UNIVERSITI PUTRA MALAYSIA

STRUCTURAL HEALTH MONITORING AND DAMAGE DETECTION FOR COMPOSITE PANEL STRUCTURES VIA STATISTICAL ANALYSIS

NISREEN N. ALI AL-ADNANI

FK 2015 103

STRUCTURAL HEALTH MONITORING AND DAMAGE DETECTION FOR COMPOSITE PANEL STRUCTURES VIA STATISTICAL ANALYSIS

By

NISREEN N. ALI AL-ADNANI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirement for the Degree of Doctor of Philosophy

May 2015

"وَقُلْ رَبِّ زِدْنِي عِلْمًا"

صَدَقَ اللهُ العَظِيمْ

To:

My father's Soul,
My beloved AL-IRAQ
All those who have contributed to my journey up the ladder of knowledge

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

STRUCTURAL HEALTH MONITORING AND DAMAGE DETECTION FOR COMPOSITE PANEL STRUCTURES VIA STATISTICAL ANALYSIS

By

NISREEN N. ALI AL-ADNANI

May 2015

Chairman: Faizal Mustapha, PhD, PEng.
Faculty : Engineering

Rectangular panels with or/and without mass loading are widely applied in civil, aerospace and mechanical engineering. Changes such as cracks, corrosion or drilled holes can affect the structure and integrity of components. This study focuses on three (3) parts of experimental works: firstly, to fabricate the three types of composite materials panels; secondly, to assess the mechanical properties, the micro structure and thermal analysis of the materials, and thirdly, to detect the damage by using smart sensor to appraise the Structural Health Monitoring (SHM) technique and damage identification. To do this, aluminium alloy type 6061-T6 and three fabricated composite materials are utilized. These composites are combined with epoxy resin as a matrix mixed individually with Twill Weave 240 g/m² carbon fiber (CFW), Plain Weave 300 g/m² Glass Fiber (GFW) and Chopped Strand Mats 450 g/m² glass fiber [GF (CSM)] as fillers. This study also includes the fabrication procedure of the three types of composite panels by using hand lay-up and vacuum bagging process. Al 6061-T6 is considered as a reference material in order to evaluate the characterizations of the new composite materials. Moreover, each material has a case study and eventually this research has four case studies. The first case (undamaged) is considered as a reference or the baseline standard data. Crack's damages are simulated variedly in the panels to reflect the three damage cases in length such as 10 mm, 15 mm and 20 mm. Piezoelectric ceramic Lead Zirconate Titanate (PZT) transducer as a sensor is used to acquire the real time data. The comparison is carried out for damage detection and identification, based on the natural frequency approach and power spectrum with accuracy performance via signal from smart sensor (PZT). Root Mean Square Deviation (RMSD) index and Frequency Reduction Index (FRI) as statistical analysis methods for damage magnitude are performed to improve the SHM technique. RMSD out coming improves the damages identification, when the crack is increased RMSD is increased as well. Finally, SHM approach using PZT is improved and eventually very noticeable and probable changes in the natural frequency are observed, particularly when the damaged depth is increased in the composites. Meanwhile, the comparison between the CFW reinforced epoxy resin and the two glass fiber reinforced epoxy include the micro structure, thermoplastic analysis and mechanical properties. In general, CFW as a composite improved a higher micro structure, thermal analysis and mechanical properties and higher resistance against the vibration effect which is more than the two types of investigated glass fibers.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMANTAUAN KESIHATAN STRUKTUR DAN PENGENALAN KEROSAKAN MELALUI ANALISA STATISTIK UNTUK PANEL KOMPOSIT

Oleh

Nisreen N. ALI AL-ADNANI

Mei 2015

Pengerusi: **Faizal Mustapha, PhD, PEng.**
Fakulti : **Kejuruteraan**

Panel segiempat tepat dengan / tanpa muatan jisim telah digunakan secara meluas dalam bidang kejuruteraan awam, aeroangkasa dan mekanikal. Perubahan-perubahan seperti retak, kakisan atau lubang yang telah digerudi, boleh menjejaskan struktur dan integriti komponen. Kajian ini bertujuan memberi tumpuan kepada tiga bahagian kerja-kerja eksperimen: pertama, untuk memfabrikasi tiga jenis bahan komposit panel, kedua, untuk menilai sifat-sifat bahan mekanik, struktur mikro dan analisis terma bahan dan ketiga, untuk mengesan kerosakan dengan menggunakan sensor bijak untuk menilai teknik Pemantauan Kesihatan Struktur *(donation)* serta mengenal pasti kerosakan. Oleh itu, Aluminium aloi jenis 6061-T6 dan tiga fabrikasi bahan komposit digunakan. Komposit ini menggabungkan epoksi resin sebagai matriks bercampur secara individu dengan Twill Weave 240 g / m² carbon fiber (CFW), Plain Weave 300 g / m² Glass fiber (GFW) dan Chopped Strand Mats 450 g serat / m² Glass fiber [GF (CSM)] sebagai pengisi. Kajian ini juga termasuk prosedur fabrikasi daripada ketiga-tiga jenis panel komposit dengan menggunakan proses kaedah sapuan *(hand lay-up)* dan *vacuum bagging* . A 6061-T6 dianggap sebagai bahan rujukan untuk menilai pencirian bahan komposit baru. Selain itu, setiap bahan mempunyai kajian kes dan akhirnya kajian ini mempunyai empat kajian kes. Kes pertama (tidak rosak) dijadikan sebagai rujukan atau garis dasar data standard. Manakala, untuk mencerminkan tiga kes kerosakan dalam panel, ditunjukkan perbezaan simulasi berbeza ukuran, seperti 10mm, 15mm dan 20 mm. *Piezoelectric ceramic Lead Zirconate Titanate (PZT) transducer* sebagai sensor digunakan untuk memperoleh data masa sebenar. Perbandingan ini dijalankan untuk mengenalpasti serta mengesan kerosakan , berdasarkan kepada pendekatan frekuensi semulajadi dan spektrum kuasa dengan ketepatan prestasi melalui isyarat daripada sensor pintar (PZT). Dalam kajian ini, indeks *Root Mean Square Deviation (RMSD)* dan *Frequency Reduction Index (FRI)* dijalankan bagi mendapatkan analisis statistik untuk magnitud kerosakan bagi memperbaiki teknik Pemantauan Kesihatan Struktur *(SHM) (donation)*. Didapati *Root Mean Square Deviation (RMSD)* berfungsi meningkatkan aktiviti kenalpasti kerosakan dan didapati juga apabila keretakan meningkat, *Root Mean Square Deviation (RMSD)* juga meningkat. Akhir sekali, *SHM* melalui pendekatan PZT adalah bertambah baik dan telah disedari beberapa perubahan dalam frekuensi semulajadi terutamanya apabila kedalaman kerosakan meningkat di dalam komposit. Apabila kedalaman keretakan meningkat, frekuensi didapati menurun. Sementara itu, perbandingan juga dibuat di antara CFW resin epoksi dengan dua gentian kaca bertetulang epoksi termasuk struktur mikro, analisis termoplastik serta sifat-sifat mekanik bagi ketiga-tiga jenis. Umumnya, CFW sebagai komposit adalah lebih baik dalam struktur mikro, analisis terma dan

sifat-sifat mekanik serta ketahanan yang lebih tinggi terhadap kesan getaran dimana lebih daripada dua jenis gentian kaca telah diujikaji.

ACKNOWLEDGEMENTS

Praise is to ALLAH Almighty, the Most Gracious and the Most Merciful: from HIM I got the health, the power and the patience to finish this research. The first word sent from ALLAH to our Prophet Mohammed was "إِقْرَأْ" **[Read].** I believe in the massive meaning for this word and how it is revealed that the knowledge is crucial for our existence.

I would like to gratefully acknowledge my supervisor Assoc. Prof. Ir. Dr. Faizal Mustapha for his excellent technical and generous guidance, valuable assistance and encouragement. Similarly, I would like to spread my thankfulness and acknowledge for my thesis committee members, Professor Ir. Dr. Mohd Sapuan Salit, Assoc. Prof. Ir. Dr. Raizal Saifulnaz Muhammad Rashid and Assoc. Prof. Dr. Ahmad Ruzdi Mahmmud for their time, valuable advice and comments. Their incomparable knowledge in their significant fields has helped importantly in the completion of this research and made it possible to be complete.

This study has been possible with the support from Research University Grant Scheme no. [RUGS- 9348100], this financial, academic and technical supports are seriously appreciated. In the same time, I would like to appreciate the Graduation and Financial Assistance Section for their support and Fee's payment to publish in the "International Conference on Advances in Structural Health Management and Composite Structures" 2014 in Korea, and in Journal of Intelligent Material Systems and Structures.

