UNIVERSITI PUTRA MALAYSIA

SCANNING LASER THERMOGRAPHIC SYSTEM FOR NONDESTRUCTIVE EVALUATION OF INCIPIENT THERMAL DAMAGES IN AIRCRAFT COMPOSITE PANEL

AFIQAH MUSA

FK 2018 141

SCANNING LASER THERMOGRAPHIC SYSTEM FOR NON-DESTRUCTIVE EVALUATION OF INCIPIENT THERMAL DAMAGES IN AIRCRAFT COMPOSITE PANEL

By

AFIQAH MUSA

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

May 2018

DEDICATION

This work is dedicated

To my parents

Family, friends, and husband

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Master of Science

SCANNING LASER THERMOGRAPHIC SYSTEM FOR NON-DESTRUCTIVE EVALUATION OF INCIPIENT THERMAL DAMAGES IN AIRCRAFT COMPOSITE PANEL

By

AFIQAH MUSA

May 2018

Chairman : Chia Chen Ciang, PhD
Faculty : Engineering

Composite materials applied in aerospace structure are getting popular due to advantages such as high specific strength and stiffness with favorable strength to weight ratio. However, incipient thermal damage (ITD) that can cause reduction of 60% of composite mechanical strength are still unable to be detected using conventional NDT&E method.

This project aims to develop an effective NDT&E tool that can detect or evaluate ITD through these three objectives. First, to synchronize laser system, laser scanner system and thermal imager as an active infrared imaging system. Second, to develop corresponding data acquisition and noise removal algorithm for extraction of local temperature-time profiles. Third, to validate the effectiveness of the system and algorithm for non-destructive evaluation of ITD in glass fiber reinforced composite plate (GFRP). In correspondence to research objective, laser pulse was implemented as a powerful thermal energy source in thermography method for evaluating ITD. GFRP plate was insulted with high temperature at range of material glass transition temperature, $0.8T_g$,$1.0T_g$,$1.1T_g$,$1.2T_g$ and $1.3T_g$(T = 97°C,121°C,133°C,145°C and 157°C) at time t = 120, 60, 30, 15, 10 and 5 minutes to prepare ITD as well as thermal damage (TD) for reference. Focus was done on ITD which are insulted at borderline temperature of $T_g$with relatively longer insult time; $0.8T_g$ and $1.0T_g$ at t = 120,60,30 minute. ITD evaluation in this study are realized in the form of percentage difference between damage and reference derived from thermal contrast base principle. Following this, result gained represents outliers with respective to reference area and thus indicate detection of damage. Result gained for ITD at $0.8T_g$ are 1.93851%, 0.30561% and 0.20913% meanwhile 2.02966%, 1.73518% and 0.53167% at

$1.0T_g$ for $t = 120,60,30$ minute. A gradual decrement trend can be seen from longer insult time to lower insult time to indicate level of severity on damage detected. According to system resolution and capability, these values are within the range and thus proves the detection of ITD. Further verification done using ultrasonic method also proves the inability of conventional NDT&E method to detect ITD as expected. Hence, with proposed Scanning Laser Thermographic system, all ITD that were insulted with temperature at borderline of T_g at relatively longer insult time had been successfully detected at minimum of 0.20913% at insult temperature; $0.8T_g$ with insult time t = 30 minute and at maximum of 2.02966% at insult temperature; $1.0T_g$ with insult time t = 120 minute.

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

SISTEM IMBASAN LASER TERMOGRAFI UNTUK UJIAN TIDAK MEROSAKKAN KEATAS KEROSAKAN TERMAL AWAL PADA PANEL KOMPOSIT KAPAL TERBANG

Oleh

AFIQAH MUSA

Mei 2018

Pengerusi : Chia Chen Ciang, PhD
Fakulti : Kejuruteraan

Bahan-bahan komposit yang diaplikasikan pada struktur aeroangkasa semakin meningkat populariti disebabkan oleh kelebihan-kelebihan seperti spesifik kekuatan dan kekenyalan yang tinggi serta nisbah berat kepada kekuatan yang berpatutan. Walaubagaimanapun, kerosakan termal awal (ITD) yang boleh mengakibatkan pengurangan 60% daripada kekuatan mekanikal bahan komposit masih lagi tidak boleh dikesan menggunakan cara ujian tidak merosakkan konvensional.

Tujuan kajian ini adalah untuk membangunkan alat NDT&E yang berkesan serta dapat mengesan atau menilai ITD menerusi tiga objektif ini. Pertama, untuk menyegerakkan sistem laser, sistem pengimbas laser dan pengimejan termal sebagai sistem pengimejan inframerah yang aktif. Kedua, untuk membangunkan algoritma pemerolehan data dan penghapusan hingar yang bersesuaian untuk pengekstrakan profil suhu setempat-masa. Ketiga, untuk mengesahkan keberkesanan sistem dan algoritma untuk penilaian tidak merusak ITD pada plat komposit polimer gentian kaca (GFRP). Dalam perkaitan pada objektif penyelidikan ini, sumber laser telah digunakan sebagai sumber tenaga haba yang kuat dalam kaedah termografi untuk menilai ITD. Plat GFRP dirosakkan dengan suhu tinggi pada julat suhu peralihan kaca bahan, $0.8T_g$,$1.0T_g$,$1.1T_g$,$1.2T_g$ dan $1.3T_g$(T = 97°C,121°C,133°C,145°C and 157°C) pada masa t = 120, 60, 30, 15, 10 dan 5 minit untuk menyediakan ITD serta kerosakan termal (TD) untuk rujukan. Tumpuan telah dilakukan pada ITD yang dirosakkan pada suhu sempadan T_g dengan masa yang lebih lama; $0.8T_g$ dan $1.0T_g$pada t = 120,60,30 minit. Penilaian ITD dalam kajian ini direalisasikan dalam bentuk peratusan perbezaan antara kerosakan dan rujukan yang diperoleh dari prinsip asas perbezaan termal. Berikutan itu, keputusan yang diperoleh mewakili keluarbatasan berbanding kawasan

rujukan, dengan itu menunjukkan pengesanan kerosakan. Hasil yang diperolehi untuk ITD pada $0.8T_g$ ialah 1.93851%, 0.30561% dan 0.20913% manakala 2.02966%, 1.73518% dan 0.53167% pada $1.0T_g$ untuk $t = 120,60,30$minit. Gaya penurunan secara beransur-ansur boleh dilihat bermula dari masa kerosakan yang lebih lama kepada masa keroskan yang lebih sebentar untuk menunjukkan tahap keparahan kerosakan yang dikesan. Menurut resolusi dan keupayaan sistem, nilai-nilai ini berada dalam lingkungannya dan dengan itu membuktikan pengesanan ITD. Pengesahan selanjutnya yang dilakukan menggunakan kaedah ultrasonik juga membuktikan ketidakupayaan kaedah NDT&E konvensional untuk mengesan ITD seperti yang dijangkakan. Oleh itu, dengan sistem pengimbasan Laser Termografik yang dicadangkan, semua ITD yang dirosakkan dengan suhu di sempadan T_g pada masa kerosakan yang lebih lama telah berjaya dikesan dengan sekurang-kurangnya 0.20913% pada suhu kerosakan; $0.8T_g$ dengan masa kerosakan $\boldsymbol{t}$ = 30 minit dan maksimum 2.02966% pada suhu kerosakan; $1.0T_g$ dengan masa kerosakan t = 120 minit.

