



Cairo University

SIMULATION OF LIGHTNING STRIKE EFFECTS ON AIRCRAFT SKIN COMPOSITE LAMINATE

By

Muhammad Elsayed Hamza Khalil

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Aerospace Engineering

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2018

SIMULATION OF LIGHTNING STRIKE EFFECTS ON AIRCRAFT SKIN COMPOSITE LAMINATE

By

Muhammad Elsayed Hamza Khalil

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Aerospace Engineering

Under the Supervision of

Prof. Dr. Nader M. Abuelfoutouh

Assistant Prof. Dr. Gasser F. Abdelal

.....
Emeritus Professor
Aerospace Engineering Department
Faculty of Engineering, Cairo University

.....
Assistant Professor
School of Mechanical and Aerospace
Engineering, Queen's University Belfast, UK.

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2018

SIMULATION OF LIGHTNING STRIKE EFFECTS ON AIRCRAFT SKIN COMPOSITE LAMINATE

By

Muhammad Elsayed Hamza Khalil

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE
in
Aerospace Engineering

Approved by the Examining Committee

Prof. Dr. Nader M. Abuelfoutouh
Emeritus Professor at Aerospace Engineering,
Cairo University

Thesis Main Advisor

Assistant Prof. Dr. Gasser F. Abdelal
Assistant Professor at School of Mechanical and Aerospace
Engineering, Queen's University Belfast, UK

Advisor

Prof. Dr. Atef O. Sherif
Emeritus Professor at Aerospace Engineering,
Cairo University

Internal Examiner

Prof. Dr. Adrian Murphy
Professor at School of Mechanical and Aerospace
Engineering, Queen's University Belfast, UK

External Examiner

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2018

Engineer: Muhammad Elsayed Hamza Khalil

Date of Birth: 25/ 03/ 1989

Nationality: Egyptian

E-mail: Muhammad.hamza@eng1.cu.edu.eg

Address: Samatay, Qoutour, Gharbyia, Egypt

Registration Date: 01/ 03/ 2012

Awarding Date: 2018

Award: Master of Science

Department: Aerospace Engineering

Supervisors: Prof. Dr. Nader M. Abuelfoutouh
Assistant Prof. Dr. Gasser F. Abdelal

Assistant Professor at Queen's University Belfast, UK

Examiners: Prof. Dr. Nader M. Abuelfoutouh, Thesis Main Advisor

Assistant Prof. Gasser F. Abdelal, Advisor

Assistant Professor at Queen's University Belfast, UK

Prof. Dr. Atef O. Sherif Internal Examiner

Prof. Dr. Adrian Murphy External Examiner

Professor at Queen's University Belfast, UK



Title of Thesis:

Simulation of Lightning Strike Effects on Aircraft Skin Composite Laminate

Key Words:

Lightning Strike, Electric Arc, Composite Laminates, Thermal Plasmas, Magnetohydrodynamic Modeling (MHD).

Summary:

Aircraft carbon fiber/epoxy composite material is sensitive to lightning strike. Its damage and protection design suffering from lightning strike is becoming increasingly important. A numerical model is proposed to describe an arc and its interaction with a composite material in an anodic configuration. After a validation step with published experimental results in two dimensions (2D), the model is used to quantify the degradation level of the material versus the pulse duration and the current intensity value. A three-dimensional (3D) model is then developed and used to evaluate the degradation of the composite material. This model shows the behaviour of the plasma column representing the lightning strike and quantifies the power transferred to the anode. The contribution of this study is modeling the composite panels' material properties as temperature dependent, which was excluded by other researchers. The order of estimated temperature (of the order of 45,000 K) and pressure (of the order of 0.1-0.2 MPa) suggests that the waveform – C damage is mainly due to thermoelectric effect, while pressure effect is minimum.

Acknowledgment

Thanks Allah first, last and forever for giving me knowledge, willingness and patience.

I would like to express my sincere gratitude to my advisor Prof. Mohamed N. Abu El-foutouh for the continuous support of my MSc study and related research, for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my MSc study.

My sincere thanks also goes to Prof. Gasser F. Abdelal who provided me an opportunity to join their team as intern, and who gave access to the laboratory and research facilities. Without their precious support it would not be possible to conduct this research.

Besides my advisors, I would like to thank the rest of my thesis committee: Prof. Atef o. Sherif, Prof. Adrian murphy for their insightful comments and encouragement, but also for the hard question which incited me to widen my research from various perspectives.

Last but not the least, I would like to thank my family: my parents and to my brothers and sisters for supporting me spiritually throughout writing this thesis and my life in general.

Dedication

To my father for his partnership in every success in my life.