A deepest gratitude is due to friend Puan Rosnita Abdul Rashid and my colleagues Mr. Mohammed Mustafa Al-Habshi for all their support throughout my research, for their assistance, encouragement, guidance were invaluable. I would like to acknowledge all the laboratory staffs in Engineering departments: Aerospace, Mechanical, Civil, Agriculture, and Chemical, as well as in UPM-INTROP (Bio-Composite laboratory) and UniKL-MIAT (Composite laboratory). I am very grateful for everyone provided assistance and technical support which played a main roles with regard to this study from the early stages of the composites fabrication process, experimental testing to data collection.

A deepest gratitude must go out to my family. I wish to express my thanks and appreciation to my mother for her love, constant prayers and support, sisters and brothers for their inspiration, great help and support.

Thanks a lot for all those who have supported me during this retro of struggle and without them I would not have been able to accomplish this milestone and that providing an opportunity to realize my vision. Last but not least, I want to express my love and wish peace and prosperity for all Humans, Muslims and my beloved country (AL-IRAQ), and hope that I can help for its development and education of our people. Besides, I would prompt my love and thanks to my second country (MALAYSIA).

I certify that an Examination Committee met on 26th May 2015 to conduct the final examination of Nisreen N. Ali on her thesis entitled "Structural Health Monitoring And Damage Identification Via Statistical Analysis For Composite Panel Structures Using Smart Sensor" in accordance with Universities and University Colleges Act 1971 and the Constitution of Universiti Putra Malaysia [P.U. (A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctore of Philosophy.
Members of the Examination Committee are as follows:

Zulkiflle Leman, PhD
Assoc. Prof.
Faculty of Engineering,
Universiti Putra Malaysia
(Chairman)

Mohd Khairol Anuar Mohd Ariffin, PhD
Assoc. Prof. Ir.
Faculty of Engineering,
Universiti Putra Malaysia
(Internal Examiner)

Raizal Zahari, PhD
Assoc. Prof.
Faculty of Engineering,
Universiti Putra Malaysia
(Internal Examiner)

Wesley Cantwell, PhD
Professor
Liverpool University
(External Examiner)

____

ZULKARNAIN ZAINAL, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 17 June 2015

This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctorate of Philosophy.

The members of the Supervisory Committee were as follows:

Faizal Mustaph, PhD
Associate Professor, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd Sapuan Salit, PhD
Professor, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Raizal Saifulnaz Muhammad Rashid, PhD
Associate Professor, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Member)

____
BUJANG KIM HUAT, 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 other 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.: ____

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

Signature:	____________________	Signature:	____________________
Name of Chairman of Supervisory Committee:	____________________	Name of Member of Supervisory Committee:	____________________
Signature:	____________________	Signature:	____________________
Name of Member of Supervisory Committee:	____________________	Name of Member of Supervisory Committee:	____________________

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AE	Acoustic Emission
Al 6061-T6	Aluminium Alloy Type 6061-T6
CFRP	Carbon Fibre Reinforced Plastic
CFW	Twill Weave 240 g/m^2 Carbon Fibre
DAQ	Data Acquisition
DMA	Dynamic Mechanical Analysis
DP	Damage Prognosis
DPH	Diamond Pyramid Hardness
EDS	Energy Dispersive Spectrometer
EDX	Energy Dispersive X-Ray
EDXA	Energy Dispersive X-Ray Analysis
EMI	Electro Mechanical Impedance
ESGs	Electric Strain Gauges
FBG	Fiber Bragg Grating
FE	Finite Element
FRI	Frequency Reduction Index
GF (CSM)	Chopped Strand Mats 450 g/m^2 Glass Fibre
GFW	Plain Weave 300 g/m^2 glass fiber
GNTVT	Guangzhou New Television Tower
HMM	Hidden Markov Modeling
HV	Vickers Hardener
IPN's	Interpenetrating Polymer Networks
MLP	Multi-Layer Perceptron
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Technique
NI	National Instruments
NCF	Non-Crimp Fabric
OA	Outlier Analysis
OFS	Optical Fiber Sensor
PDMS	Polydimethy Siloxane
PWAS	Piezoelectric Wafer Active Sensors
PZT	Piezoelectric ceramic Lead Zirconate Titanate
RC	Reinforced Concrete
RMSD	Root Mean Square Deviation
RPM	Revolution Per Minute
RTD	Room Temperature Density
SDIM	Structural Damage Detection Method
SEM	Scanning Electron Microscopy
SHM	Structural Health Monitoring
SNS	Structural Neural System
TEOS	Tetraethoxysilane
TETA	Triethylene Tetra Amine
TG	Thermo Gravimetry
TGA	Thermo gravimetric analysis
TNEWS	Transient Non-Linear Elastic Wave Spectroscopy.
TTA	Thermal Travimetric Analysis

UBC	University of British Columbia
UV	Ultraviolet
VI	Virtual Instrument
XRD	X-Ray Diffraction

LIST OF SYMBOLS

A	cross-sectional area of specimen, mm^2,
A_o	the original cross sectional area of specimen through which the force is applied,
b	width of beam tested, mm,
d	depth of beam tested, mm,
$d\varepsilon_{axial}$	axial strain, positive for axial tension and negative for axial compression,
$d\varepsilon_{trans}$	transverse strain, negative value for axial tension(stretching) and positive for axial compression,
D_f	maximum deflection of the centre of the beam, mm
E	Young's modulus,
F	the force applied on specimen under tensile,
F_{tu}	ultimate tensile strength, MPa,
L	support span, mm,
L_o	the original length of the specimen,
ΔL	the amount by which the length of the object changes,
M_d	Measured composite density, g/cm^3.
P	load at a given point on the load deflection curve, N
P_i	load at *i*th data point, N,
P_{max}	maximum load before failure, N,
ρ	density,
ρ_r	density of resin,
ρ_{reinf}	density of reinforcement
r	resin, weight%,
R	resin in Composite, weight %,
Sp	specific gravity,
T_d	theoretical composite density, g/cm^3,
υ	Poisson's ratio,
V	void content, volume %,
W_c	conditioned weight, (g),
W_w	wet weight, (g),
w_{reinf}	reinforcement, weight%,
σ	stress,
σ_i	tensile stress at *i*th data point, MPa,
σ_o	stress in the outer fibers at midpoint, MPa,
ε	strain, and
ε_o	strain in the outer surface, mm/mm.

CHAPTER 1

INTRODUCTION

1.1 General

Civil, aerospace and mechanical structures are the most expensive national assets of any country. These structures have long service life and are very costly to maintain and replace once they are built. In the past few years, Structural Health Monitoring (SHM) technique has been a growing issue, acknowledged as an important consideration and outstanding in its extensive applications. SHM is the implementation and procedure of damage detection to assess, improve and ensure the integrity, safety and reliability of the engineering substructures before they reach a critical state. Once the life of these structures and their substantial usage have started, it becomes crucial to monitor and assess their structural integrity.

Damage detection existences in these structures can enhance the safety, security, and prolong the structures' service life, and reduce the operational and maintenance costs. Early detection of the damage or structural degradation prior to local failure can prevent a catastrophic collapse of those structures. Typical damage in these infrastructures might be due to the development of cracks, degradation of structural connections, bearing wearing and shearing in rotating machinery, or from excessive external loads such as: strong winds, earthquakes, explosions and vehicle impacts. The most important structures include high-rise buildings, bridges, power utilities, nuclear power plants, and dams, in addition to aircraft and mechanical applications (Figure 1.1).

Figure 1.1 Examples of the Greatest Expensive Infrastructures.
(Kinematics, 2015)

The goal of SHM is to improve safety and reliability of infrastructure systems by detecting damage before it reaches a critical state and allow rapid post-event assessment. Tall buildings that materialized in the late nineteenth century have developed into a worldwide architectural marvel. Universally, many tall buildings were built especially in Asian countries, such as Japan, Malaysia, Korea and China. Conventionally, the tall buildings development functions have been as commercial office buildings due to rapidly increased or residential, mixed-use, and hotel towers. The construction of tall buildings will continue due to their important economic suitability in dense urban land use. "Tall building development involves various complex factors such as economics, technology, municipal rules, and politics, and economics has been the primary governing factor. The new structures types however, would not have been possible without supporting technologies", (Ali & Moon, 2007).

Recently, extensive research work in civil and aerospace applications has been extended by using fibre-reinforced plastic composite materials. Composite materials are increasingly being used in substructure applications such as reinforcement in structural shapes, various hybrid structures, pre-stressing for new concrete structures, strengthening for existing concrete as well as for bridge decks. These materials contain strong and continuous fibres bound together by a continuous matrix of polymer resin. The development of composite materials has been enhanced rapidly because of improvements in process technology and economic benefits. Significant mechanical properties results of composite materials have great advantages ranging from increased strength and durability features to weight reduction and lower petroleum ingesting compared with conventional and competitive materials. Structural vibration control along with smart materials is gradually being used for flexible structures and it has achieved impressive development. This is apparently in response to the high demand for safer structures and lower costs. For rational structural health monitoring applications, the large size of host structures may require innovative sensing technologies and use of appropriate software and hardware systems for data acquisition or reduction. Novel smart sensors and actuators, such as Piezoelectric Ceramic Lead Zirconate Titanate (PZT) transducers have been identified as the method of structural health monitoring technology development and it is widely used for monitoring requests. PZT materials are utilized as a powerful and innovative tool for local damage detection of various structures.

