant damages have been detected on sample 1 matrix made of epoxide resin and partial damages of carbon fibers. Studies of sample 2 with the use of stereoscopic microscope have shown heavy damages not only on the surface but in inner layers of composite material. However, the performance of optical analysis was hampered due to upper layer destruction. That is why the both samples were subjected to nondestructive inspection method with the use of X-ray microtomography. The results for sample 1 are shown on Figure 1 where one can see fiber destruction inside sample with blind cracks between inner layers of composite material. Results for sample 2 are given on Figure 2.

![Figure 1](image1)

**Figure 1.** Results of sample 1 X-ray microtomography: a) 3D type of carbon fibers and their damages, matrix of epoxide resin is not shown; b) 2D section plane through sample.
Figure 2. Results of sample 2 X-ray microtomography: a) 3D type of carbon fibers and their damages, damages of epoxyde resin matrix; b) 2D section plane through sample.

On Figure 2 there are significant damages of composite matrix external layers, multiple destructions of carbon fiber bundles at the depth of several layers, layer delamination and cavities formed inside sample.

4. Electrothermal and thermomechanical analysis
The purpose of electrothermal analysis was to get electrical potential distribution on sample volume. At that, the sample lower layer was grounded and the current was supplied to the sample in central part of upper layer. In the first layer carbon fibers are on the angle 45°. The electrical conductivity along fibers is extremely high as compared to that one across fibers. This influences potential distribution, in the first layer it is of ellipsoidal shape. In the second layer carbon fibers are on the angle 0°, so potential distribution is of another shape. Moreover, the potential amplitude is far less in the second layer as compared to the first one.

The goal of thermomechanical analysis is to define the ultimate breaking strength of a sample once upon lightning current passing through it. For this purpose one should take out of a sample under electrothermal analysis components in a part as wide as 25 mm and as long as 250 mm as recommended by ASTM 3039 standard for performing mechanical tests [21]-[23]. One can simulate mechanical test for a given 25x250 mm plate when one end is fixed and another one is extended. Temperature variations result in variations of mechanical properties of samples, their dependence on temperature is shown in Table 3 and on Figure 3.

| Table 3. Carbon fiber-reinforced plastic mechanical properties within different temperature ranges. |
|-------------------------------------------------|----------|-----------|-----------|-----------------|
| Temperature range, °C | | 25-260 | 260-600 | More than 600 |
| Elastic modulus, hPa | | | | |
| Ex | 137 | 82.2 | 13.7 |
| Ey | 8.2 | 4.92 | 0.82 |
| Ez | 8.2 | 4.92 | 0.82 |
| Poisson ratio | | | | |
| vxy | 0.34 | 0.35 | 0.36 |
| vyz | 0.34 | 0.35 | 0.36 |
| vxz | 0.34 | 0.35 | 0.36 |
| Shearing elastic modulus, hPa | | | | |
| Gxy | 4.36 | 2.616 | 0.436 |
| Gyz | 4.36 | 1.8 | 0.3 |
| Gxz | 3 | 2.616 | 0.436 |
5. Simulation results

The results of deformation simulation obtained for samples with layers 45/0/-45/90 are shown on Figure 4 for several amplitude values of lightning current pulse passed through sample on the first stage of simulation. The significance of lightning current pulse amplitude for limit strength and elastic modulus has been proven. The greater is the amplitude value of current pulse passed through sample the more marked is the degradation of its mechanical properties.

Computed values of elastic modulus E and strength limit at extension $\sigma_l$ are given in Table 4. At current pulse component of 50 kA amplitude passing, the elastic modulus is reduced by 77 per cent as compared to undamaged sample and its strength limit – by 59 per cent.

Table 4. Relationships between mechanical properties and lightning current pulse amplitude for composite samples.

| Reference sample currentless | E, MPa | Reduction | $\sigma_l$, MPa | Reduction |
|-----------------------------|--------|-----------|-----------------|-----------|
|                             | 51660  | 100%      | 454             | 100%      |
| 10 kA                       | 49797  | 96%       | 297             | 65%       |
| 30 kA                       | 43959  | 85%       | 286             | 63%       |
| 50 kA                       | 39972  | 77%       | 269             | 59%       |
Similar analysis has been performed for a sample with unidirectionally oriented carbon fibers. Obtained performance is shown on Figure 5.

![Figure 5. Relationships between deformation and potential for a sample with unidirectionally oriented fibers not subjected to lightning current pulse action (violet curve), subjected to lightning current pulse of 10 kA amplitude (red curve), 30 kA (blue curve), 50 kA (green curve).](image)

6. Conclusions
1. First investigations of damaged samples have been performed by applying non-destructive inspection method with the help of X-ray microtomography. There have been demonstrated internal damages of composite samples under lightning current effect. The mechanism of damages has been described on the basis of obtained data. Electrical, mechanical, thermal properties of samples have been defined in experimental way by using modern techniques and devices.

2. Investigations have shown significant distinctions between damages of samples under the effect of lightning current of standard shape and those ones close to actual lightning currents. In the second case internal damages of carbon fibers and epoxy resin matrix cause the degradation of their mechanical properties. Such a comparison of standard and actual lightning current effect for composite materials was performed for the first time and it should be applied for lightning resistance testing of blades of wind-driven power plants, aircraft and helicopter components which may be subjected to lightning stroke effect.

