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
COPYRIGHT

All material contained within the thesis, including without limitation text, logos, icons, photographs and all other artwork, is copyright material of Universiti Putra Malaysia unless otherwise stated. Use may be made of any material contained within the thesis for non-commercial purposes from the copyright holder. Commercial use of material may only be made with express, prior, written permission of University Putra Malaysia.

Copyright © Universiti Putra Malaysia
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 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 variably 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

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 menyebabkan 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 diujiikaji.
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 “إِقرأَ” [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 Mahmud 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 26\textsuperscript{th} 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 Member of Supervisory Supervisory Committee: __________________________ Committee: __________________________

Signature: __________________________ Signature: __________________________
Name of Member of Member of Supervisory Supervisory Committee: __________________________ Committee: __________________________

Signature: __________________________
Name of Member of Supervisory Committee: __________________________
# TABLE OF CONTENT

<table>
<thead>
<tr>
<th>ABSTRACT</th>
<th>i</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRAK</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENT</td>
<td>iv</td>
</tr>
<tr>
<td>APPROVAL</td>
<td>v</td>
</tr>
<tr>
<td>DECLARATION</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xiii</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td>xx</td>
</tr>
<tr>
<td>LIST OF SYMBOLS</td>
<td>xxii</td>
</tr>
</tbody>
</table>

## CHAPTER 1

### INTRODUCTION

1.1 Introduction 1
1.2 Problem Statement 3
1.3 Research Objectives 4
1.4 Research Scopes 5
1.5 Thesis Layout 5

## CHAPTER 2

### LITERATURE REVIEW

2.1 Introduction 7
2.2 Structural Health Monitoring (SHM) 7
  2.2.1 SHM for Buildings and Frames 9
  2.2.2 SHM for Different Structures 13
  2.2.3 SHM for Composite Structures 23
2.3 Smart Sensors 25
  2.3.1 Strain Gauge 25
  2.3.2 Accelerometer Sensor for Structure’s Integrity 27
  2.3.3 Piezoelectric Zirconate Titanate (PZT) 29
2.4 National Instrument and LabVIEW SignalExpress 35
  2.4.1 NI and LabVIEW Software for SHM 35
2.5 Composites 38
  2.5.1 Composite Structures (Fabrications and Characterisations) 38
2.6 Mechanics of Failure due to Crack 50
2.7 Summary and Overview 51

## CHAPTER 3

### RESEARCH METHODOLOGY AND COMPOSITES FABRICATION

3.1 Introduction 53
3.2 The Research Work Flow Chart 53
3.3 Mechanical Vibration Exciter 55
3.4 Frame Structure’s Simulation and Setup 56
3.5 Floor Panels 58
  3.5.1 Aluminium Alloy 6061-T6 58
3.6 Composite Fabrications
3.6.1 Composite Materials (Fibres and Resin) 59
3.6.2 Fabrication Method 61
3.6.3 Tools, Ply and Bagging’s Materials, and Mold 62
3.6.4 Composites Fabrication’s Description (Process and Curing) 67
3.6.5 Dimensions of Final Specimens 76
3.7 Material Property Tests 79
3.7.1 Tensile Strength 79
3.7.2 Flexural Strength 83
3.7.3 Vickers Hardness 85
3.7.4 Impact Izod Pendulum 86
3.7.5 Specific of Gravity (Relative Density) and Density (ρ) 87
3.7.6 Water Absorption 88
3.7.7 Void Content 89
3.8 Micro Structure Analysis 91
3.8.1 Scanning Electron Microscopy (SEM) 91
3.8.2 Energy Dispersive Spectrometer (EDS) 92
3.8.3 X-Ray Diffraction (X-RD) 93
3.9 Thermo Plastic Analysis 94
3.9.1 Dynamic Mechanical Analysis (DMA) 94
3.9.2 Thermo Gravimetric Analysis (TGA) 96
3.10 Structural Health Monitoring (SHM) 98
3.10.1 Structure’s Frame (Prototype) Setup 98
3.10.2 Smart Sensor (Piezoelectric Ceramic Lead Zirconate Titanate) 99
3.10.3 National Instruments (Device and Software) 99
3.11 Data Acquisition and Damage Detection 101
3.11.1 Undamaged (Case 1) 101
3.11.2 Crack Length 10 mm (Case 2) 102
3.11.3 Crack Length 15 mm (Case 3) 102
3.11.4 Crack Length 20 mm (Case 4) 102
3.12 Statistical Analysis and Damage Identification 103
3.12.1 Root Mean Square Deviation (RMSD) Index 103
3.12.2 Frequency Reduction Index (FRI) 104
3.13 Summary 104