National Instrument and LabVIEW software is a graphical programming environment for developing refined measurement, test, and control systems by using intuitive graphical icons and wires that resemble a flowchart. LabVIEW software provides a small, simple, and affordable system for making vibration measurements in the lab and field. LabVIEW offers unrivalled integration with thousands of hardware devices, including NI-DAQ, (LabVIEW™ SinalExpress). It provides hundreds of built-in libraries for advanced analysis and data visualization as well as analyze data in real time, and creates custom reports using the industry standard tool. In general, a typical SHM system includes four major components (Dong et al., 2010):

1. Structure prototype,
2. A sensor system,
3. A data processing system including: data acquisition, program, and storage, and
4. A health evaluation system: including diagnostic information and organization.

1.2 Problem Statement

The maintenance and inspection infrastructures are very critical, and necessary to minimize the time period that the structures are out of service. Via SHM, the inspection, maintenance time and cost can be reduced. In addition, “SHM systems give online details about the structural safety” (Alexopoulos et al., 2010). A robust SHM scheme requires the unique characterization of the presence, location and severity of the damage. All structures in civil, aerospace and mechanics age and deteriorate with time. Vibration effects on structures are due to seismic or/and traffic, and this research considers the effect of traffic vibration.

The most common failures in material plate as a component are cracks and it is extensively found in civil, aerospace, shipbuilding, and additional productions. Quantitative indication of crack size and its location is of principal importance for damage identification in order to improve and maintain its life prediction. Frequency measurement is used to detect damage located at districts of low stress which might be undependable otherwise a shift in natural frequency might provide sufficient information for integrity monitoring when the damage is in a significant load bearing member (Salawu, 1997).

In structures, one of the critical portions is the mid-span and its up loading which creates the maximum bending moment. In a beam with a pin or a roller which supports at both ends, the moment is zero, while its maximum is at the load point and in this case it is the mid span (Sozen & Ichinose, 2008). At the higher load, the moment will be distributed to the mid span as shown in Figure 1.2. More attention must be paid to this portion to study the crack and negative effects especially in tall buildings. Several investigators have contributed to the study of crack detection and identification in various structure materials.

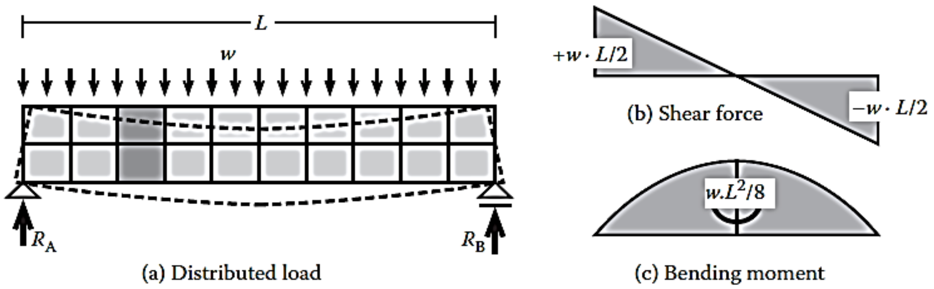

Figure 1.2. Simply Supported Beam under Uniformly Distributed Load.
(Sozen & Ichinose, 2008)

This research included an evaluation of the mechanical properties, micro structure and thermal analysis of the different fabricated composite panels as new materials to assess their characterizations. SHM was adopted in this research as a non-destructive technique to detect the damage via experimental procedures analysis to identify different cases of damages.

Real time monitoring for damage detection and identification of structures utilizing simple technique, and inexpensive available hardware connected with active and smart sensors is a great challenge. Nevertheless, to the best of the researcher's knowledge, no results have been published on the subject of SHM for damage identification regarding the same specification of these composite structures and selected damage parameters using smart sensor (PZT) and National Instrument LabVIEW SignalExpress software under the effect of mechanical vibration exciter.

1.3 Research Objectives

The aim of this research is damage detection and identification to incorporate a robust Structural Health Monitoring (SHM) scheme. This technique is applied on an aluminum alloy and composite materials that emulate three-storey structures through an application by using smart materials technology such as PZT sensor. This sensor is used to capture natural frequency and power spectrum responses to distinguish structural status. The objectives of this research are as follows:

1. To fabricate a three-storey aluminium frame to be the structure (prototype) for the four case studies. Also added is a definition for the materials, sensor and data acquisition with suitable software.
2. To compute the mechanical properties, micro structure and thermo plastic analysis of the new fabricated composites as a new material's components. Based on these characterization's results, these new composites can be evaluated then compared with the Al 6061-T6 alloy properties.

3. To acquire the real time signals for crack's damage using a smart system. This research consists of four material's panels in four cases: undamaged as a 1st case and considered as a reference, in addition to three cracks formed with lengths of 10 mm, 15 mm and 20 mm to simulate 2nd, 3rd and 4th cases, respectively.
4. To evaluate and assess the vibration effects on composite structures and to provide the significance and efficiency of the SHM system for damage detection and identification for composite panels. Statistical analysis according to RMSD and FRI equations was performed the results compared to the three composites with an Al 6061-T6 panel's results.

1.4 Research Scope

This research scope included:

1. **Design and Construction:** An aluminum frame designed to be the base for the structure's prototype.
2. **Composites Fabrication:** Three fibre/epoxy composites fabricated involving three types of fibres mixed individually with epoxy resin as a matrix.
3. **Operational Evaluation**: Evaluate the new composite materials by computng the mechanical properties, micro structure and thermo plastic analysis.
4. **Data Acquisition and Feature Extraction to Identify the Damage:** Acquire data via SHM technique using PZT sensor and NI LabVIEW SignalExpress software. Observation and evaluation of the natural frequency distinction as one of the dynamic properties of structures via the specimen's excitation and from the large set of data acquisition.
5. **Statistical Pattern Recognition:** To predict the structures integrity, Frequency Reduction Index (FRI) and Root Mean Square Deviation (RMSD) index were employed to evaluate the collected data.

1.5 Thesis Layout

This thesis organized into seven chapters which can be summarized as follows:
Chapter 1: This chapter introduces the background of structural health monitoring technique and damage detection in structures, composite materials as a part of future work in construction materials, and National Instrument and LabView SignalExpress related with smart sensor (PZT) to acquire vibration data. The problem statement, objectives, scope of the study, and thesis layout are also explained briefly.

Chapter 2: This chapter comprises the literature review of previous research related to the subject area including: SHM technique and damage detection contributed in monitoring structures, composite materials development and fabrication process, sensors types and PZT as a smart sensor and National Instrument and LabView SignalExpress as a part of SHM monitoring system to acquire the data.

Chapter 3: Chapter 3 illustrates the flow chart of the research work. In this chapter all details of experimental work are presented such as: the composite materials fabrication design, tests to measure the mechanical properties, the micro structural and thermo plastic analysis of these new composite materials. The application of the proposed SHM technique to detect the damage in the proposed structures is presented as: national instrument, data acquisition, and software which is used for damage identification. Four study cases are used to detect damage in each selected material using aluminum alloy as reference to compare the results with the three fabricated composite materials.

This chapter presents the composite materials fabrication by using new technique and process to control the thickness of the product and use of different types of reinforced composite fibre to improve the best fibres/resin ratio with suitable number of the fibres reinforced layers.

Chapter 4: This chapter illuminates the computed results such as: mechanical properties, micro structure, thermo plastic analysis for the new fabricated composite materials. The properties of aluminum alloy type 6061-T6 are also illustrated.

Chapter 5: Chapter 5 presents the captured signals via NI USB-9234 DAQ device and LabVIEW Signal Process software, damage detection and the data collection. Four case studies (undamaged, crack length 10mm, crack length 15 mm and crack length 20mm) in four different structure materials are statistically analyzed in this chapter based on Root Mean Square Deviation (RMSD) index and Frequency Reduction Index (FRI) to realize the damage magnitude.

Chapter 6: The main identification findings of this research are presented in this chapter, while the contribution to scientific knowledge is also presented. Moreover, recommendations for future work are provided in this chapter.

REFERENCES

Alamri, H., Low, I. M., and Alothman, Z. (2012). Mechanical, thermal and microstructural characteristics of cellulose fibre reinforced epoxy/organoclay nanocomposites. *Composites Part B: Engineering, 43*(7), 2762-2771.