ACKNOWLEDGEMENTS

All praise to Allah S.W.T, the Almighty God, and May peace and blessing are upon His beloved Prophet Muhammad. I would like to express my deepest gratitude to my parents for their never-ending support throughout this journey.

I would like to extend my thanks to Dr. Chia Chen Ciang for his encouragement, valuable advice, and guidance through this journey. Not to forget, thanks to my lab member, Gan Chia Seng for his supporting assistance in research work. Last but no least, thanks to all who have helped me in this journey.

I certify that a Thesis Examination Committee has met on 16 May 2018 to conduct the final examination of Afiqah Musa on her thesis entitled "Scanning Laser Thermographic System for Non-Destructive Evaluation of Incipient Thermal Damages in Aircraft Composite Panel" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

Members of the Thesis Examination Committee were as follows:

Mohd Sapuan bin Salit @ Sinon, PhD
Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohamed Thariq bin Hameed Sultan, PhD
Associate Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Rozli bin Zulkifli, PhD
Associate Professor
Universiti Kebangsaan Malaysia
Malaysia
(External Examiner)

RUSLI HAJI ABDULLAH, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 30 August 2018

This thesis was submitted to the Senate of the 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:

Chia Chen Ciang, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohamad Ridzwan Ishak, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Fairuz Izzuddin Romli, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

____
ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software

Signature: ______________________ Date: ________________

Name and Matric No: Afiqah Musa, GS41176

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) were adhered to.

Signature: ____________________

Name of Chairman of Supervisory Committee: Dr. Chia Chen Ciang

Signature: ____________________

Name of Member of Supervisory Committee: Dr. Mohamad Ridzwan Ishak

Signature: ____________________

Name of Member of Supervisory Committee: Dr. Fairuz Izzuddin Romli

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

T_g	Glass transition temperature
AE	Acoustic emission
AWPI	Anomalous wave propagation imaging
CFRP	Carbon fiber reinforced polymer
DAQ	Data acquisition
FAA	Federal aviation administration
FOV	Field of view
GFRP	Glass fiber reinforced polymer
ITD	Incipient thermal damage
LDV	Laser doppler vibrometer
LIF	Laser induced fluorescence
LMS	Laser mirror scanner
NDT&E	Nondestructive testing and evaluation
NI	National instrument
POM	Polyoxymethylene
PZT	Piezoelectric
Ref	Reference
ROI	Region of interest
SBS	Short beam shear
SLT	Scanning laser thermography
TC	Thermocouple
TD	Thermal damage
TNDT	Thermal nondestructive testing
ULW	Ultrasonic lamb wave

UPI	Ultrasonic propagation imaging
UT	Ultrasonic thermography
UWPI	Ultrasonic wave propagation imaging
VTWAM	Variable time window amplitude mapping
WUPI	Wavelet ultrasonic propagation imaging

CHAPTER 1

INTRODUCTION

This chapter presents introduction of research done on incipient thermal damage detection on composite aerospace structure using laser based thermography. *Section 1.1 Research Background* describes current deployment and usage scenario in aerospace structural parts. The deployment difficulties are highlighted at the end of the session, and the core of the problems is stated in *Section 1.2 Problem Statement*. Hypothesis on solving problems is described in *Section 1.3 Hypothesis* followed by detailed objectives as well as scope of research in *Section 1.4 Research Objectives* and *Section 1.5 Scopes of Research*. Finally, *Section 1.6 Thesis Organization* shall provide brief flows and statement throughout chapters in this thesis.

1.1 Research Background/Introduction

Composite materials such as carbon, glass, and Kevlar fibers reinforced plastics are getting popular in aerospace sector nowadays. Composite materials are gaining such popularity primarily because they provide much higher specific strength and specific stiffness over metallic counterparts. These characteristics could be translated into significant improvement of fuel efficiency, which is a great concern for aerospace sector due to hike of fuel price and the fact that fuel cost is the major cost for aerospace structures ownership and operational cost ("A350XWB Special Edition," 2013). Other advantages of composite materials include corrosion resistance and ability to withstand harsh chemical. This provide benefit over metallic structure that are exposed to corrosion over time especially over uncontrolled severe weather. Also, because composites are build based on part consolidation, a single piece of composite material can replace an entire assembly of metal parts resulting to reduction of number of joints and mechanical fastener to save more time and maintenance.

In aerospace structure, composite have been applied in both primary and secondary part of aircraft. Graph illustrated in Figure 1.1 stated number of composite weight percentage over time since 1980s ("No Title," 2009). Initially, composite was applied on secondary part only where composite percentage is lower than 5%. In 60 years, number of composite percentage has been increasing up to 50% and used at both primary and secondary structure. Primary structures in aircraft are structure that carries flight, ground, loads and whose failure would reduce the structural integrity of the aircraft or may causes injury and death to passenger or crew (Cutler, 2006). This part will carry critical load bearing structure on an aircraft and plays important role during service. Examples of primary structure of an aircraft are fuselage, wing spar, and wing rib. In other hand, secondary part is non-primary part and mainly functionalize to provide enhanced aerodynamics to aircraft. Differ from primary structure, failure at this part will be less critical and would not reduce the structural integrity of the aircraft. Among listed secondary parts are floor and other ancillary structure such as windows and fairing (Cutler, 2006)(Rupke, 2002). Figure 1.2 shows illustration by Airbus company of structure that deploy composite material in Airbus A380 and proves high percentage of composite as it has been applied to both primary and secondary part (*Jane's All the World's Aircraft*, n.d.).