4 RESULTS AND DISCUSSION (MATERIALS CHARACTERIZATION)
4.1 Introduction 105
4.2 Mechanical Properties 106
4.2.1 Tensile Strength 101
4.2.2 Flexural Strength 114
4.2.3 Vickers Hardness 118
4.2.4 Impact Izod Pendulum 120
4.2.5 Specific Gravity and Density (ρ) 121
4.2.6 Water Absorption 122
4.2.7 Void Content 122
4.3 Micro Structural Analysis 124
4.3.1 Scanning Electron Microscopy (SEM) 124
4.3.2 Energy Dispersive Spectrometer (EDs) 139
4.3.3 X-Ray Diffraction (X-RD) 134
4.4 Thermo Plastic Analysis 138
4.4.1 Dynamic Mechanical Analysis (DMA) 138
4.4.2 Thermo Gravimetric Analysis (TGA) 143
4.5 Summary 148

5 RESULTS AND DISCUSSION (DAMAGE IDENTIFICATION)
5.1 Introduction 149
5.2 Material’s Floors and Frame (Prototype) Setup 150
5.3 Data Acquisition and Damage Detection 154
5.3.1 Undamaged (Case 1) 159
5.3.2 Crack Length 10 mm (Case 2) 164
5.3.3 Crack Length 15 mm (Case 3) 167
5.3.4 Crack Length 20 mm (Case 4) 170
5.4. Zoom Spectrum Comparison of Four Materials 173
5.5 Statistical Analysis and Damage Identification 177
5.5.1 Root Mean Square Deviation (RMSD) Index 177
5.5.2 Frequency Reduction Index (FRI) 182
5.6 Summary 184

6 CONCLUSIONS AND RECOMMENDATIONS
6.1 Introduction 185
6.2 Conclusions 185
6.3 Contributions 188
6.4 Recommendations for Future work 188

REFERENCES 190
APPENDICES 207
Appendix A: Damage Detection’s Data. 208
Appendix B: Fabrication’s Tools, Devices and Tests Procedures. 226
Appendix C: Data Sheet. 228
Appendix D: Apparatus, Instruments and Materials. 229
Appendix E: Tests and Publications. 233
Appendix F: Laboratories, Instruments, Tests and Laboratories’ Staffs. 235