Alexopoulos, N., Bartholome, C., Poulin, P., and Marioli-Riga, Z. (2010). Damage detection of glass fiber reinforced composites using embedded PVA- carbon nanotube (CNT) fibers. *Composites Science and Technology*, *70*(12), 1733-1741.

Ali, M. M., and Moon, K. S. (2007). Structural developments in tall buildings: current trends and future prospects. *Architectural Science Review*, *50*(3), 205-223.

Alibiglu, A., Shakeri, M., and M. R. and Kari (2007). Free vibration of rectangular composite plates with localized patch mass. Transactions, SMiRT, *19*, P. # B02/5.

AL-Talah, Z. A. (2010). *Damage identification and localization of Cantelever Steel beam with Circular Cross Section Using Modal analysis*. Master Thesis, Universiti Putra Malaysia.

Annamdas, V. G. M., and Soh, C. K. (2010). Application of electromechanical impedance technique for engineering structures: review and future issues. Journal of Intelligent Material Systems and Structures, *21*(1), 41-59.

Annamdas, V. G. M., Yang, Y., and Soh, C. K. (2010). Impedance based concrete monitoring using embedded PZT sensors. *International journal of civil and structural engineering. 1*(3): 414-424.

Ansar, M., Xinwei, W., and Chouwei, Z. (2011). Modeling strategies of 3D woven composites: a review. *Composite Structures, 93*(8), 1947-1963.

APC International, Ltd, (Manual). *Piezoelectric Ceramics: principles and Applications, American Products, INC. Duck Run USA*, pp.22.

Aris, K. D. M., Mustapha, F., Salit, M. S., and Majid, D. L. A. A. (2014). Condition Structural Index using Principal Component Analysis for undamaged, damage and repair conditions of carbon fiber-reinforced plastic laminate. *Journal of Intelligent Material Systems and Structures, 25*(5), 575-584.

Aris, K. M., Mustapha, F., Sapuan, S., and Majid, D. A Structural Health Monitoring of a Pitch Catch Active Sensing of PZT Sensors on CFRP Panels: A Preliminary Approach. *DOI: 10.5772/48097*. Book, Chapter 1. Retrieved 23 Jan 2015 from: http://www.stamplive.com/apu.php?n=&zoneid=8191&cb=1725730654&popunder=1&direct=1.

Aslan, Z. l., Karakuzu, R., and Okutan, B. (2003). The response of laminated composite plates under low-velocity impact loading. *Composite Structures, 59*(1), 119-127.

ASTM B 557M- 02a, Standard Test Methods for Tension Testing Wrought and Cast Aluminium- and Magnesium-Alloy Products.

ASTM D 256- 04, Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics.

ASTM D 570- 98, Standard Test Methods for Water Absorption of Plastics.

ASTM D 790- 00, Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials.

ASTM D 792- 00, Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement.

ASTM D 2734- 94, Standard Test Method for Void Content of Reinforced Plastics.

ASTM D 3039/D 3039M– 00, standard test methods for Tensile Properties of Polymer Matrix Composite Materials.

ASTM D 4065- 01, Standard Practice for Plastics: Dynamic Mechanical Properties: Determination and Report of Procedures.

ASTM D 5023– 00, Standard Test Method for Plastics: Dynamic Mechanical Properties: In Flexure (Three- Point Bending).

ASTM E 384- 99, Standard Test Method for Microindentation Hardness of Materials.

ASTM E 1131- 03, Standard Test Method for Compositional Analysis by Thermo gravimetry.

Bhalla, S., Soh, C. K., and Liu, Z. (2005). Wave propagation approach for NDE using surface bonded piezoceramics. *NDT & E International, 38*(2), 143-150.

Bhalla, S., and Kiong Soh, C. (2003). Structural impedance based damage diagnosis by piezo-transducers. *Earthquake engineering and structural dynamics. 32*(12): 1897-1916.

Bakis, C. E. *Life Cycle Analysis Issues in the Use of Frp Composites in Civil Infrastructure*. Proceedings of US-Japan Workshop on Life Cycle Assessment of Sustainable Infrastructure Materials Sapporo, Japan, October 21-22, 2009.

Baptista, F. G., Filho J. V. and Inman, D. (2011). Sizing PZT Transducers in Impedance-Based Structural Health Monitoring. *Sensors Journal, IEEE, 11*(6), 1405-1414.

Baptista, F. G. and Filho, J. V. (2009). A new impedance measurement system for PZT-based structural health monitoring. *Instrumentation and Measurement, IEEE Transactions on, 58*(10), 3602-3608.

BERTRAM31.Com. Basic Vacuum Bagging. Retrieved 23 Jan 2015 from http://www.bertram31.com/proj/tips/vaccuum.htm.

Caccese, V., Mewer, R., and Vel, S. S. (2004). Detection of bolt load loss in hybrid composite/metal bolted connections. *Engineering Structures, 26*(7), 895-906.

Caccese, V., Richard Mewer, a., and Vel, S. S. (2004). Detection of Bolt Load Loss Using Frequency Domain Techniques, October 24-27, Bar Harbor, Maine, USA. Proceeding of the 15th International Conference on Adaptive Structures and Technologies.

Camanho, P. P., DÃ¡vila, C. G., Pinho, S. T., Iannucci, L., and Robinson, P. (2006). Prediction of in situ strengths and matrix cracking in composites under transverse tension and in-plane shear. *Composites Part A: Applied Science and Manufacturing, 37*(2), 165-176.

Cantwell, W., and Morton, J. (1991). The impact resistance of composite materials- a review. *composites, 22*(5), 347-362.

Cawley P. and Sarsentis N. (1988). A Quick Method for the Measurement of Structural Damping. *Mechanical System and Signal Processing*, *2*(1): 39-47.

Chang F. K. (1997). Structural Health Monitoring: A Summary Report on the First International Workshop on Structural Health Monitoring. *Proceedings of the 2rd International Workshop on Structural Health Monitoring*, pp. 3–11, Technomic Publishing Company, Lancaster, UK.

Chen, W., and Jia, P. (2012). Interlaminar stresses analysis and the limit state function approximating methods for composite structure reliability assessment: A selected review and some perspectives. *Journal of Composite Materials, 47,* 1535-1547.

Chen, Y., Scarpa, F., Farrow, I., Liu, Y., and Leng, J. (2013). Composite flexible skin with large negative Poisson's ratio range: numerical and experimental analysis. *Smart Materials and Structures, 22*(4), 045005 (12 pp).

Chipara, M., Lozano, K., Hernandez, A., and Chipara, M. (2008). TGA analysis of polypropylene-carbon nanofibers composites. *Polymer degradation and stability*, 93(4), 871-876.

Choi SR, Bansal NP, and Garg A. (2007). Mechanical and microstructural characterization of boron nitride nanotubes-reinforced SOFC seal glass composite. *Material Science Engineering. 460,* 509-515.

Chong, K. P. (1999). Health monitoring of civil structures, *Journal of Intelligent Material Systems and Structures*. *9*(11): 892–898.

Corcione, C. E., and Frigione, M. (2012). Characterization of nano composites by thermal analysis. *Materials. 5*, 2960-2980.

Corum J, Battiste R, and Ruggles-Wrenn M. (2003). Low-energy impact effects on candidate automotive structural composites. Composite Science and Technology. *63*, 755-769.

Corum J, Battiste R, Liu K, and Ruggles M. Basic properties of reference crossply carbon-fiber composite (2000). Retrieved in 20 Jan 2015 from: http://web.ornl.gov/~webworks/cpr/v823/rpt/106099.pdf.

Crider, I., and Jeffrey, S. (2007). *Damage detection using Lamb waves for structural health monitoring*: DTIC Document Online Information for the Defence Community. Retrieved in 20 Jan 2015 from: http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA469262.

Danai Abhijeet, R., Swami, M., and Patil, P. (2015). A Review on Study of Composite Materials in Presence of Cracks. *International Journal of Research in Engineering and Technology 4*(2), 43-45.

De Morais W, d'Almeida J, and Godefroid L. (2003). Effect of the fiber reinforcement on the low energy impact behavior of fabric reinforced resin matrix composite materials. J the Brazil Soc Mech Sci Engineerin. *25*: 325-328.

De Moura Jr, J. D. R. V., Park, S., Steffen Jr, V., and Inman, D. J. (2007). *Damage characterization based on impedance-based signatures and Lamb Wave techniques*. Paper presented at the Conference Proceedings of the Society for Experimental Mechanics Series.

Differential Scanning Calorimetry (DSC) and Thermo Gravimetric Analysis (TGA). Retrieved 23 Jan 2015 from http://www.itc.tu-bs.de/Abteilungen/Makro/Methods/dsc.pdf.

Dincal, S. (2005). *Structural damage detection using frequency response functions*. PhD. Thesis**,** Texas A&M University.