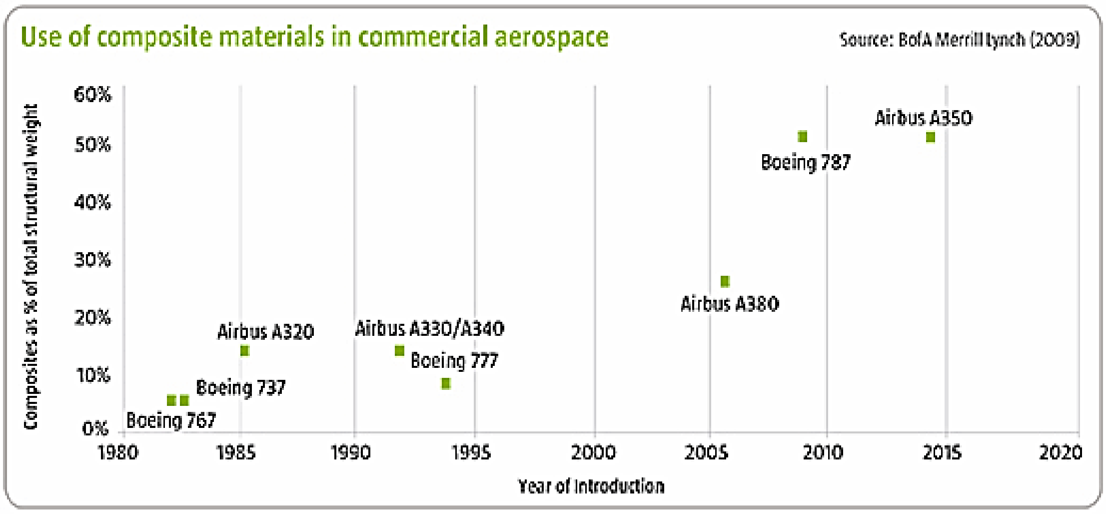

Figure 1.1 : Percentage of composite per weight over time ("No Title," 2009)

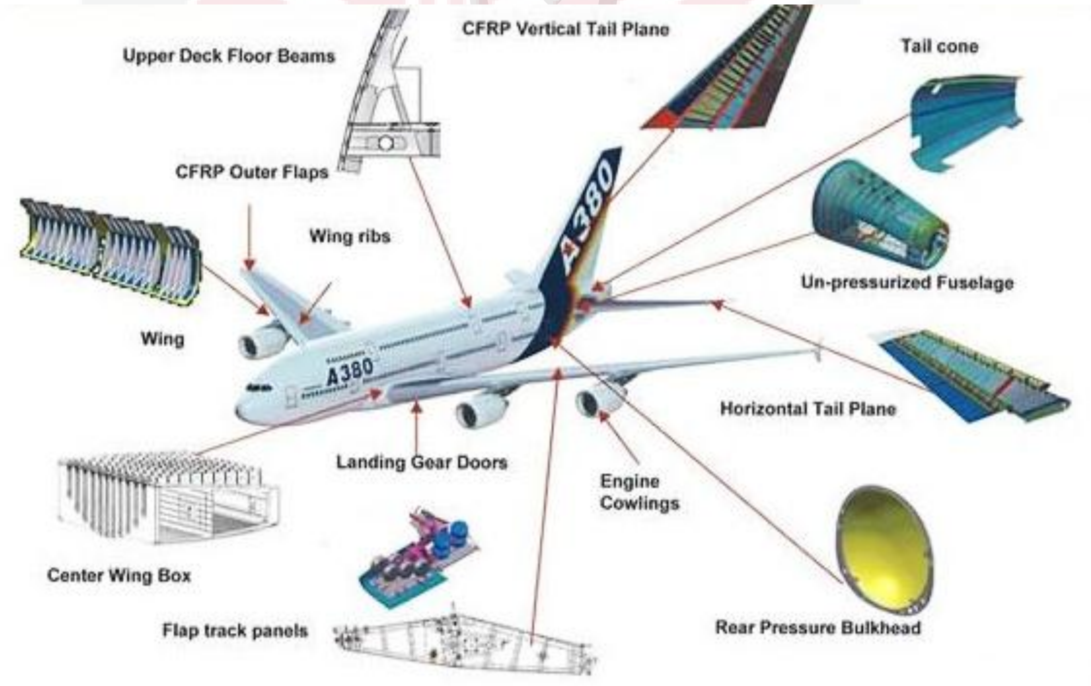

Figure 1.2 : Composite deployment in Airbus A380 including primary and secondary part of aircraft structure (*Jane's All the World's Aircraft*, n.d.)

Similar to conventional metallic structures, composite structures are also susceptible to damages that are classified into manufacturing and in-service damages. Manufacturing damages are introduced during manufacturing and fabrication processes meanwhile in-service damages occur during service or operation of a structure within its lifetime (Ghobadi, 2017). Common damages in manufacturing damage are porosity and inclusion that results to reduction of material and structural strength. For in service damages, three major damages that commonly happens in-service are impact, fatigue, and lightning & thermal damage. These damages are usually interrelated to each other and most possibly leads to other extensive damages such as delamination, cracks, and debonding.

In recent research, lightning and thermal damage are given more focus due to detrimental effects that it may consume on composite aerospace structure. These damage that shares the same effect of high thermal exposure have been considered lately as significant damage because it may lead to catastrophic effect to aircraft at the range of visible to non-visible for current damage detection technique. Non-visible damage or so called incipient thermal damage (ITD) are damage specially occurred at early stage of thermal damage. Even though it is invisible to current damage detection technique, reduction of mechanical properties from these damages are significant and had been proven to have reduction values as high as 60% (Maria, 2013) (Tucker Howie, Pate, Morasch, & Flinn, n.d.). At this level, mechanical properties of composite had already changed and deteriorated to reduce composite strength. Hence, detection of ITD in aerospace had been focused to overcome any severe damage that it may lead or any irreversible damage to happen.

In accordance to the fact that each material is highly exposed to imperfections and damages at different stages, NDT&E technique provides a systematic damage detection method. Ultrasonic scan, eddy current, dye penetrant and infrared thermography are among technique used in NDT&E and found to be the most effective way for a precise and non-intrusive damage detection especially for conventional material (Cutler, 2006; "FAST 32," 2003; Maria, 2013). Nevertheless, in the advancement of material development of composite material, there are numbers of limitation in damage detection. As for nowadays NDT&E technique, only severe damage such as delamination, crack and debonding can be excellently recognized leaving incipient thermal damage undetected.

In this regard, an effective NDT&E tool that can evaluate incipient thermal damage is needed for a better safety and maintenance. This research explores NDT&E techniques specifically infrared thermography in evaluating incipient thermal damage by considering the aspect of conventional and advance technology in thermography.

1.2 Problem statement

Incipient thermal damage (ITD) could reduce mechanical strength of composite materials for up to 60%, but conventional non-destructive test and evaluation (NDT&E) techniques established for composite material inspection are not capable of detecting it. This problem posts a potential catastrophic structural failure and fatal accident, hence an effective NDT&E tool that can detect or evaluate ITD is imperatively needed.

Due to thermo-mechanical properties of ITD, it's local changes or discontinuities caused by heat are very small and are outside of conventional NDT&E capability. Understanding that there are local changes due to ITD, thermography method was chosen with the implementation of laser as an active source.

Using laser pulse as localized heat source and thermal imager as sensor, it is possible to acquire local temperature-time profile at specific points of inspection. In method such as flying laser spot thermography and ultrasonic wave propagation imaging, laser had been used and proves it's effectiveness in detecting less severe damage such as lightning damage which are closely related to ITD. Thus, the implementation of laser source in proposed Scanning Laser Thermographic System with appropriate noise removal algorithm should be able to detect and evaluate ITD.

