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INVESTIGATION OF LIGHTNING DAMAGES IN GLASS FIBRE-REINFORCED PREPREG COMPOSITES

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INVESTIGATION OF LIGHTNING DAMAGES IN GLASS FIBRE-REINFORCED PREPREG COMPOSITES

By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

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INVESTIGATION OF LIGHTNING DAMAGES IN GLASS FIBRE-REINFORCED PREPREG COMPOSITES

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Chair : Chia Chen Ciang, PhD
Faculty : Engineering

Glass fibre reinforced polymers (GFRP) are typically used in aircraft parts where lightning strikes the most. Recent studies had been focusing on lightning damage on carbon fibre reinforced polymers (CFRP) instead of GFRP. Besides that, the main nondestructive evaluation (NDE) technique used to detect lightning damage in these studies is water immersion ultrasonic c-scan instead of Ultrasound Propagation Imaging (UPI). Thus, it can be seen that the detection and evaluation of lightning damages on GFRP using UPI is not well investigated. This study aims to accurately and statistically detect, define the shape and size, and evaluate the severity of lightning damages in GFRP using UPI. Four 1-layer and two 3-layer GFRP specimens had been manufactured and struck using various breakdown voltages, which are 6kV, 7kV, and 16kV 1.2/50µs impulse voltages, for three of the 1-layer specimens respectively, and 18kV 1.2/50µs impulse voltage for the rest of the specimens. The lightning simulation standards used in this study are IEC 60060-1 (2010), IEC 60060-2 (2010), and IEC 60060-3 (2006). Ultrasonic data were obtained using a UPI system and were subsequently processed using the Statistically Thresholded Anomaly Mapping (STAM) technique that was developed in this study. The results show that the damage size increases proportionally with the increase of breakdown voltage, which are 27.75mm^2, 29.72mm^2, and 38.5mm^2 for 6kV, 7kV and 16kV breakdown voltages respectively for the 1-layer specimens. A significant increase in damage size (847.25mm^2) was detected on Specimen 4 due to an unexpected surface flashover event. 3-layer specimens suffered greater damages, measuring 597.25mm^2 and 573.5mm^2 respectively, compared to 1-layer specimens due to 3-layer specimens being susceptible to delaminations. The results proved that lightning damage in GFRP could be detected using the UPI system. The STAM technique developed in this project could distinct damage from the noise based on a statistical threshold, hence could provide higher reliability and accuracy in evaluating the size of lightning damage. Lastly,

it was found that the size of lightning damages increases when breakdown voltage increases, subjected to further investigations.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains.

PENYELIDIKAN KEROSAKAN KILAT DALAM KOMPOSIT PRAPREG DIPERKUAT GENTIAN KACA

Oleh

GAN CHIA SHENG

Mac 2019

Pengerusi : Chia Chen Ciang, PhD
Fakulti : Kejuruteraan

Komposit prapreg diperkuat gentian kaca (GFRP) biasanya digunakan untuk membuat komponen-komponen kapal terbang yang sering dipanah kilat. Walau bagaimanapun, kajian-kajian akhir-akhir ini hanya menumpukan perhatian kepada kerosakan kilat pada komposit prapreg diperkuat gentian karbon (CFRP) manakala kerosakan kilat pada GFRP telah diabaikan. Sementelahan itu, teknik uji tanpa musnah (NDE) yang digunakan oleh kajian-kajian tersebut ialah ultrasonik imbas-C jenis rendaman air, bukan Pengimejan Rambatan Ultrabunyi (UPI). Oleh itu, hal ini bolehlah dikatakan bahawa pengesanan and penilaian kerosakan kilat pada GFRP dengan menggunakan sistem UPI tidak dikaji dengan secukupnya. Pengajian ini bertujuan untuk mengesan dan mengimej bentuk dan saiz kerosakan kilat secara tepat dan berstatistik, di samping menilai keterukannya dengan menggunakan UPI. Empat keping GFRP 1-lapis dan dua keping GFRP 3-lapis telah dibuat dan disambar dengan voltan dedenyut 1.2/50µs 6kV, 7kV, dan 16kV, bagi tiga daripada empat GFRP 1-lapis masing-masing, dan voltan dedenyut 1.2/50µs 18kV bagi spesimen-spesimen yang lain. Standard-standard penyelakuan panahan kilat yang digunakan dalam kajian ini ialah IEC 60060-1 (2010), IEC 60060-2 (2010), dan IEC 60060-3 (2006). Data ultrabunyi telah diperolehkan dengan menggunakan sistem UPI dan seterusnya diproses dengan teknik Pemetaan Anomali Berambang Statistik (STAM) yang telah diperkenalkan dalam kajian ini. Keputusan kajian ini menunjukkan bahawa saiz kerosakan bertambah secara berkadar dengan peningkatan voltan pecah tebat, iaitu 27.75mm^2, 29.72mm^2, dan 38.5mm^2 bagi 6kV, 7kV, dan 16kV voltan pecah tebat masing-masing untuk spesimen-spesimen 1-lapis. Spesimen 4 telah mengalami peningkatan saiz kerosakan yang ketara berbanding dengan spesimen 1-lapis yang lain akibat daripada sambaran kilat yang berlaku pada permukaan spesimen sahaja. Spesimen-spesimen 3-lapis telah mengalami kerosakan yang teruk berbanding dengan spesimen-spesimen 1-lapis, iaitu 597.25mm^2 dan 573.5mm^2 masing-masing. Hal ini adalah kerana spesimen 3-layer boleh mengalami pelekangan manakala spesimen 1-lapis tidak akan