Dong, Y., Song, R. and Liu, H. Bridges Structural Health Monitoring and Deterioration Detection Synthesis of Knowledge and Technology, Final Report, December 2010, Alaska University Transportation Center. Retrieved 31 Jan 2015 from: http://ine.uaf.edu/autc/files/2011/08/Final_Report_3090361.pdf.

Easy Composites. Retrieved 23 Jan 2015 from: http://www.easycomposites.co.uk/products/carbon-fibre-cloth-fabric/22-twill-240gsm-3k-1.25m.aspx.

Easy Composites. Retrieved 23 Jan 2015 from: http://www.easycomposites.co.uk/Products/Kevlar-Aramid-Others/Diolen-Cloth-300g-96cm.aspx.

Easy Composites. Retrieved 23 Jan 2015 from: http://www.easycomposites.co.uk/products/chopped-strand-mat/450g-emulsion-bound-csm-per-metre.aspx.

El-Hacha, R., R. G. Wight, Green M. F. (2004). Prestressed carbon fiber reinforced polymer sheets for strengthening concrete beams at room and low temperatures. *Journal of composites for construction. 8*(1): 3-13.

El-Shekeil, Y. A., Sapuan, S. M., Abdan, K., and Zainudin, E. S. (2012). Influence of fiber content on the mechanical and thermal properties of Kenaf fiber reinforced thermoplastic polyurethane composites. *Materials & design, 40*, 299-303.

Engineer's Hand Book, Manufacturing Processes-Hand Lay-up Composite Molding. Retrieved 30 Jan 2015-a from: http://www.engineershandbook.com/MfgMethods/handlayup.htm.

Engineer's Hand Book, Manufacturing Processes-Hand Lay-up Composite Molding-Retrieved 30 Jan 2015-b from: http://www.engineershandbook.com/MfgMethods/vacuumbagmolding.htm.

Faizal, M. A., Beng, Y. K., and Dalimin, M. N. (2006). Tensile Property of Hand Lay-up Plain-weave Woven e-glass/polyester Composite: Curing Pressure and Ply Arrangement Effect. *Borneo Science, 19*, pp. 27-34.

Farrar, C. R., and Lieven, N. A. (2007). Damage prognosis: the future of structural health monitoring. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 365*(1851), 623-632.

Farrar, C. R., and Worden, K. (2007). An introduction to structural health monitoring. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*. *365*(1851), 303-315.

Filip, P., Weiss, Z., and Rafaja, D. (2002). On friction layer formation in polymer matrix composite materials for brake applications. *Wear*, *252*(3), 189-198.

Flaga, K. (2000). Advances in materials applied in civil engineering. *Journal of Materials Processing Technology, 106*(1): 173-183.

Franco, V. R., Bueno, D. D., Junior, A. A. C., Gonsalez, C. G., Perini, E. A., and Junior, V. L.. *Structural health monitoring in smart structures using lamb waves approaches*. International Conference on Engineering Optimization. EEngOpt (2008). Rio de Janeiro, Brazil, 01 - 05 June 2008.

Fujita A, Hamada H, and Maekawa Z. (1993). Tensile properties of carbon fiber triaxial woven fabric composites. *Journal of Composite Material*, *27*, 1428-1442.

Garden, H. and L. Hollaway (1998). An experimental study of the influence of plate end anchorage of carbon fibre composite plates used to strengthen reinforced concrete beams. *Composite Structures. 42*(2): 175-188.

Garcia-Castillo, S. K., Navarro, C., and Barbero, E. (2014). Damage in preloaded glass/vinylester composite panels subjected to high-velocity impacts. *Mechanics Research Communications, 55*, 66-71.

Giurgiutiu, V. (2008).Structural Health Monitoring with Piezoelectric Wafer Active Sensors. Acadimic Press. pp.1.

Giurgiutiu, V. (2005). Tuned Lamb wave excitation and detection with piezoelectric wafer active sensors for structural health monitoring. *Journal of Intelligent Material Systems and Structures, 16*(4), 291-305.

Giurgiutiu, V., and Zagrai, A. (2005). Damage detection in thin plates and aerospace structures with the electro-mechanical impedance method. *Structural Health Monitoring. 4*(2): 99-118.

Giurgiutiu, V. (2002). *Lamb wave generation with piezoelectric wafer active sensors for structural health monitoring.* Paper presented at the Smart Structures and Materials. SPIE's 10th Annual International Symposium on Smart Structures and Materials and 8th Annual International Symposium on NDE for Health Monitoring and Diagnostics, Mar. 2-6, 2002, San Diego, CA. paper # 5056-17.

Giurgiutiu, V., and Zagrai, A. N. (2002). Embedded self-sensing piezoelectric active sensors for on-line structural identification. *Journal of Vibration and Acoustics, 124*(1), 116-125.

Giurgiutiu, V., Zagrai, A., and Bao, J. J. (2002). Piezoelectric wafer embedded active sensors for aging aircraft structural health monitoring. *Structural Health Monitoring. 1*(1): 41-61.

Giurgiutiu, V. and Zagrai A. (2001). Electro-Mechanical Impedance Method for Crack Detection in Metallic Plates. *SPIE's 8th Annual International Symposium on Smart Structures and Materials and 6th Annual International Symposium on NDE for Health Monitoring and Diagnostics*, 4-8 March 2001, Newport Beach, CA. paper # SS02 4335-22.

Giurgiutiu, V., and Zagrai, A. N. (2000). Characterization of piezoelectric wafer active sensors. *Journal of Intelligent Material Systems and Structures, 11*(12), 959-976.

Green, P. (1991). Fibre volume fraction determination of carbon-epoxy composites using an acid digestion bomb. *Journal of materials science letters, 10*(19), 1162-1164.

Hanoosh, W. S., and Abdelrazaq, E. M. (2009). Polydimethyl siloxane toughened epoxy resins: Tensile strength and dynamic mechanical analysis. *Malaysian Polyer Journal, 4*, 52-61.

Hassan, M., Naderi, S., and Bushroa, A. (2014). Low-velocity impact damage of woven fabric composites: Finite element simulation and experimental verification. *Materials and design, 53*, 706-718.

Hassan, A., Hornsby, P., and Folkes, M. (2003). Structure-property relationship of injection-molded carbon fibre-reinforced polyamide 6, 6 composites: the effect of compounding routes. *Polymer testing, 22*(2), 185-189.

Hatta, H., Goto, K., Ikegaki, S., Kawahara, I., Aly-Hassan, M. S., and Hamada, H. (2005). Tensile strength and fiber/matrix interfacial properties of 2D-and 3D-carbon/carbon composites. *Journal of the European Ceramic Society, 25*(4), 535-542.

Heβ, H, and Himmel N. (2011). Structurally stitched NCF CFRP laminates. Part 2: Finite element unit cell based prediction of in-plane strength. *Composite Science and Technology. 71*, 569-585.

Heimbs S, Heller S, and Middendorf P. *Simulation of Low Velocity Impact on Composite Plates with Compressive Preload.* (2008). Paper presented at the 7th German LS-DYNA Forum, Bamberg.

Hey, F., Bhalla, S., and Soh, C. K. (2006). Optimized parallel interrogation and protection of piezo-transducers in electromechanical impedance technique. *Journal of Intelligent Material Systems and Structures*, *17*(6), 457-468.

HiSupplier.com. Retrieved 23 Jan 2015 from: http://www.hisupplier.com/a-chopped-strand-mat/

Hoa, S. V. (2009). *Principles of the manufacturing of composite materials*: DEStech Publications, Inc.439 North Duke Street, Lancaster, Pennsylvania 17602 U.S.A. (Book), pp.13-14.

Hollaway, L. (2010). A review of the present and future utilisation of FRP composites in the civil infrastructure with reference to their important in-service properties. *Construction and Building Materials, 24*(12), 2419-2445.

Hollaway, L. (2003). The evolution of and the way forward for advanced polymer composites in the civil infrastructure. *Construction and Building Materials,* 17(6), 365-378.

Hong, Y., Han, B.-h., Kim, B.-j., Hong, D.-p., and Kim, Y.-m. (2007). Estimation for bolt fastening conditions of thin aluminum structure using PZT sensors. *Journal of Mechanical Science and Technology, 21*(6), 891-895.

Huda, M. S., Drzal, L. T., Mohanty, A. K., and Misra, M. (2008). Effect of fiber surface-treatments on the properties of laminated biocomposites from poly (lactic acid) (PLA) and kenaf fibers. *Composites Science and Technology, 68*(2), 424-432.

Huda, M., Drzal, L., Mohanty, A., and Misra, M. (2007). The effect of silane treated- and untreated-talc on the mechanical and physico-mechanical properties of poly (lactic acid)/newspaper fibers/talc hybrid composites. *Composites Part B: Engineering, 38*(3), 367-379.