1.3 Hypothesis

Thermal damage (TD) and incipient thermal damage (ITD) in composite materials are local changes or discontinuities of material properties caused by heat. These changes or discontinuity prevents normal continuous, uniform flow of heat flux. Hence, by using laser pulse as localized heat source and thermal imager as sensor, it is possible to acquire local temperature-time profile at specific points of inspection. Comparing the profiles could highlight outliers and hence indicate TD or ITD.

1.4 Research Objectives

This project aims to develop an effective NDT&E tool that can detect or evaluate ITD through the following objectives:

1. To synchronize laser system, laser scanner system, and thermal imager as an active infrared imaging system suitable for non-destructive evaluation purposes.
2. To develop corresponding data acquisition and noise removal algorithm for extraction of local temperature-time profiles.
3. To validate the effectiveness of the system and algorithm for non-destructive evaluation of ITD in glass fiber reinforced composite plate.

1.5 Scopes of Research

This study covered the development and application of a laser-based, active thermography system with noise removal algorithm for non-destructive detection of TD and ITD inflicted with controlled insult time and temperature on thin (~1 mm), flat plate of glass fiber reinforced polymer as a simple representation of aircraft skin. In damage preparation, especially thermal damage, term 'insult' is most appropriately used to describe specifically to damage (Pelivanov, Ambrozinski, & O'Donnell, 2016). Note that, term 'insult' was used to describe damage throughout this study. This study was conducted to only one category of ITD at insult temperature in borderline of T_g and long insult time. Temperature in borderline of T_g shall be based on fabricated GFRP plate properties insulted to time higher than 30 minutes to 120 minutes. Finally, validation was done with reference to existing conventional NDT&E method used for composite material that is ultrasound method.

1.6 Thesis Organization

This thesis work will be divided into 5 chapters. *Chapter 2 Literature Review* discuss briefly on introductory and conceptual understanding in regarding to research scope. Included, previous research and significant finding in damage detection of composite aerospace structure. Lightning, thermal and incipient thermal damage are given focus in accordance to objectives and problem statement stated in *Chapter 1 Introduction*. Damage detection method in composite are also discussed especially for ultrasonic and thermal imaging method.

Chapter 3 Research Methodology describes the process design for scanning laser thermographic system. Fabrication of composite material (glass fibre reinforced plastic) with aerospace standard was explained including damage preparation on specimen. Then, image processing steps was explained in accordance to noise removal algorithm. Damage detection calculation using thermal contrast base algorithm was presented here. Comparison using conventional method, ultrasonic method is also presented for verification purpose.

Chapter 4 Result and Discussion discuss results collected and processed from scanning laser thermographic system. Observation and analysis throughout image processing algorithm of thermographic data on thermal damage and incipient thermal damage was discussed. Damage detection is presented in the form of percentage difference (%) between damage and reference area. Also included result and discussion of ultrasonic method for verification.

Lastly, *Chapter 5 Conclusion and Recommendation for future work* summarize final result and findings of incipient thermal damage as well as thermal damage detection in composite material specifically GFRP in developed scanning laser thermographic system. Ultimately, the ability of developed system to detect incipient thermal damage in GFRP will determine the relevance of the results for future studies.

REFERENCES

12 Things to Consider Before Buying an Infrared Camera. (2014). *FLIR System*.

A350 vision takes shape. (2006, December). *Flight International*.

A350XWB Special Edition. (2013, June). *Airbus Technical Magazine*.

Adams, R. D., & Cawley, P. (1988). A review of defect types and nondestructive testing techniques for composites and bonded joints. *NDT International*, *21*(4), 208–222.

Aircraft Paint Damage and Failure Analaysis. (2016). Hamburg,Germany: Lufthansa Technik.

An, Y.-K., Park, B., & Sohn, H. (2013). Complete noncontact laser ultrasonic imaging for automated crack visualization in a plate. *Smart Materials and Structures*, *22*, 25022. https://doi.org/10.1088/0964-1726/22/2/025022

Anastasi, R. F., Zalameda, J. N., & Madaras, E. I. (2004). Damage detection in rotorcraft composite structures using thermography and laser-based ultrasound.

Avdelidis, N. P., Hawtin, B. C., & Almond, D. P. (2003). Transient thermography in the assessment of defects of aircraft composites. *NDT & E International*, *36*(6), 433–439. https://doi.org/10.1016/s0963-8695(03)00052-5

Aviation Investigation Report A14Q0068. (2014). Canada. Retrieved from http://www.bst-tsb.gc.ca/eng/rapports-reports/aviation/2014/a14q0068/a14q0068.asp

Bagavathiappan, S., Lahiri, B. B., Saravanan, T., Philip, J., & Jayakumar, T. (2013). Infrared thermography for condition monitoring - A review. *Infrared Physics and Technology*. https://doi.org/10.1016/j.infrared.2013.03.006

Bajwa, U. I., Vardasca, R., Ring, F., & Plassmann, P. (2010). Comparison of boundary detection techniques to improve image analysis in medical thermography. *The Imaging Science Journal*, *58*(1), 12–19.

Basic Principles of Ultrasonic Testing Theory and Practice. (2012). Krautkramer NDT Ultrasonic Systems.

Bates, D., Smith, G., Lu, D., & Hewitt, J. (2000). Rapid thermal non-destructive testing of aircraft components. *Composites Part B: Engineering*, *31*(3), 175–185. https://doi.org/10.1016/S1359-8368(00)00005-6

Broberg, P. (2013). Surface crack detection in welds using thermography. *NDT & E International*, *57*, 69–73.

Burrows, S. E., Dixon, S., Pickering, S. G., Li, T., & Almond, D. P. (2011). Thermographic detection of surface breaking defects using a scanning laser source. *NDT & E International*, *44*(7), 589–596.

Burrows, S. E., Rashed, A., Almond, D. P., & Dixon, S. (2007). Combined laser spot imaging thermography and ultrasonic measurements for crack detection. *Nondestructive Testing and Evaluation*, *22*(2–3), 217–227. https://doi.org/10.1080/10589750701448605

Cernuschi, F., Bison, P. G., Marinetti, S., Figari, a., Lorenzoni, L., & Grinzato, E. (2002). Comparison of thermal diffusivity measurement techniques. *Proceedings of Quantitative InfraRed Thermography*, *6*(1), 24–27.

Chen, M. W., You, S., Suslick, K. S., & Dlott, D. D. (2014). Hot spots in energetic materials generated by infrared and ultrasound, detected by thermal imaging microscopy. *Review of Scientific Instruments*, *85*(2).

Choi, Y.-S., Jeong, H., & Lee, J.-R. (2014). Laser Ultrasonic System for Surface Crack Visualization in Dissimilar Welds of Control Rod Drive Mechanism Assembly of Nuclear Power Plant. *Shock and Vibration*, *2014*, 1–10. https://doi.org/10.1155/2014/296426

Chong, S. Y., & Lee, J. (2014). Development of Laser Ultrasonic Propagation Imaging System With Twenty-Kilohertz Scanning Frequency For Nondestructive Evaluation Applications. In *Advances in Structural Health Management and Composite Structures 2014 (ASHMCS 2014)* (Vol. I, pp. 27–30).