mengalami kerosakan jenis tersebut. Keputusan-keputusan kajian ini membuktikan bahawa kerosakan kilat pada GFRP dapat dikesan dengan menggunakan sistem UPI. Teknik STAM yang diperkenalkan dalam projek ini dapat membezakan kerosakan dan hingar dengan menggunakan ambang statistik. Oleh itu, STAM dapat meningkatkan keutuhan dan ketepatan penilaian kerosakan kilat. Akhirnya, kajian ini telah mendapati bahawa saiz kerosakan kilat meningkat apabila voltan pecah tebat meningkat. Dapatan ini adalah di bawah penyelidikan yang akan datang.

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The thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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LIST OF ABBREVIATIONS

A	Asymmetric
A/D	Analog to digital converter
AWPI	Anomalous Wave Propagation Imaging
AWPM	Anomalous Wave Propagation Movie
DFT	Discrete Fourier Transform
DT	Damage Threshold
DWS	Dual-energy Wave Subtraction
GFRP	Glass fibre reinforced polymore
H	Total number of horizontal points
FK	Frequency-wavenumber
LDV	Laser Doppler Vibrometer
LMS	Laser mirror scanner
LWT	Local Wavenumber Technique
M	Constant multiplier in the STAM technique
MAWS	Multidirectional Adjacent Wave Subtraction
$n\Delta t$	n multiplied by Δt, where n represents slice number and Δt represents time interval
N	Total number of samples/pixels used
Nd:YAG	Neodymium-doped yttrium aluminium garnet
NDE	Nondestructive Evaluation
NDI	Nondestructive Inspection
NDT	Nondestructive Testing
P	Percentage of total number of pixels/samples
PC	Computer
PL	Pulsed laser
PZT	Lead zirconate titanate

R	Number of samples/pixels used
S	Symmetric
STAM	Statistically Thresholded Anomaly Mapping
T	Total number of time samples
ToF	Time of flight
UPI	Ultrasonic Propagation Imaging
UWPI	Ultrasonic Wave Propagation Imaging
UWPM	Ultrasonic Wave Propagation Movie
V	Total number of vertical points
VTWAM	Variable Time Window Amplitude Map

CHAPTER 1

INTRODUCTION

This thesis explains the investigation of lightning damage of aerospace-grade glass fibre reinforced polymer (GFRP) using an Ultrasonic Propagation Imaging (UPI) technique called Statistically Thresholded Anomaly Mapping (STAM) developed in this study. The imaging technique was developed as functionality extension for a nondestructive evaluation system known as scanning laser ultrasonic wavefield propagation imager. In this chapter, the background of the problem is described in Subchapter 1.1 Problem Background. The problem statement is discussed in Subchapter 1.2 Problem Statement, followed by the objectives and aim of this study in Subchapter 1.3 Aim and Objectives. Subchapter 1.4 Scope of Work defines the scope and limitations of this study. Other than that, the outline of the thesis is also stated in Subchapter 1.5 Thesis Layout, and contents of each following chapter are briefly explained.