Huda, M. S., Drzal, L. T., Mohanty, A. K., and Misra, M. (2006). Chopped glass and recycled newspaper as reinforcement fibers in injection molded poly (lactic acid)(PLA) composites: a comparative study. *Composites Science and Technology*, *66*(11), 1813-1824.

INSTRON, Vickers Test. Retrieved 25 Jan 2015 from: http://www.instron.de/wa/applications/test_types/hardness/vickers.aspx.

Intertek, Energy Dispersive X-ray Analysis (EDX). Retrieved 15 Jan. 2015 from: http://www.intertek.com/analysis/microscopy/edx/.

Isometsii, J., and Lahtinen, H. (1996). Criteria for Matrix Failure in Continuous FRP-Composites-A Literature Study. Part 1: *Matrix Cracking*. *29*, 3-28.

Ju J., and Morgan RJ. (2004). Characterization of micro crack development in BMI-carbon fiber composite under stress and thermal cycling. *Journal of Composite Material*. 38: 2007-2024.

Kaddami, H., Dufresne, A., Khelifi, B., Bendahou, A., Taourirte, M., Raihane, M., et al. (2006). Short palm tree fibers-Thermoset matrices composites. *Composites Part A: Applied Science and Manufacturing*, *37*(9), 1413-1422.

Kanazawa, K. (2006). *Structural damage detection from natural frequency eliminated by temperature effect.* Paper presented at the Proceedings of the International Modal Analysis Conference (IMAC), St. Louis, USA.

Kang, K.-T., Chun, H.-J., Lee, J. A., Byun, J.-H., Um, M.-K., Lee, S.-K., et al. (2011). Damage Detection of Composite Plates Using Finite Element Analysis Based on Structural Health Monitoring. *Journal of Materials Science and Engineering B, 1*(1), 14-21.

Kessler, S. S., Spearing, S. M., and Atalla, M. J. (2002). *In-situ damage detection of composites structures using Lamb wave methods.* Paper presented at the Proc. First European Workshop on Structural Health Monitoring 10-12 July 2002 Paris France.

Kessler, S. S. (2002). *Piezoelectric-based in-situ damage detection of composite materials for structural health monitoring systems.* Massachusetts Institute of Technology.

Kessler, S. S., Spearing, S. M., Atalla, M. J., Cesnik, C. E., & Soutis, C. (2002). Damage detection in composite materials using frequency response methods. *Composites Part B: Engineering*, 33(1), 87-95.

Kim, J.-T., Ryu, Y.-S., Cho, H.-M., and Stubbs, N. (2003). Damage identification in beam-type structures: frequency-based method vs mode-shape-based method. *Engineering Structures, 25*(1), 57-67.

Kim, C. P., Busch, R., Masuhr, A., Choi-Yim, H., and Johnson, W. L. (2001). Processing of carbon-fiber-reinforced bulk metallic glass composites. *Applied Physics Letters, 79*(10), 1456-1458.

Kinematics. Structural Health Monitoring. Retrieved 23 Jan 2015 from: http://www.kinemetrics.com/p-198-Structural%20Health%20Monitoring.aspx.

Kirikera, G. R., Shinde, V., Schulz, M. J., Ghoshal, A., Sundaresan, M. J., and Allemang, R. J., (2008). A structural neural system for real-time health monitoring of composite materials. *Structural Health Monitoring, 7*(1), 65-83.

Kolar, R. *Modal analysis and damage assessment of cracked plates*. Conference: 2003 IMAC-XXI: Conference and Exposition on Structural Dynamics.

LabVIEW^{TM} SinalExpress, *Getting started with LabVIEW SignalExpress*, National Instrument June 2012, Manual.

Lecture 22: Thermal Methods. Retrieved 31 Jan 2015 from: http://radchem.nevada.edu/classes/chem455/lecture_22__thermal_methods.htm.

Li, Z., T. H. Chan, et al. (2001). Fatigue analysis and life prediction of bridges with structural health monitoring data- Part I: methodology and strategy. *International Journal of Fatigue*, *23*(1): 45-53.

Li, G., Pourmohamadian, N., Cygan, A., Peck, J., Helms, J. E., and Pang, S.-S. (2003). Fast repair of laminated beams using UV curing composites. *Composite Structures, 60*(1), 73-81.

Lim, S., and Hong, C. (1989). Prediction of transverse cracking and stiffness reduction in cross-ply laminated composites. *Journal of Composite Materials, 23*(7), 695-713.

Lin Li. DMA Basic and beyond, Thermal Analysis, PerkinElmer Inc., April 2000. Retrieved 23 Jan 2015 from: http://depts.washington.edu/mseuser/Equipment/RefNotes/LinLiDma-SF.pdf.

Liu, J., Wang, X., Yuan, S., and Li, G. (2006). On Hilbert-Huang transform approach for structural health monitoring. *Journal of Intelligent Material Systems and Structures, 17*(8-9), 721-728.

Liu, Y.-L., Wei, W.-L., Chen, Y.-J., Wu, C.-S., and Tsai, M.-H. (2004). Novel thermosetting resins based on 4-(N-maleimido) phenylglycidylether: III. Studies on the thermal degradation kinetics and mechanisms of the cured resins. *Polymer degradation and stability, 86*(1), 135-145.

Ma, S., Liu, W., Su, Q., and Liu, Y. (2010). Studies on the thermal properties of epoxy resins modified with two kinds of silanes. *Journal of Macromolecular Science, Part B: Physics, 49*(1), 43-56.

Marshall, D., Cox, B. N., and Evans, A. G. (1985). The mechanics of matrix cracking in brittle-matrix fiber composites. *Acta Metallurgica, 33*(11), 2013-2021.

Mascarenas, D. L., Todd, M. D., Park, G., and Farrar, C. R. (2007). Development of an impedance-based wireless sensor node for structural health monitoring. *Smart Materials and Structures, 16*(6), 2137.

Mascareñas, D. L. (2006). *Development of an impedance method based wireless sensor node for monitoring of bolted joint preload.* Master Thesis. Structural Engineering, University of California, San Diego, USA.

Meo, M., Zumpano, G. Meng X., Cosser, E., Roberts, G. Dodson, A. (2006). Measurements of dynamic properties of a medium span suspension bridge by using the wavelet transforms" *Mechanical Systems and Signal Processing 20*(5): 1112-1133.

Min, J., Shim, H., and Yun, C.-B. *Electromechanical Impedance-based Damage Identification Using Multiple Piezoelectric Sensors*. The 6th International Workshop on Advaced Smart Materials and Smart Structures Technology (ANCRiSST 2011) July 25-26, 2011, Dalian. China.

Modi, D., Correia, N., Johnson, M., Long, A., Rudd, C., and Robitaille, F. (2007). Active control of the vacuum infusion process. *Composites Part A: Applied Science and Manufacturing, 38*(5), 1271-1287.

Moon, C.-R., Bang, B.-R., Choi, W.-J., Kang, G.-H., and Park, S.-Y. (2005). A technique for determining fiber content in FRP by thermogravimetric analyzer. *Polymer testing, 24*(3), 376-380.

Morassi, A. (2011). Detecting damage in rods and beams from natural frequency and anti-resonant frequency measurements. *Proceedings of the 8th International Conference on Structural Dynamics, EURODYN 2011*(Leuven, Belgium, 4-6 July 2011).

Mufti, A. (2005). Structural health monitoring of innovative bridge decks. *Structure and Infrastructure Engineering, 1*(2): 119-133.

Mufti, A. A. (2002). Structural health monitoring of innovative Canadian civil engineering structures. *Structural Health Monitoring, 1*(1), 89-103.

Mustapha, F., Worden, K., Pierce, S., and Manson, G. (2007 a). Damage detection using stress waves and multivariate statistics: an experimental case study of an aircraft component. *Strain, 43*(1), 47-53.

Mustapha, F., Manson, G., Worden, K., and Pierce, S. (2007 b). Damage location in an isotropic plate using a vector of novelty indices. *Mechanical Systems and Signal Processing, 21*(4), 1885-1906.

Mustapha, F., Manson, G., Pierce, S., and Worden, K. (2005). Structural health monitoring of an annular component using a statistical approach. *Strain, 41*(3), 117-127.

Naidu, A., and Soh, C. (2004). Damage severity and propagation characterization with admittance signatures of piezo transducers. *Smart Materials and Structures, 13*(2), 393.

Natarajan, S., P. M. Baiz, S. Bordas, T. Rabczuk, P. Kerfriden. (2011). Natural frequencies of cracked functionally graded material plates by the extended finite element method. *Composite Structures, 93*(11): 3082-3092.

NDT, Resource Center, Tensile proprites. Retrieved 23 Jan 2015 from: https://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Mechanical/Tensile.htm.