Ciang, C. C., Ariff, O. K., Jeong, H., Gomes, C., Lim, S. C., Lee, J.-R., & Salami, E. (2014). Evaluation of Lightning Damages in Composite Wing. *The 2nd International Conference on Advances in Structural Health Management and Composite Structures (ASHMCS 2014)*, *I*(ASHMCS).

Ciang, C. C., Jeong, H., Lee, J. R., & Park, G. (2011). Composite aircraft debonding visualization by laser ultrasonic scanning excitation and integrated piezoelectric sensing. *Structural Control and Health Monitoring*, *19*(June 2012), 605–620. https://doi.org/10.1002/stc

Ciang, C. C., Lee, J.-R., & Shin, H.-J. (2009). Hot target inspection using a welded fibre acoustic wave piezoelectric sensor and a laser-ultrasonic mirror scanner. *Measurement Science and Technology*, *20*(12), 1–8. https://doi.org/10.1088/0957-0233/20/12/127003

Ciang, C. C., & Lee, J. R. (2014). Anti-Aliasing for the Visualization of Wavefield Propagation. *Applied Mechanics and Materials*, *629*(January), 493–497. https://doi.org/10.4028/www.scientific.net/AMM.629.493

Ciang, C. C., Lee, J. R., & Kim, J. H. (2009). Development of Ultrasonic Wave Propagation Imaging System. *Journal of the Korean Society for Nondestructive Testing*, *29*(4), 283–292.

Ciang, C. C., Lee, J. R., & Park, C. Y. (2012). Radome health management based on synthesized impact detection, laser ultrasonic spectral imaging, and wavelet-transformed ultrasonic propagation imaging methods. *Composites Part B: Engineering*, *43*(8), 2898–2906. https://doi.org/10.1016/j.compositesb.2012.07.033

Ciang, C. C., Lee, J. R., Park, C. Y., & Jeong, H. (2012). Laser ultrasonic anomalous wave propagation imaging method with adjacent wave subtraction: Algorithm. *Optics & Laser Technology*, *44*(5), 1507–1515. https://doi.org/10.1016/j.optlastec.2011.08.007

Ciang, C. C., Lee, J. ryul, Park, J. sung, Yun, C. yong, & Kim, J. H. (2008). New design and algorithm for an ultrasonic propagation imaging system. In *Defektoskopie 2008* (pp. 63–70).

Comparison of Carbon Fiber, Kevlar (Aramid) and E Glass used in Composites for Boatbuilding. (2017). Retrieved September 15, 2017, from http://www.christinedemerchant.com/carbon-kevlar-glass-comparison.html

Cutler, J. (2006). *Understanding Aircraft Structures*. (J. Liber, Ed.) (4th editio). Blackwell Publishing. Retrieved from http://www.amazon.com/Understanding-Aircraft-Structures-John-Cutler/dp/1405120320

D638-10, A. S. (2008). Standard test method for tensile properties of plastics. *ASTM International*. https://doi.org/10.1520/D0638-10.1

Dara, I. H., Ankara, A., Akovali, G., & Suzer, S. (2005). Heat damage assessment of carbon-fiber-reinforced polymer composites by diffuse reflectance infrared spectroscopy. *Journal of Applied Polymer Science*, *96*(4), 1222–1230.

Eibl, S., & Wolfrum, J. (2012). Prospects to separately estimate temperature and duration of a thermal pre-load on a polymer matrix composite. *Journal of Composite Materials*, 1–15. https://doi.org/10.1177/0021998312460714

FAST 32. (2003). *Airbus*, (July). Retrieved from http://www.airbus.com

Feraboli, P., & Kawakami, H. (2010). Damage of Carbon/Epoxy Composite Plates Subjected to Mechanical Impact and Simulated Lightning. *Journal of Aircraft*, *47*(3), 999–1012. https://doi.org/10.2514/1.46486

Fisher, W. G., Storey, J. M. E., Sharp, S. L., Janke, C. J., & Wachter, E. A. (1995). Nondestructive Inspection of Graphite-Epoxy Composites for Heat Damage Using Laser-Induced Fluorescence. *Appl. Spectrosc.*, *49*(9), 1225–1231. Retrieved from http://as.osa.org/abstract.cfm?URI=as-49-9-1225

FLIR-Systems. (2012). Technical Data FLIR E50. FLIR Technical Series. Retrieved from http://support.flir.com/DsDownload/Assets/39903-1301_en_40.pdf

Fundamentals of Ultrasonic Imaging. (2010). Retrieved August 9, 2017, from www.ni.com/white-paper/3368/en/

Ghobadi, A. (2017). Common Type of Damages in Composites and Their Inspections. *World Journal of Mechanics*, *7*(2), 24. https://doi.org/10.4236/wjm.2017.72003

Grandt Jr, A. . F. (2003). *Fundamentals of structural integrity: damage tolerant design and nondestructive evaluation*. John Wiley & Sons.

Green, R. E. (2004). Non-contact ultrasonic techniques. *Ultrasonics*, *42*(1–9), 9–16. https://doi.org/10.1016/j.ultras.2004.01.101

Griffin, S. (2009). What can you do with smart structures? In *Advances in Structural Health Management and Composite Structures 2014 (ASHMCS 2014)* (Vol. I, pp. 1–4).

Guo, X., & Vavilov, V. (2013). Crack detection in aluminum parts by using ultrasound-excited infrared thermography. *Infrared Physics & Technology*, *61*, 149–156. https://doi.org/10.1016/j.infrared.2013.08.003

Haridas, A., Song, C., Chan, K., & Murukeshan, V. M. (2017). Nondestructive characterization of thermal damages and its interactions in carbon fibre composite panels. *Fatigue & Fracture of Engineering Materials & Structures*, *40*(10), 1562–1580. https://doi.org/10.1111/ffe.12657

Hasiotis, T., Badogiannis, E., & Tsouvalis, N. G. (2011). Application of ultrasonic C-scan techniques for tracing defects in laminated composite materials. *Strojniski Vestnik/Journal of Mechanical Engineering*, *57*(3), 192–203. https://doi.org/10.5545/sv-jme.2010.170

He, Y., Tian, G., Pan, M., & Chen, D. (2014). Impact evaluation in carbon fiber reinforced plastic (CFRP) laminates using eddy current pulsed thermography. *Composite Structures*, *109*, 1–7. https://doi.org/10.1016/j.compstruct.2013.10.049

HexPly ® F155 Resin Systems for Advanced Composites. (2016). Hexcel Corporation.

Higgins, F. (2014). Non-Destructive Evaluation of Composite Thermal Damage with Agilent ' s New Handheld 4300 FTIR Application note.

Hirano, Y., Katsumata, S., Iwahori, Y., & Todoroki, A. (2010). Artificial lightning testing on graphite/epoxy composite laminate. *Composites Part A: Applied Science and Manufacturing*, *41*(10), 1461–1470. https://doi.org/10.1016/j.compositesa.2010.06.008

Howie, T. (2014). Composite Thermal Damage Measurement With Handheld FTIR. Joint Advanced Materials & Structures Center Of Excellence (JAMS).