1.1 Problem Background

Composites used in aircraft structural applications have greater mechanical properties compared to aluminium alloy such as high specific stiffness and strength (Hirano, Katsumata, Iwahori, & Todoroki, 2010). The fact that these composites are much superior to their aluminium counterparts in aircrafts have drawn wide interest in the aircraft manufacturing industry. Among the types of composites used for aircrafts, there exists a composite called Glass Fibre Reinforced Polymer (GFRP), which is mainly used in the making of radomes (Dutton, Kelly, & Baker, 2004). Due to its location on the tip of a plane, also known as the nose, it is more likely to suffer lightning damage than other aircraft parts since the nose of an aircraft is the most common lightning attachment point (Sweers, Birch, & Gokcen, 2012), as shown in Figure 1.1. Compared to aluminium alloy, GFRP has a much lower electrical (Kawakami & Feraboli, 2011) and thermal conductivities (Scott & Scala, 1982), which make them highly susceptible to lightning damages. Combining the fact that the highly lightning damage susceptible GFRP is very likely to be hit by lightning and the fact that it is mainly used for the construction of radomes which houses important radar and communication instruments, it can clearly be seen that the relationship between lightning damages and GFRP should be well studied.

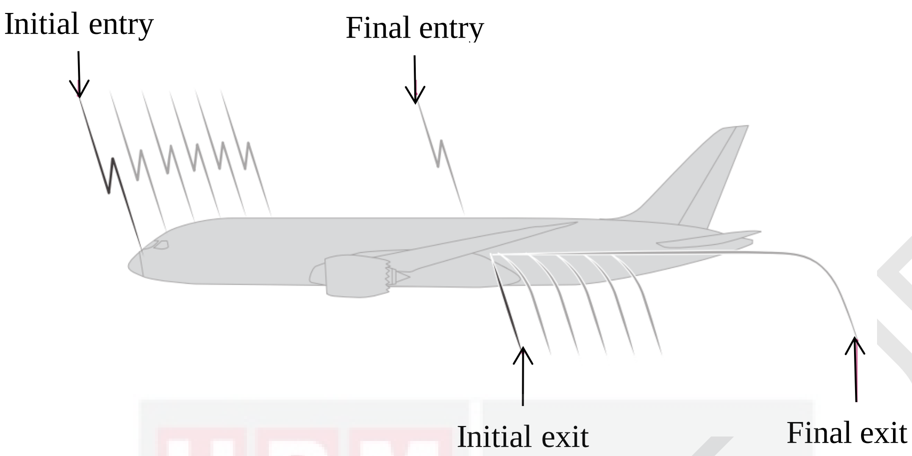

Figure 1.1: Lightning Entry and Exit Points on an Airplane. Source: (Sweers et al., 2012)

There are a few types of lightning damage on GFRP, such as fibre breakages, delaminations, and charring at the lightning attachment point. Lightning damages on GFRP are typically caused by acoustic shock or through resistive heating during a lightning strike. Acoustic shocks from lightning strikes are caused by the rapid heating of air in a short span of time, normally only lasting tens of nanoseconds to a second (Dwyer & Uman, 2014), when lightning travels through an ionized channel of air which guides the lightning current to its destination. This in turn causes a rapid expansion of air at supersonic speeds that further results in shockwaves (Dwyer & Uman, 2014; Feraboli & Miller, 2009; Kawakami & Feraboli, 2011; Rupke, 2002). Damages are inflicted on GFRP when these shockwaves come into contact with it, which causes a pressure rise on the surface of GFRP, causing fragmentation, delamination, and cracks to the composite.

Damages through resistive heating are caused by the rise in temperature as lightning current travels through GFRP, also known as Joule Heating or Ohmic Heating. The power (energy per second) of resistive can be calculated using Joule's first law, which states that the power of the heat generated when current travels through a conductor is proportional to the product of the conductor's resistance and the current squared, shown in Equation 1.1.

$$P \propto I^2 \cdot R \tag{1.1}$$

Due to high temperatures caused by the lightning current, the resin/fibre interface of GFRP breaks down through pyrolysis and burning (Kawakami & Feraboli, 2011). Other than that, the resin in GFRP releases gases during pyrolysis (Schulte-Fischedick, Seiz, Lützenburger, Wanner, & Voggenreiter, 2007), which will form an air bubble if the gases are trapped within the interlaminar layer of the GFRP and thus causing the GFRP to delaminate. Furthermore, explosive fractures occur (Hirano et al., 2010) when these air bubbles are struck with the aforementioned acoustic shocks.