Neto, R. M. F., Steffen, V., Rade, D. A., Gallo, C. A., and Palomino, L. V. (2011). A low-cost electromechanical impedance-based SHM architecture for multiplexed piezoceramic actuators. *Structural Health Monitoring, 10*(4), 391-402.

Ni, Y., and Zhou, H. (2010). *Guangzhou new TV tower: integrated structural health monitoring and vibration control.* Paper presented at the Structures Congress, 2010 ASCE.

Nickerson, S., Mayes, J. S., Paul, C., and Welsh, J. S. (2004). *Modeling matrix failure in composites due to cryogenic temperatures.* Paper presented at the Aerospace Conference, 2004. Proceedings. 2004 IEEE.

Nji, J., and Li, G. (2010). A self-healing 3D woven fabric reinforced shape memory polymer composite for impact mitigation. *Smart Materials and Structures,* 19(3), 035007 (9 pp).

Nordin, Z. (2009). *The potentional application of virtual refrencec station-real time kinematic instructural health monitoring.* Master Thesis, Universiti Teknologi Malaysia.

Nordin, Z., Akib, W. A. A. W. M., Amin, Z. M., and Yahya M.H. (2009). *Investigation on VRS-RTK Accuracy and Integrity for Survey Application*. International Symposium and Exhibition on Geoinformation. August 10-11, 2009.

Newman Jr, J. (1971). An improved method of collocation for the stress analysis of cracked plates with various shaped boundaries. NASA TECHNICAL NOTE, D-6376, National Aeronautics and Space Administration, Washington, D.C. August 1971, USA.

Ou, J., and Li, H. (2010). Structural health monitoring in mainland China: review and future trends. Structural Health Monitoring. *9*(3): 219-231.

Paiva, A. O., Duarte, M. G., Fernandes, M. H. V., Gil, M. H., and Costa, N. S. G. (2006). In Vitro studies of bioactive glass/polyhydroxybutyrate composites. *Materials Research, 9*(4), 417-423.

Palomino, L. V., Moura, J., Tsuruta, K., Rade, D. A., and Steffen, V. (2011) Impedance-based health monitoring and mechanical testing of structures. *Smart Structures and Systems*, *7*(1), 15-25.

Pang, K., and Gillham, J. (1989). Anomalous behavior of cured epoxy resins: density at room temperature versus time and temperature of cure. *Journal of Applied Polymer Science, 37*(7), 1969-1991.

Panigrahi, R., Bhalla, S., and Gupta, A. (2010). A Low-Cost Variant of Electro-Mechanical Impedance (EMI) Technique For Structural Health Monitoring. *Experimental Techniques*, *34*(2), 25-29.

Park, G., and Inman, D. J. 2007. Structural health monitoring using piezoelectric impedance measurements. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 365*(1851): 373-392.

Park, G., Farrar, C. R., di Scalea, F. L., and Coccia, S. (2006 b). Performance assessment and validation of piezoelectric active-sensors in structural health monitoring. *Smart Materials and Structures. 15*(6): 1673.-1683.

Park, G., and Inman, D. (2001). Smart bolts: an example of self-healing structures. *Smart Materials Bulletin, 2001*(7), 5-8.

Park, G., Cudney, H. H., and Inman, D. J. (2000). Impedance-based health monitoring of civil structural components. *Journal of infrastructure systems. 6*(4): 153-160.

Park, S., Ahmad, S., Yun, C. B., and Roh, Y. (2006 a). Multiple crack detection of concrete structures using impedance-based structural health monitoring techniques. *Experimental Mechanics. 46*(5): 609-618.

Peairs, D. M. (2006). *High frequency modeling and experimental analysis for implementation of impedance-based structural health monitoring.* PhD. Dissertation, Virginia Polytechnic Institute and State University.

Pérez, Marco A., Gil, L., and Oller, S. (2014). Impact damage identification in composite laminates using vibration testing. *Composite Structures, 108*(0), 267-276.

Poisson's Ratio. WIKIPEDIA. Retrieved 23 Jan 2015 from: http://en.wikipedia.org/wiki/Poisson's_ratio.

Premkumar, S., Karikal Chozhan, C., and Alagar, M. (2008). Studies on thermal, mechanical and morphological behaviour of caprolactam blocked methylenediphenyl diisocyanate toughened bismaleimide modified epoxy matrices. *European polymer journal, 44*(8), 2599-2607.

Priya, S. P., Ramakrishna, H., Rai, S., and Rajulu, A. V. (2005). Tensile, flexural, and chemical resistance properties of waste silk fabric-reinforced epoxy laminates. *Journal of Reinforced Plastics and Composites, 24*(6), 643-648.

Raju, V., (1997). *Implementing Impedance-based Health Monitoring*, Master's thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Richardson, M., and Wisheart, M. (1996). Review of low-velocity impact properties of composite materials. *Composites Part A: Applied Science and Manufacturing, 27*(12), 1123-1131.

Rmili, W., Deffarges, M. P., Chalon, F., Ma, Z., and Lero, R. (2014). Dynamic Mechanical Properties and Thermal Effect of an Epoxy Resin Composite, Encapsulation Element of a New Electronic Component. *Journal of Electronic Materials, 43*(3), 702-707.

Romano, A. J., Abraham, P. B., and Williams, E. G. (1990). A Poynting vector formulation for thin shells and plates, and its application to structural intensity analysis and source localization. Part I: Theory. *The Journal of the Acoustical Society of America, 87*(3), 1166-1175.

Rozman, H., and Tay, G. (2008). The effects of NCO/OH ratio on propylene oxide-modified oil palm empty fruit **bunch-**based polyurethane composites. *Journal of Applied Polymer Science, 110*(6), 3647-3654.

Ruggles-Wrenn M. *Effects of Temperature and Environment on Mechanical Properties of Two Continuous Carbon-Fibers Automotive Structural Composites*: ORNL (Oak Ridge National Laboratory) by the US Department of Energy (2003). Retrieved 20 Jan. 2014 from: http://www.osti.gov/scitech/biblio/885829.

Rutherford, A. C., Park, G., Sohn, H., and Farrar, C. R. (2004). *The Use of Electrical Impedance Moments for Structural Health Monitoring.* Paper presented at the Proceedings of the 22nd IMAC.

Rytter, A. (1993). *Vibration Based Inspection of Civil Engineering Structures*. PhD. Thesis, University of Aalborg. Denmark.

Salawu, O. S. 1997. Detection of structural damage through changes in frequency: a review. *Engineering Structures, 19*(9): 718-723.

Saleh, A. B., Mohd Ishak, Z., Hashim, A., and Kamil, W. (2009). Compatibility, mechanical, thermal and morphological properties of epoxy resin modified with carbonyl-terminated butadiene acrylonitrile copolymer liquid rubber. *Journal of Physical Science, 20*, 1-12.

Saraç. S., and Springer, J. r. (2002). Electrografting of 3-methyl thiophene and carbazole random copolymer onto carbon fiber: characterization by FTIR-ATR, SEM, EDX. *Surface and Coatings Technology, 160*(2), 227-238.

Seth S Kessler, S Mark Spearing and Constantinos Soutis. (2002). Damage detection in composite materials using Lamb wave methods. *Smart Materials and Structures. 11*: 269–278.

Sethi, V., Song, G., and Franchek, M. A. (2008). Loop shaping control of a model-story building using smart materials. *Journal of Intelligent Material Systems and Structures, 19*(7), 765-777.

Sethi, V., and Song, G. (2005). Optimal vibration control of a model frame structure using piezoceramic sensors and actuators. *Journal of Vibration and Control, 11*(5), 671-684.

Shanker, R., Bhalla, S., Gupta, A., and Kumar, M. P. (2011). Dual use of PZT patches as sensors in global dynamic and local electromechanical impedance techniques for structural health monitoring. *Journal of Intelligent Material Systems and Structures. 22*(16): 1841-1856.

Shanker, R., Bhalla, S., and Gupta, A. (2010). Integration of Electro-mechanical Impedance and Global Dynamic Techniques for Improved Structural Health Monitoring. *Journal of Intelligent Material Systems and Structures, 21*(3), 285-295.

SHIMADZU, XRD-6000, Shimadzu X-ray Diffractometer. Retrieved 20 Jan. 2014 from: http://www.ssi.shimadzu.com/products/literature/xray/xrd-6000.pdf.

Silva, C., Rocha, B., and Suleman, A. (2011). PZT Network and Phased Array Lamb Wave Based SHM Systems [9th International Conference on Damage Assessment of Structures (DAMAS 2011)]. *Journal of Physics: Conference Series* (305), *012087 IOP Publishing*.

Silva, C., Rocha, B., and Suleman, A. (2010). *Guided Lamb Waves Based Structural Health Monitoring Through a PZT Network System.* Paper presented at the 2nd International Symposium on NDT in Aerospace.