3. Testing of pre-production units following the proposed technique will enable to carry out a correct assessment of their potential external and internal damages and to select an appropriate model of lightning protection so as to reduce their damages and prevent possible failures.

Acknowledgements
Work is performed under support of Federal target program "Research and development on priority directions of development of scientific-technological complex of Russia for 2014 - 2020 years". Agreement on the grant № 14.584.21.0019 from 30.11.2015 (Project No RFMEFI58416X0019), theme "The impact of experimentally obtained forms of lightning current pulse on the mechanical characteristics of composite structures".

References
[1] T. Ogasawara, Y. Hirano, and A. Yoshimura 2010 Coupled thermal–electrical analysis for carbon fiber/epoxy composites exposed to simulated lightning current Composites Part A: Applied Science and Manufacturing 41(8) 973–81
[2] Li Y et al 2015 Experimental study of damage characteristics of carbon woven fabric/epoxy laminates subjected to lightning strike Applied Science and Manufacturing 79 164–75
[3] Bondarenko A, Korovkin N, Lebedeva A and Minevich T 2017 Models for implementation of linear, non-linear, and parametrical circuits in traffic safety control devices Transportation research procedia 20 68–73
[4] Mazur V, Fisher B D, Gerlach J C 1984 Lightning strikes to an airplane in a thunderstorm Journal of Aircraft 21(8) 607–11
[5] Shishigin D and Shishigin S 2017 Numerical modeling in EMC problems of electric power substations when lightning strikes 17th IEEE Int. Conf. on Environment and Electrical Eng. and 2017 1st IEEE Industrial and Commercial Power Systems Europe 7977476.
[6] Plumer J A 2012 Laboratory test results and natural lightning strike effects: how well do they compare 31st International Conference on Lightning Protection ICLP 2012 6344201.
[7] Silin, N, Ignatev N, Kalmykov D 2017 Advanced electromagnetic control method of transformer equipment 2017 Int. Conf. ICIEAM 8076269.
[8] Garolera A C et al. 2016 Lightning damage to wind turbine blades from wind farms in the US IEEE Trans. on Power Delivery 31(3) 1043–9
[9] Korovkin N et al. 2012 Computing methods for building earthing devices in problems related to EMC of substations IEEE Int. Symp. on EMC 6396752.
[10] Smorgonskiy A, Rachidi, F, Rubinstein M, Korovkin N and Vassilopoulos A 2017 Are standardized lightning current waveforms suitable for aircraft and wind turbine blades made of composite materials? IEEE transactions on EMC 59(4) 1320–8 7894220
[11] Smorgonskiy A V et al 2011 A new method for the estimation of the number of upward flashes from tall structures Int. symp. on lightning protection 97–100.
[12] Silin N, Korovkin N and Minevich T 2017 Simulation of grounding devices for power system lightning protection provision Int. Conf. on Industrial Engineering, Applications and Manufacturing ICIEAM 2017 8076412.
[13] Korovkin N, Marthe E, Rachidi F and Selina E 2003 Mitigation of electromagnetic field radiated by PLC systems in indoor environment Int. Journal of Com. Systems 16(5) 417–26
[14] Eriksson A J and Meal D V 1984 Incidence of direct lightning strikes to structures and overhead lines IEEE Conference Publication 236 67–71
[15] Korovkin N, Krivosheev S and Goncharov V 2017 Evaluation of lightning-resistant samples of composite heavy-duty blades of wind generators IEEE EIConRus 1550–2
[16] Korovkin N, Adamyan Yu and Minevich T 2018 Investigating the lightning resistance of composite materials for ensuring safe operation of transport infrastructure facilities Transportation Research Procedia 36 320–5
[17] Adamyan Yu, Krivosheev S and Minevich T 2018 Investigation of the wind generator blades material resistance to the lightning current action MATEC Web of Conf. 245 15001
[18] Issa F et al 2002 Analysis of power line communication networks using a new approach based on scattering parameters matrix IEEE Int. Symp. on EMC 2(90) 1043–7
[19] Belyaev N A, Korovkin N V, Frolov O V and Chudnyi V S 2013 Methods for optimization of power-system operation modes Russian Electrical Engineering 84(2) 74–80
[20] Adalev A, Korovkin N and Hayakawa M 2008 Using linear relations between experimental characteristics in stiff identification problems of linear circuit theory IEEE transactions on circuits and systems I: fundamental theory and applications 55(5) 1237–47
[21] Abdelal G and Murphy A 2014 Nonlinear numerical modelling of lightning strike effect on composite panels with temperature dependent material properties Composite Structures 109 268–78
[22] Wang Y and Zhupanska O I 2015 Lightning strike thermal damage model for glass fiber reinforced polymer matrix composites and its application to wind turbine blades Composite Structures 132 1182–91
[23] Wang F S, Ji Y Y, Yu X S, Chen H and Yue Z F 2016 Ablation damage assessment of aircraft carbon fiber/epoxy composite and its protection structures suffered from lightning strike *Composite Structures* **145** 226–41