Howie, T. L. (2013). *Detection of Incipient Thermal Damage Of Carbon Fiber/Epoxy Composites Using Fluorescent Thermal Damage Probes*.

Hradecky, S. (2015). Accident: British Airways B772 at Las Vegas on Sep 8th 2015, rejected takeoff due to engine fire, engine failure uncontained. Retrieved July 28, 2017, from http://avherald.com/h?article=48c10434

Hwang, S., An, Y.-K., & Sohn, H. (2017). Continuous Line Laser Thermography for Damage Imaging of Rotating Wind Turbine Blades. *Procedia Engineering*, *188*, 225–232. https://doi.org/https://doi.org/10.1016/j.proeng.2017.04.478

Ibarra-Castanedo, C., Avdelidis, N. P., Grenier, M., Maldague, X., & Bendada, a. (2010). Active thermography signal processing techniques for defect detection and characterization on composite materials. *Thermosense XXXII, SPIE Conference*, *7661*, 76610O–76610O–9. https://doi.org/10.1117/12.850733

Ibarra-Castanedo, C., Bendada, A., & Maldague, X. P. V. (2011). Infrared vision applications for the nondestructive testing of materials. *5th Pan American Conference for NDT*, (October).

Ibarra-Castanedo, C., Genest, M., Piau, J.-M., Guibert, S., Bendada, A., Maldague, X. P. V, & Chen, C. H. (2007). Active Infrared Thermography Techniques for the Non-destructive Testing of Materials. *Capter XIV of the book:"Ultrasonic and Advanced Methods for Nondestructive Testing and Material Characterization", Ed. Chen CH*, 325–348.

Ibarra-Castanedo, C., & Maldague, X. (2004). Pulsed phase thermography reviewed. *Quantitative InfraRed Thermography Journal*, *1*(1), 47–70. https://doi.org/10.3166/qirt.1.47-70

Ibarra-Castanedo, C., & Maldague, X. P. V. (2013). Infrared Thermography. In *Handbook of Technical Diagnostics* (pp. 175–220). Springer.

Ibarra-Castanedo, C., Tarpani, J. R., & Maldague, X. P. V. (2013). Nondestructive testing with thermography. *European Journal of Physics*, *34*(6), S91–S109. https://doi.org/10.1088/0143-0807/34/6/S91

Internationa, A. S. T. M. (1996). *ASTM E1316-99a Standard Terminology for Nondestructive Examinations*. *Annual Book of ASTM Standards* (Vol. 3). https://doi.org/10.1520/E1316-11A.Radiologic

Jane's All the World's Aircraft. (n.d.). *GAO analysis of information*.

Junyan, L., Liqiang, L., & Yang, W. (2013). Experimental study on active infrared thermography as a NDI tool for carbon–carbon composites. *Composites Part B: Engineering*, *45*(1), 138–147. https://doi.org/10.1016/j.compositesb.2012.09.006

Katnam, K. B., Comer, A. J., Roy, D., Da Silva, L. F. M., & Young, T. M. (2014). Composite Repair in Wind Turbine Blades: An Overview. *The Journal of Adhesion*, (just-accepted).

Katnam, K. B., Comer, A. J., Roy, D., Da Silva, L. F. M., & Young, T. M. (2015). Composite Repair in Wind Turbine Blades: An Overview. *The Journal of Adhesion*, *91*(1–2), 113–139. https://doi.org/10.1080/00218464.2014.900449

Keo, S. A., Brachelet, F., Breaban, F., & Defer, D. (2014). Defect Detection in CFRP by Infrared Thermography with CO 2 Laser Excitation Compared to Conventional Lock-in Infrared Thermography. *Composites Part B: Engineering*, *69*, 1–5. https://doi.org/10.1016/j.compositesb.2014.09.018

Keo, S., Brachelet, F., Breaban, F., & Defer, D. (2013). Development of an Infrared Thermography Method with CO 2 Laser Excitation , Applied to Defect Detection in CFRP. *International Journal of Mathematical, Computational, Physical and Quantum Engineering*, *7*(8), 720–724.

Keo, S., Defer, D., Breaban, F., Brachelet, F., Sam-Ang, K., Didier, D., … Franck, B. (2013). Comparison between Microwave Infrared Thermography and CO 2 Laser Infrared Thermography in Defect Detection in Applications with CFRP. *Materials Sciences and Applications*, *2013*(October), 600–605.

Kessler, S. S., Spearing, S. M., & Soutis, C. (2002). Damage detection in composite materials using Lamb wave methods. *Smart Materials and Structures*, *269*(2), 269–278. Retrieved from http://iopscience.iop.org/0964-1726/11/2/310

Kong, D. L. Y., & Sanjayan, J. G. (2008). Damage behavior of geopolymer composites exposed to elevated temperatures. *Cement and Concrete Composites*, *30*(10), 986–991. https://doi.org/10.1016/j.cemconcomp.2008.08.001

Koskelo, E. C., & Flynn, E. B. (2017). Nondestructive evaluation of composite materials via scanning laser ultrasound spectroscopy. In *Proc. of SPIE* (Vol. 10169). https://doi.org/10.1117/12.2256301

Lamb, H. (1917). On waves in an elastic plate. *Proceedings of the Royal Society of London. Series A*, *93*(648), 114–128. https://doi.org/10.1098/rspa.1917.0008

Lee, J.-R., Ciang Chia, C., Jin Shin, H., Park, C.-Y., & Jin Yoon, D. (2011). Laser ultrasonic propagation imaging method in the frequency domain based on wavelet transformation. *Optics and Lasers in Engineering*, *49*(1), 167–175.

Lee, J.-R., Jeong, H., Ciang, C. C., Yoon, D.-J., & Lee, S.-S. (2010). Application of ultrasonic wave propagation imaging method to automatic damage visualization of nuclear power plant pipeline. *Nuclear Engineering and Design*, *240*(10), 3513–3520.

Lee, J.-R., Shin, H.-J., Chia, C. C., Dhital, D., Yoon, D.-J., & Huh, Y.-H. (2011). Long distance laser ultrasonic propagation imaging system for damage visualization. *Optics and Lasers in Engineering*, *49*(12), 1361–1371.

Lee, J. R., Ciang, C. C., Jin Shin, H., Park, C. Y., & Jin Yoon, D. (2011). Laser ultrasonic propagation imaging method in the frequency domain based on wavelet transformation. *Optics and Lasers in Engineering*, *49*(1), 167–175.