Table of Contents

Acknowledgment	1
Dedication	i
Table of Contents	ii
List of Tables	iv
List of Figures	v
Nomenclature	vii
Abstract	x
Chapter 1: Introduction	1
1.1. Background	1
1.2. Lightning and aircrafts: damage and protections	2
1.2.1. Aircraft Zoning	2
1.2.2. Direct effects	3
1.2.3. Indirect effects	4
1.2.4. Laboratory tests for certification considerations	4
1.3. Objectives of present work	6
1.4. Organization of the thesis	6
Chapter 2: Literature Review	7
2.1. Direct effect damage induced by lightning	7
2.1.1. Metallic materials	7
2.1.2. Composite materials	8
2.2. Lightning modelling	10
2.2.1. Insights into lightning induced phenomena	10
2.2.2. Electro-thermal model	12
2.2.3. Mechanical based models	14
2.2.4. Energy based model	15
Chapter 3: Lightning Strike Multiphysics	17
3.1. Physical Modeling of the arc and governing equations	17
3.1.1. Theoretical Formulation	17
3.1.2. Assumptions	18
3.1.3. Electric Module (<i>ec</i>) & Magnetic Module (<i>mf</i>)	18
3.1.4. Fluid Flow Equations (<i>spf</i>)	18
3.1.5. Modelling of the arc-electrodes interfaces	19
3.2. Computational domain and boundary conditions	20
3.3. The heat transfer at the arc-electrodes interfaces	21

3.3.1.	The arc/anode interface	21
3.3.2.	The arc/cathode interface	23
3.4.	Waveform-C Simulation	23
3.5.	Analysis of the different regions of the process	24
3.5.1.	The arc plasma column	25
3.5.2.	The anode region.....	25
3.5.3.	The cathode region.....	26
3.6.	Finite Element Model.....	26
3.7.	Results and Discussion.....	28
3.7.1.	Experimental validation	32
Chapter 4	Interaction with the Composite Laminate	40
4.1.	Theoretical Formulation	40
4.2.	Finite Element Model.....	42
4.3.	Boundary Conditions.....	43
4.4.	Results and Discussion.....	44
Chapter 5	Lightning Strike Protection (LSP).....	48
5.1.	Introduction	48
5.1.1.	Solid Metal Foils (SMF)	49
5.1.2.	Expanded metal foils (EMF)	50
5.1.3.	Conductive paints.....	50
5.1.4.	Metalized carbon fibers.....	50
5.2.	Theoretical Formulation	52
5.3.	Finite Element Model.....	53
5.3.1.	Expanded Copper Foil (ECF)	53
5.3.2.	Glass/Epoxy Lamina.....	56
5.3.3.	Corrosion Resistance of Glass/Epoxy.....	57
5.4.	Results and Discussion.....	58
Chapter 6	Discussion and Conclusions.....	60
6.1.	Methodology	60
6.2.	Main accomplishments and findings.....	61
6.3.	Recommendations for future work.....	61
Appendix A:	The thermodynamic and transport properties of air plasma.....	63
Appendix B:	Subroutine file	69
References	76

List of Tables

Table 3-1: Material properties for all domains	20
Table 3-2: Model Boundary conditions	21
Table 4-1: Carbon fiber/epoxy thermal and electrical material properties vs. temperature [24].	43
Table 5-1: Copper thermal and electrical material properties vs. temperature [24].	54
Table 5-2: E-Glass fiber/epoxy thermal and electrical material properties	56