In order to detect these damages, nondestructive testings (NDE) are carried out. Due to ultrasound's sensitivity towards physical properties such as volume, thickness, temperature (Kouche & Hassanein, 2012), and most importantly, damages or anomalies present on the surface or within a material, such as delaminations and fibre breakages, ultrasound can be used to detect and evaluate damages on GFRP through various Ultrasonic Propagation Imaging (UPI) techniques, such as the local wavenumber technique (Juarez & Leckey, 2015) and the Anomalous Wave Propagation Imaging (AWPI) technique (Lee, Chia, Park, & Jeong, 2012). In its base form, UPI is often presented in the form of a video, where the indications of any damage are highly likely to be hidden within the incident waves. Other than that, UPI base videos are highly complex such that even with trained eyes, the result is most likely undecipherable. The situation worsens the more complex the object or structure being evaluated is. This is due to incident waves being reflected off native components such as bolts and nuts, mixing into the already complicated wavefield consisting of incident waves and anomalous waves. Figure 1.2 shows an example of the complexity of ultrasonic wavefields, where it is clear that the wave components overlap each other.

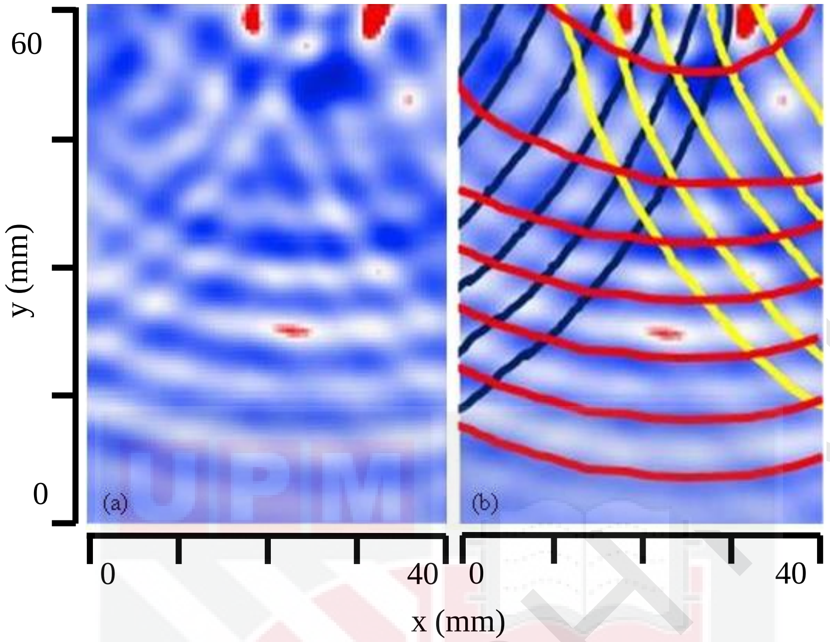

Figure 1.2: Incident wave and reflected waves from the sides, where (a) represents the original ultrasonic wavefield and (b) represents the ultrasonic wavefield with visual guide for each of its wave components where red lines are the incident waves, black lines are the reflected waves from the left side and yellow lines represent the reflected waves from the right side

In spite of UPI techniques being sensitive to damages, such as impact damages, without a statistical technique to process the UPI results, hazardous misinterpretations may occur. As aforementioned, UPI results is often highly complex due to high amplitude incident waves masking the highly sought after anomalous waves, which indicate the presence of damages. Even when suppressed, these incident waves tend to leave behind some noises that often cause the evaluation of the results, which are often images generated from the ultrasonic wavefield data, to be indecisive and inaccurate. Since it depends on the perspective of an inspector to evaluate the damages in the final result, the final judgement will differ from person to person, thus making it prone to doubts and human errors. To reliably analyze a lightning damaged GFRP, such as the determination of the damage shape and size, a statistical technique that only highlights damaged regions should be introduced.

1.2 Problem Statement

Although GFRP is used to build the radome of an aircraft, where lightning is most likely to attach to, the studies regarding the analysis of lightning damage on GFRP using UPI are lacking. The radome houses the radar antenna and other communication instruments for an aircraft and it is usually installed on aircraft parts where lightning strikes the most, such as an aircraft’s nose cone. Thus, lightning damage to the radome or its material, GFRP, should be well studied for fairly new nondestructive evaluation (NDE) techniques such as UPI to find out its efficacy in the detection of lightning damage. As such, investigations should be carried out to know the extent of UPI in the detection of lightning damages on GFRP.

Secondly, a statistical technique to determine the shape, size, and location of lightning damage is also currently not available for UPI techniques. Currently, UPI techniques require manual interpretations of final results in order to determine the presence of lightning damage in the inspected area. Such interpretations are prone to errors as perspectives differ from one inspector to another. However, with the use of a statistical technique to interpret the results, damaged areas will be clearly defined and the final conclusion made by any inspector on the presence of damage and its characteristics will be identical.