Li, T., Almond, D. P. and Rees, D. A. S. (2011). Crack imaging by scanning laser line thermography and laser spot thermography. *Measurement Science & Technology*, *22*(3). Retrieved from http://dx.doi.org/10.1088/0957-0233/22/3/035701

Li, T., Almond, D. P. and Rees, D. A. S., Li, T., Almond, D. P., & Rees, D. A. S. (2011). Crack imaging by scanning laser line thermography and laser spot thermography. *Measurement Science & Technology*, *22*(3). https://doi.org/10.1088/0957-0233/22/3/035701

Li, T., Almond, D. P., & Rees, D. A. S. (2011). Crack imaging by scanning laser-line thermography and laser-spot thermography, *35701*. https://doi.org/10.1088/0957-0233/22/3/035701

Li, T., Weekes, B., Almond, S. P., Rees, A., Burrows, S. E., & Dixon, S. (2010). Crack imaging by pulsed laser spot and pulsed laser line thermography. *Journal of Physics: Conference Series 214, 12072*. https://doi.org/10.1088/1742-6596/214/1/012072

Lindgren, E., Welter, J., Sathish, S., & Ripberger, E. (2007). Detection of incipient thermal damage in polymer matrix composites. *International SAMPE Symposium and Exhibition (Proceedings)*, *52*. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-34748826722&partnerID=tZOtx3y1

Maierhofer, C., Myrach, P., Reischel, M., Steinfurth, H., Röllig, M., & Kunert, M. (2014). Characterizing damage in CFRP structures using flash thermography in reflection and transmission configurations. *Composites Part B: Engineering*, *57*, 35–46.

Maldague, X. P. V. (2001). *Theory and practice of infrared technology for non destructive testing*. John Wiley-Interscience. Retrieved from http://books.google.com.my/books/about/Theory_and_practice_of_infrared_technolo.html?id=ts9RAAAAMAAJ&redir_esc=y

Maria, M. (2013). Advanced composite materials of the future in aerospace industry. *Incas Bulletin*, *5*(3), 139–150. https://doi.org/10.13111/2066-8201.2013.5.3.14

Matzkanin, G. A. (1994). Nondestructive Characterization of Heat Damage in Graphite/Epoxy Composites. In R. E. Green, K. J. Kozaczek, & C. O. Ruud (Eds.), *Nondestructive Characterization of Materials VI* (pp. 517–523). Boston, MA: Springer US. https://doi.org/10.1007/978-1-4615-2574-5_65

McShane, H., Arafat, E. S., McLaughlin, P., Cochran, R., Miller, K., & Arnold, F. (1999). *Heat Damage Assessment for Naval Aircraft Composites*. Maryland.

Meola, C., Boccardi, S., Carlomagno, G. M., Boffa, N. D., & Ricci, F. (2015). Nondestructive evaluation of carbon fibre reinforced composites with infrared thermography and ultrasonics, *134*, 845–853.

Meola, C., & Carlomagno, G. M. (2004). Recent advances in the use of infrared thermography. *Measurement Science and Technology*, *15*(9), R27–R58. https://doi.org/10.1088/0957-0233/15/9/R01

Meola, C., & Carlomagno, G. M. (2014). Infrared thermography to evaluate impact damage in glass/epoxy with manufacturing defects. *International Journal of Impact Engineering*, *67*, 1–11. https://doi.org/10.1016/j.ijimpeng.2013.12.010

Michaels, T. E., & Michaels, J. E. (2006). Application Of Acoustic Wavefield Imaging to Non-Contact Ultrasonic Inspection of Bonded Components. *Review of Quantitative Nondestructive Evaluation*, *25*, 1484–1491.

Montinaro, N., Cerniglia, D., & Pitarresi, G. (2017a). Detection and characterisation of disbonds on Fibre Metal Laminate hybrid composites by flying laser spot thermography. *Composites Part B: Engineering*, *108*, 164–173. https://doi.org/10.1016/j.compositesb.2016.09.084

Montinaro, N., Cerniglia, D., & Pitarresi, G. (2017b). Flying Laser Spot Thermography technique for the NDE of Fibre Metal Laminates disbonds. *Composite Structures*, *171*, 63–76. https://doi.org/10.1016/j.compstruct.2017.03.035

No Title. (2009). Bank of America Merill Lynch.

Ong, R., & Wang, C. H. (2014). Effect of Incipient Heat Damage on the Fatigue Properties of Aircraft Composites. *Advanced Materials Research*, *891–892*(February), 1810–1815. https://doi.org/10.4028/www.scientific.net/AMR.891-892.1810

Ong, R., Wang, C. H., Lawrence, S., & Aerospace, W. (2014). Detection of Incipient Heat Damage in Aircraft. In *European conference on composite materials*.

Park, B., An, Y. K., & Sohn, H. (2014). Visualization of hidden delamination and debonding in composites through noncontact laser ultrasonic scanning. *Composites Science and Technology*, *100*, 10–18. https://doi.org/10.1016/j.compscitech.2014.05.029

Park, S., Han, D., Kang, L., Kang, D., & Transportation, N. (2014). Impact Location Detection Demonstration System for a Rectangular Plate Using Piezoelectric Paint Sensor. In *Advances in Structural Health Management and Composite Structures 2014 (ASHMCS 2014)* (Vol. I, pp. 2–6).

Pawar, S. S., & Peters, K. (2013). Through-the-thickness identification of impact damage in composite laminates through pulsed phase thermography. *Measurement Science and Technology*, *24*(11), 115601. https://doi.org/10.1088/0957-0233/24/11/115601

Pelivanov, I., Ambrozinski, L., & O'Donnell, M. (2016). Heat damage evaluation in carbon fiber-reinforced composites with a kHz A-scan rate fiber-optic pump-probe laser-ultrasound system. *Composites Part A: Applied Science and Manufacturing*, *84*, 417–427. https://doi.org/10.1016/j.compositesa.2016.02.022

Rainieri, S., & Pagliarini, G. (2002). Data filtering applied to infrared thermographic measurements intended for the estimation of local heat transfer coefficient. *Experimental Thermal and Fluid Science*, *26*(2), 109–114. https://doi.org/https://doi.org/10.1016/S0894-1777(02)00116-4

Rein, A., & Seelenbinder, J. (n.d.). Thermal Damage in Composites – Correlation of Short Beam Shear Data with Fourier Transform Infrared Spectroscopy. Germany: Polytec.

Rein, A., Seelenbinder, J., & Technologies, A. (n.d.). Article 2 : Composite thermal damage – Correlation of short beam shear data with FTIR spectroscopy portable , non- destructive analysis Authors.

Roemer, J., Pieczonka, L., Marius, Uhl, T., & J. Staszewskil, W. (2013). Thermography of Metallic and Composite Structures - review of applications. Canada.

Roemer, J., Pieczonka, Ł., & Uhl, T. (2014). Laser Spot Thermography of Welded Joints. *Diagnostyka*, *15*(2), 43–49.

Rupke, E. (2002). Lightning direct effects handbook. In *Lightning Technologies, Inc.,Report no. AGATE-WP3.1-031027-043-Design guideline*. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Lightning+Direct+Effects+Handbook#0

Sathish, S., Welter, J. T., Jata, K. V., Schehl, N., & Boehnlein, T. (2012). Development of nondestructive non-contact acousto-thermal evaluation technique for damage detection in materials. *Review of Scientific Instruments*, *83*(9). https://doi.org/10.1063/1.4749245

SCANcube, intellicube. (2014). SCANLAB.