List of Figures

Figure 1-1: Formation of the leaders during a cloud-to-earth lightning strike	1
Figure 1-2: Airplane initiating a lightning strike	2
Figure 1-3: Aircraft zoning [1,2]	3
Figure 1-4: Normalized current for lightning strike tests in laboratory [3]	6
Figure 2-1: Lightning damage on aluminum skins (pinhole and magnetic forces action) [8-10]	8
Figure 2-2: Phenomena contributing to lightning direct effect on a fuselage panel [28]	11
Figure 2-3: Multi-physical actions of a lightning strike on composite material: thermal, electromagnetic and other components [25]	12
Figure 2-4: Possible phenomenon occurring with through-thickness electrical conduction [13]	12
Figure 2-5: Surface damage after a lightning strike [17]	13
Figure 2-6: Ultrasonic C-scan of post lightning strike specimens at 30, 50 and 70kA [27]....	16
Figure 2-7: Ultrasonic C-scan of post impact specimens at several energy (6.78J, 20.34J, 33.89J) [27]	16
Figure 3-1: Computational domain used for calculations, dimensions are in mm.	20
Figure 3-2: Definition of the normal vectors used in the model.	22
Figure 3-3: A typical pulsed current used in our model.	24
Figure 3-4: Evolution of the electric potential along the arc plasma axis.	25
Figure 3-5: Flowchart of multiphysics calculations.....	27
Figure 3-6: Schematic grid for the calculation domain.	28
Figure 3-7: Total heat flux injected at the surface of the anode	29
Figure 3-8: Plasma conduction heat flux injected at the surface of the anode	30
Figure 3-9: Condensation heat flux at the surface of the anode	30
Figure 3-10: Radiation loss at the surface of the anode.....	31
Figure 3-11: Current density injected at the surface of the anode	32
Figure 3-12: Current density injected at the surface of the anode.	33
Figure 3-13: Temperature profile of waveform-C at (a) $t = 0.25$ s and (b) $t = 0.5$ s.	34
Figure 3-14: Temperature profile of waveform-C at the anode surface	34
Figure 3-15: Velocity field of waveform-C at (a) $t = 0.25$ s and (b) $t = 0.5$ s.	35
Figure 3-16: Absolute pressure profile of waveform-C at (a) $t = 0.25$ s and (b) $t = 0.5$ s.	36
Figure 3-17: Electric Field of waveform-C at (a) $t = 0.25$ s and (b) $t = 0.5$ s.....	36
Figure 3-18: Magnetic flux density of waveform-C at (a) $t = 0.25$ s and (b) $t = 0.5$ s.	37
Figure 3-19: Magnetic Potential of waveform-C at (a) $t = 0.25$ s and (b) $t = 0.5$ s.	38
Figure 3-20: Electric Potential of waveform-C at (a) $t = 0.25$ s and (b) $t = 0.5$ s.....	38
Figure 4-1: Benchmark composite panel setup from impulse electrical current with applied boundary conditions.....	44
Figure 4-2: Geometry used by Jennings and Hardwick [19].	45
Figure 4-3: Material degradation experimentally obtained by Jennings and Hardwick [19]. .	45
Figure 4-4: Decomposed laminate layout.	46
Figure 4-5: Top lamina temperature profile.....	46
Figure 4-6: Temperature profile for 2 nd layer.	47
Figure 4-7: Temperature profile for 3 rd layer.	47
Figure 4-8: Temperature profile for 4 th layer.....	48
Figure 5-1: Protections against lightning strikes (a) ECF and (b) SCF	49
Figure 5-2: Visible damage after lightning strike on (a)unprotected sample and.....	51

Figure 5-3: modelling of the copper protection panel (ECF)	55
Figure 5-4: Benchmark protected meshed composite panel setup from impulse electrical current with applied boundary conditions.....	56
Figure 5-5: Protected meshed composite panel at the panel center.	56
Figure 5-6: Temperature profile for the composite laminate including the copper mesh metal (ECF) and GF.....	58
Figure 5-7: Temperature profile for the composite laminate including the copper mesh metal (ECF) and GF at the panel center	58

Nomenclature

Abbreviations

LTE	Local Thermodynamic Equilibrium
MHD	Magnetohydrodynamic
LSP	Lightning Strike Protection system
FEA	Finite Element Analysis
SMF	Solid Metal Foils
ECF	Expanded Metal Foils
CFRP	Carbon Fiber Reinforced Polymers

Symbols

\vec{H}	Vector magnetic field intensity
\vec{D}	Electric displacement vector
σ	Electrical conductivity
\vec{J}	Current density
ε	Dielectric constant (permittivity)
μ_0	Permeability
\vec{E}	Electrical field intensity
V	Electrical potential
\vec{B}	Magnetic flux density
\vec{A}	Magnetic potential
\vec{v}	Velocity vector
t	Time
ρ	Density
μ	Viscosity
p	Pressure
k	Thermal conductivity
T	Temperature
T_0	Ambient Temperature
k_B	Stefan-Boltzmann constant
e	Electron charge

ϵ_N	Net emission coefficient
q_a	Anode heat flux
q_c	Cathode heat flux
q_{pl}	Plasma heat flux
\vec{n}	Vector normal to the electrodes surfaces
j_i	Ion current density
j_e	Electron current density
V_i	Air ionization potential
ϕ_c	Cathode work function
ϕ_a	Anode work function
ϕ_e	Effective work function
V_A	Anode fall voltage
A_r	Richardson's constant
j_r	Richardson current density
r_c	Internal volumetric current source per unit volume
P_{ec}	Electrical energy
η_v	Energy conversion factor
\dot{U}	Time rate of the internal energy
r	Heat generated within the body
T_b	Boiling temperature
T_{tc}	Critical temperature
m	Atomic mass of the material
L_v	Latent heat of vaporization of the material
x, y, z	Space coordinates
C_p	Specific heat at constant pressure
C_{pb}, C_{pa}	Specific heat of composite and char
f_a, f_b	Volume fraction of composite and char
H_s	Decomposition heat
α	Decomposition degree
M_i	Initial mass of composite
M_e	Final mass of composite