Sohn, H., Park, H. W., Law, K. H., and Farrar, C. R. (2007). Combination of a time reversal process and a consecutiv outlier analysis for baseline-free damage diagnosis. *Journal of Intelligent Material Systems and Structures, 18*(4), 335-346.

Song, G., Sethi, V., and Li, H.-N. (2006). Vibration control of civil structures using piezoceramic smart materials: A review. *Engineering Structures*, *28*(11), 1513-1524.

Sozen, M. A., and Ichinose, T. (2008). *Understanding structures: an introduction to structural analysis*. Pp.163. CRC Press.

Spectral Density. Retrieved 23 Jan 2015 from: http://en.wikipedia.org/wiki/Spectral_density.

Srinivas, V., Sasmal, S., & Ramanjaneyulu, K. (2009). Studies on methodological developments in structural damage identification. *Structural Durability and Health Monitoring, 5*(2), 133-160.

SRS, Stanford Research System. Retrieved 23 Jan 2015 from: www.thinkSRS.com.

Sun, M., Staszewski, W., and Swamy, R. (2010). Smart sensing technologies for structural health monitoring of civil engineering structures. *Advances in Civil Engineering, 2010*. Hindawi Publishing Corporation, Advances in Civil Engineering, Volume 2010, Article ID 724962, (13 pp).

Tai, N., Yip, M., and Lin, J. (1998). Effects of low-energy impact on the fatigue behavior of carbon/epoxy composites. *Composites Science and Technology,* 58(1), 1-8.

Tavakkolizadeh, M. and H. Saadatmanesh (2003). Strengthening of steel-concrete composite girders using carbon fiber reinforced polymers sheets. *Journal of Structural Engineering*, *129*(1): 30-40.

Tee, K., Koh, C., and Quek, S. 2009. Numerical and experimental studies of a substructural identification strategy. *Structural Health Monitoring, 8*(5), 397-410.

Terekhina, S., Salvia, M., and Fouvry, S. (2011). Contact fatigue and wear behaviour of bismaleimide polymer subjected to fretting loading under various temperature conditions. *Tribology International, 44*(4), 396-408.

Thomason, J., and Vlug, M. (1997). Influence of fibre length and concentration on the properties of glass fibre-reinforced polypropylene: 4. Impact properties. *Composites Part A: Applied Science and Manufacturing*, *28*(3), 277-288.

Uomoto, T., Mutsuyoshi, H., Katsuki, F., and Misra, S. (2002). Use of fiber reinforced polymer composites as reinforcing material for concrete. *Journal of Materials in Civil Engineering, 14*(3), 191-209.

User Guide and Specifications NI USB-9234. Retrieved 23 Jan 2015 from: http://www.ni.com/pdf/manuals/372307a.pdf.

Wambua, P., Ivens, J., and Verpoest, I. (2003). Natural fibres: can they replace glass in fibre reinforced plastics? *Composites Science and Technology, 63*(9), 1259-1264.

Waanders, J. W. (1991). Piezoelectric Ceramics, Proprties and applications, Philips Components, EINDHOVEN, The Netherlands. First Edition April 1991.

Wang, D., Song, H., & Zhu, H. (2014). Embedded 3D electromechanical impedance model for strength monitoring of concrete using a PZT transducer. *Smart Materials and Structures, 23*(11), 115019.

Wang, D., and Zhu, H. (2011). Monitoring of the strength gain of concrete using embedded PZT impedance transducer. *Construction and Building Materials, 25*(9), 3703-3708.

Wang, S.-X., Wu, L.-Z., and Ma, L. (2010). Low-velocity impact and residual tensile strength analysis to carbon fiber composite laminates. *Materials & design, 31*(1), 118-125.

Wu, Z., Qing, X. P., and Chang, F.-K. (2009). Damage detection for composite laminate plates with a distributed hybrid PZT/FBG sensor network. *Journal of Intelligent Material Systems and Structures*. (9 pp.)

Xia, Y., Ni, Y. q., Zhang, P., Liao, W. y., and Ko, J. m. (2011). Stress development of a supertall structure during construction: Field monitoring and numerical analysis. *Computer-Aided Civil and Infrastructure Engineering, 26*(7), 542-559.

Xu, B., Zhang, L., and Song, G. (2008). *Identification for a Model Frame Structure Using Vibration Measurements from FBG Displacement Sensors.* Paper presented at the Earth & Space 2008 @ sEngineering, Science, Construction, and Operations in Challenging Environments.

Xu, J., Yang, Y., and Soh, C. K. (2004). Electromechanical impedance-based structural health monitoring with evolutionary programming. *Journal of Aerospace Engineering, 17*(4), 182-193.

Xue, S., Tang, H., Okada, J., Hayashi, T., Zong, G., and Arikawa, S. (2009). *Natural frequency changes for damaged and reinforced real structure in comparison with shake table and simulation.* Paper presented at the Materials forum. Institute of Materials Engineering Australasia Ltd.

Yan, S., Wu, J., Sun, W., Ma, H., and Yan, H. (2013). Development and Application of Structural Health Monitoring System Based on Piezoelectric Sensors. *International Journal of Distributed Sensor Networks,* (12 pp).

Yan, W., and Chen, W. (2010). Structural health monitoring using high-frequency electromechanical impedance signatures. *Advances in Civil Engineering, 2010*. 11 pp.

Yang, Y., Annamdas, V. G. M., Wang, C., and Zhou, Y. (2008). Application of multiplexed FBG and PZT impedance sensors for health monitoring of rocks. *Sensors, 8*(1), 271-289.

Yang, Y., Divsholi, B. S., and Soh, C. K. (2010). A reusable PZT transducer for monitoring initial hydration and structural health of concrete. *Sensors, 10*(5), 5193-5208.

Yang, Y., and Hu, Y. (2008). Electromechanical impedance modeling of PZT transducers for health monitoring of cylindrical shell structures. *Smart Materials and Structures, 17*(1), 015005. (11pp).

Yang, Y., Liu, H., Annamdas, V. G. M., and Soh, C. K. (2009). Monitoring damage propagation using PZT impedance transducers. *Smart Materials and Structures, 18*(4), 045003, (9 pp).

Yang, Y., and Miao, A. (2008). Effect of external vibration on PZT impedance signature. *Sensors, 8*(11), 6846-6859.

Yaowen Yang and Aiwei Miao. (2008). Effect of External Vibration on PZT Impedance Signature. *Sensors, 8*, 6846-6859.

Yaowen Yang , Bahador Sabet Divsholi and Chee Kiong Soh. (2010). A Reusable PZT Transducer for Monitoring Initial Hydration and Structural Health of Concrete. *Sensors. 10*: 5193-5208.

Yorkgitis, E. M., Eiss Jr, N. S., Tran,C. , Wilkes,G. L., and McGrath,J. E. (1985). Siloxane-modified epoxy resins. *Epoxy Resins and Composites I: Advances in Polymer Science 72*(1985), 79-109.

Yun, C.-B., and Min, J. (2011). Smart sensing, monitoring, and damage detection for civil infrastructures. *KSCE Journal of Civil Engineering, 15*(1), 1-14.

Yun, J., Choi, Y., and Lee, H. (2009). *Crack-healing capability and high temperature oxidation resistance of multilayer coatings for carbon-carbon composites.* Paper presented at the J. Ceram. Proc. Ress.

Zagrai, A. N., and Giurgiutiu, V. (2001). Electro-mechanical impedance method for crack detection in thin plates. *Journal of Intelligent Material Systems and Structures. 12*(10): 709-718.

Zhang, Z., and Richardson, M. (2007). Low velocity impact induced damage evaluation and its effect on the residual flexural properties of pultruded GRP composites. *Composite Structures, 81*(2), 195-201.

Zhao, N., and Yan, S. (2010). *Experimental research on damage detection of large thin aluminum plate based on Lamb wave.* Paper presented at the SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring. Proceedings of SPIE - The International Society for Optical Engineering, 7647, art. no. 76474E.

Zhou, W., Chakraborty, D., Kowali, N., Papandreou-Suppappola, A., Cochran, D., and Chattopadhyay, A. *Damage classification for structural health monitoring using time-frequency feature extraction and continuous hidden Markov models.* Paper presented at the Signals, Systems and Computers, ACSSC, 4-7 Nov. (2007). Conference Record of the Forty-First Asilomar Conference on, Pacific Grove, CA. pp. 848-852, IEEE Xplore.

Zhou, Y., Pervin, F., Rangari, V. K., and Jeelani, S. (2006). Fabrication and evaluation of carbon nano fiber filled carbon/epoxy composite. *Materials Science and Engineering: A, 426*(1), 221-228.

Zumpano, G., and Meo, M. (2008). Damage localization using transient non-linear elastic wave spectroscopy on composite structures. *International Journal of Non-Linear Mechanics, 43*(3), 217-230.