Thirdly, the relationship between the voltage of a lightning strike and GFRP is also not explored thoroughly. Although it is common knowledge that GFRP is used in the making of aircrafts, studies recently had only been focusing on the effects of lightning strikes on Carbon Fibre Reinforced Polymers (CFRP). Even though GFRP is only used in small quantities compared to CFRP, lightning damage to GFRP should not be ignored since it is more likely to be struck by lightning due to its position on an aircraft. As such, it is important to understand the relationship between the voltage of a lightning strike and the subsequent damage that it causes onto GFRP.

1.3 Aim and Objectives

The aim of this study is to accurately and statistically detect, define the shape and size, and evaluate the severity of lightning damages in aerospace-grade glass fibre reinforced polymers (GFRP) through Ultrasonic Propagation Imaging (UPI) by using frequency-wavenumber analysis of ultrasonic wavefields. This aim will be achieved through the following objectives:

1. To analyze lightning damage on aerospace-grade glass fibre reinforced polymer using Ultrasonic Propagation Imaging

2. To develop a reliable statistical damage threshold to accurately determine the size of the lightning damage.

3. To investigate the relationship between the voltage of a lightning strike and the severity of the lightning damage.

1.4 Scope of Work

This study focuses on the development of a technique that involves the use of the frequency-wavenumber domain that is able to statistically and accurately determine the location, shape and size of lightning damages on lightning struck aerospace-grade GFRP. Only four 1-layer and two 3-layer (0/90) type-E GFRP specimens were used due to the shortage of resources. These GFRP specimens were struck under IEC 60060-1 (2010), IEC 60060-2 (2010), and IEC 60060-3 (2006) standards by using a combination wave generator under various breakdown voltages with a fixed current since we are interested in the relationship between the voltage of a lightning strike and the severity of the damage caused by the lightning strike. Due to the time constraint, the relationship between current amplitudes and their effects on GFRP is not studied. The severity of the damages inflicted upon the specimens obtained using the proposed technique were compared with visual inspections with backlight illumination. This technique was proposed and accepted as an appropriate technique in the past so it is suitable to be used in this study. Aluminium aerospace materials are not of concern in this study as well because we are only interested on the effects of lightning strikes on composites since aluminium aerospace materials are much less susceptible to lightning damages. Optimization of the technique is also not included in the study as we are currently only focusing on developing the technique.

1.5 Thesis Layout

This thesis is divided into five chapters. Chapter 1 Introduction briefs the reader about the background of the problem as well as the aim and objective of this study. Chapter 2 Literature Review discusses and reviews the recent researches conducted by other researchers, such as recent UPI techniques used to detect damages. Chapter 3 Research Methodology discusses the methodology used to prepare the specimens to ensure that they are of aerospace-grade quality, such as the curing method used and the way the specimens were cut. This chapter also provides detailed explanation on the Statistically Thresholded Anomaly Mapping (STAM) technique developed in this study which was used to solve the problems stated in Chapter 1. Chapter 4 Results and Discussions displays the results of the experiments while stating logical explanations to each of the results. Chapter 5 Conclusions concludes the findings of this research and states the research yet to be done and which should be conducted in the future.

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LIST OF PUBLICATIONS

Chia Sheng Gan, Chen Ciang Chia, Lin Yaw Tan, M. Norkhairunnisa, Joel B. Harley (2018). Statistical evaluation of damage size based on amplitude mapping of damage-induced ultrasonic wavefield. *IOP Conf. Ser.: Mater. Sci. Eng. 405 012006.*

Chen Ciang Chia, Chia Sheng Gan, and F. Mustapha (2017). Local Wavefield Velocity Imaging for Damage Evaluation. *AIP Conf. Proc. 1806, 030001*

Gan Chia Sheng, Chia Chen Ciang, M. Norkhairunnisa, Joel B. Harley, Jung-Ryul Lee (2019). Statistically Thresholded Anomaly Mapping Method for Ultrasound Full Wavefield Data. Submitted to *NDT&E Int.*

Chia Sheng Gan, Lin Yaw Tan, Chen Ciang Chia, F. Mustapha, and Jung-Ryul Lee (2019). Nondestructive Detection of Incipient Thermal Damage in Glass Fiber Reinforced Epoxy Composite using the Ultrasonic Propagation Imaging. *Functional Composites and Structures* 1 025006. https://doi.org/10.1088/2631-6331/ab260a

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