Schlichting, J., Maierhofer, C., & Kreutzbruck, M. (2012). Crack sizing by laser excited thermography. *NDT & E International*, *45*(1), 133–140. https://doi.org/10.1016/j.ndteint.2011.09.014

Schlichting, J., Ziegler, M., Maierhofer, C., & Kreutzbruck, M. (2012). Flying Laser Spot Thermography for the Fast Detection of Surface Breaking Cracks. In *18th World Conference on Nondestructive Testing* (pp. 16–20). Durban, South Africa.

Scott, I. G., & Scala, C. M. (1982). A review of non-destructive testing of composite materials. *NDT International*. https://doi.org/10.1016/0308-9126(82)90001-3

Scruby, Christopher B and Drain, L. E. (1990). *Laser ultrasonics techniques and applications*. CRC press. Retrieved from http://books.google.com.my/books?hl=en&lr=&id=KgXPqx9ST-wC&oi=fnd&pg=PR7&dq=laser+ultrasonics+techniques+and+applications&ots=Wa5LzHJP3J&sig=Q9hUWnXDBuEmDWGjpfsdNz8lG00#v=onepage&q=laser ultrasonics techniques and applications&f=false

Seale, M. D., Smith, B. T., & Prosser, W. H. (1998). Lamb wave assessment of fatigue and thermal damage in composites. *The Journal of the Acoustical Society of America*, *103*(5), 2416–2424. https://doi.org/10.1121/1.422761

Smith, R. A. (n.d.). Composite Defects and Their Detection. In *Encyclopedia of Life Support Sytems (EOLSS)* (Materials, Vol. III).

Srivatsan, T. S. (1995). A review of: "Fundamentals of Composites Manufacturing: Materials, Methods and Applications" by A. Brent Strong. *Materials and Manufacturing Processes*, *10*(5), 1121–1122. https://doi.org/10.1080/10426919508935097

Staszewski, W. J., Lee, B. C., & Traynor, R. (2007). Fatigue crack detection in metallic structures with Lamb waves and 3D laser vibrometry. *Measurement Science and Technology*, *18*(3), 727. Retrieved from http://stacks.iop.org/0957-0233/18/i=3/a=024

Su, Z., Ye, L., & Lu, Y. (2006). Guided Lamb waves for identification of damage in composite structures: A review. *Journal of Sound and Vibration*, *295*(3–5), 753–780. https://doi.org/10.1016/j.jsv.2006.01.020

Sweers, G., Birch, B., & Gokcen, J. (2012, April). Lightning Strikes: Protection, Inspection and Repair. *AERO*, 19–28.

T. Uhl, M. Szwedo, P. Hellstein, L. P. (2014). Image-Based Structural Health Monitoring of Composite Structures. In *29th Congress of the International Council of the Aeronautical Science*. Russia.

Thomas, R. L. (2002). Thermal NDE techniques-from photoacoustics to thermosonics. In *Quantitative Nondestructive Evaluation* (Vol. 615, pp. 3–13). AIP Publishing.

Tucker Howie, A. T., Pate, D., Morasch, J., & Flinn, B. (n.d.). *The Detection of Composite Thermal Damage With Handheld FTIR*.

Usamentiaga, R., Venegas, P., Guerediaga, J., Vega, L., & López, I. (2013). A quantitative comparison of stimulation and post-processing thermographic inspection methods applied to aeronautical carbon fibre reinforced polymer. *Quantitative InfraRed Thermography Journal*, *10*(1), 55–73.

Vacuum Bagging Equipment and Techniques for Room Temperature Applications. (n.d.). Retrieved August 27, 2017, from http://www.fibreglast.com/product/vacuum-bagging-equipment-and-techniques-for-room-temp-applications/Learning_Center

Vavilov, V., Maldague, X., Dufort, B., Robitaille, F., & Picard, J. (1993). Thermal nondestructive testing of carbon epoxy composites: detailed analysis and data processing. *NDT & E International*, *26*(2), 85–95. https://doi.org/10.1016/0963-8695(93)90258-V

Vavilov, V. P. (2014). Modeling and characterizing impact damage in carbon fiber composites by thermal/infrared non-destructive testing. *Composites Part B: Engineering*, *61*, 1–10.

Vavilov, V. P., & Burleigh, D. D. (2015). Review of pulsed thermal NDT : Physical principles , theory and data processing. *NDT&E International Journal*, *73*, 28–52.

Vergani, L., Colombo, C., & Libonati, F. (2013). A review of thermographic techniques for damage investigation in composites. *Fracture and Structural Integrity*, *8*(27), pages 1-12. https://doi.org/10.3221/IGF-ESIS.27.01

Welter, J., Sathish, S., Ripberger, E., & Lindgren, E. (2007). Detection of localized heat damage in a polymer matrix composite by a thermoelastic technique. *Materials Evaluation*, *65*(8), 823–826.

Wolfrum, J., Eibl, S., & Lietch, L. (2009). Rapid evaluation of long-term thermal degradation of carbon fibre epoxy composites. *Composites Science and Technology*, *69*(3), 523–530.

Wong, Y. H., Thomas, R. L., & Hawkins, G. F. (1978). Surface and subsurface structure of solids by laser photoacoustic spectroscopy. *Applied Physics Letters*, *32*(9), 538–539.

Yang, B., Liaw, P. K., Wang, H., Huang, J. G. Y., Kuo, R. C., & Huang, J. G. Y. (2003). Thermography: a new nondestructive evaluation method in fatigue damage. *JOM-E*, *55*. Retrieved from http://www.tms.org/pubs/journals/jom/0301/yang/yang-0301.html

Ye, L., Lu, Y., Su, Z., & Meng, G. (2005). Functionalized composite structures for new generation airframes : a review. *Composite Science and Technology*, *65*, 1436–1446. https://doi.org/10.1016/j.compscitech.2004.12.015

Yousuf, A., & Kulowitch, P. (2000). Detecting heat damage in composites using laser induced fluorescence. *2000 ASEE Annual Conference and Exposition: Engineering Education Beyond the Millenium*. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-8644269678&partnerID=40&md5=c1698ccf3ec9a5c16bcfac03d76b26e7

Zhou, Y. C., Long, S. G., Duan, Z. P., & Hashida, T. (2001). Thermal Damage in Particulate-Reinforced Metal Matrix Composites. *Journal of Engineering Materials and Technology*, *123*(3), 251–260. https://doi.org/10.1115/1.1362675

Zweschper, T., Riegert, G., Dillenz, a., & Busse, G. (2005). Ultrasound excited thermography - advances due to frequency modulated elastic waves. *Quantitative InfraRed Thermography Journal*, *2*(1), 65–76. https://doi.org/10.3166/qirt.2.65-76