BIODATA OF CANDIDATE 237
LIST OF PUBLICATIONS 238

xi
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Ions concentration (mM) in plasma and in SBF.</td>
</tr>
<tr>
<td>4.1</td>
<td>Tensile Test’s Results of Al 6061-T6 and the Three Composites.</td>
</tr>
<tr>
<td>4.2</td>
<td>The Flexural Test Results of Al 6061-T6 and the Three Composites.</td>
</tr>
<tr>
<td>4.3</td>
<td>A Comparison between the Impact Izod Pendulum Test’s Results of the Three Composites.</td>
</tr>
<tr>
<td>4.4</td>
<td>Density and Specific Gravity of Al 6061-T6 and the Three Composites.</td>
</tr>
<tr>
<td>4.5</td>
<td>Comparison between the Water Absorption of the Three Composites.</td>
</tr>
<tr>
<td>4.6</td>
<td>Comparison between the Void Content of the Three Composites.</td>
</tr>
<tr>
<td>4.7</td>
<td>ED’s Spectrum and its Quantitative Results of Tensile Fracture Surfaces</td>
</tr>
<tr>
<td>4.8</td>
<td>ED’s Spectrum and its Quantitative Results of the Surface</td>
</tr>
<tr>
<td>4.9</td>
<td>Storage Modulus and Loss Modulus vs Temperatures for the Three Composites.</td>
</tr>
<tr>
<td>4.10</td>
<td>A Comparison between Storage Modulus of the Three Composites at 50°C and 70°C.</td>
</tr>
<tr>
<td>4.11</td>
<td>A Comparison between Loss Modulus of the Three Composites.</td>
</tr>
<tr>
<td>4.12</td>
<td>A Comparison for Loss Factor (Tan Delta) of the Three Composites.</td>
</tr>
<tr>
<td>4.13</td>
<td>TGA Results of the Three Composites.</td>
</tr>
<tr>
<td>4.14</td>
<td>Weight Losses Results of the Three Composites at Limited Temperatures.</td>
</tr>
<tr>
<td>4.15</td>
<td>A Comparison between Derivative Weights of the Three Composites.</td>
</tr>
<tr>
<td>5.1</td>
<td>LabVIEW SignalExpress and Data acquisition’s Steps.</td>
</tr>
<tr>
<td>5.2</td>
<td>RMSD Increased Value % of Four Investigated Materials in Four Cases.</td>
</tr>
<tr>
<td>E.1</td>
<td>Design for Research’s Tests and Publications.</td>
</tr>
<tr>
<td>F.1</td>
<td>Tests, Equipment and Laboratories used in This Research.</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Examples of the Greatest Expensive Infrastructures.</td>
</tr>
<tr>
<td>1.2</td>
<td>Simply Supported Beam under Uniformly Distributed Load.</td>
</tr>
<tr>
<td>2.1</td>
<td>Measurement Setup.</td>
</tr>
<tr>
<td>2.2</td>
<td>Two-Storey Experimental Setup.</td>
</tr>
<tr>
<td>2.3</td>
<td>Experimental Setup of Four-Storey Structure.</td>
</tr>
<tr>
<td>2.4</td>
<td>Three-Storey Experimental Setup.</td>
</tr>
<tr>
<td>2.5</td>
<td>Comparative between Powers Spectral Density Plots.</td>
</tr>
<tr>
<td>2.6</td>
<td>Reinforced Concrete Frame Setup.</td>
</tr>
<tr>
<td>2.7</td>
<td>PZT Admittance Test of Concrete Cubes.</td>
</tr>
<tr>
<td>2.8</td>
<td>Aircraft Panel.</td>
</tr>
<tr>
<td>2.9</td>
<td>Experimental Setup for Damage Detection using PZT Patches.</td>
</tr>
<tr>
<td>2.10</td>
<td>Setup of a SHM System using Lamb Waves Approach.</td>
</tr>
<tr>
<td>2.11</td>
<td>Beam Specimen with PZT Transducer and Mini Shaker.</td>
</tr>
<tr>
<td>2.12</td>
<td>Square Structure (Four Aluminium Beams).</td>
</tr>
<tr>
<td>2.13</td>
<td>Setup for Structural Material and Damage in a Bolted Joint.</td>
</tr>
<tr>
<td>2.14</td>
<td>Lay-out of PZT Patches and Location of Damage.</td>
</tr>
<tr>
<td>2.15</td>
<td>An Aluminium Plate with PZT Transducers Attached.</td>
</tr>
<tr>
<td>2.16</td>
<td>Schematics of the Aging Aircraft Panel Specimens and PWAS Configuration.</td>
</tr>
<tr>
<td>2.17</td>
<td>Schematic Sketch of Experimental Setup.</td>
</tr>
<tr>
<td>2.18</td>
<td>Experimental Setup for Rectangular Plate.</td>
</tr>
<tr>
<td>2.19</td>
<td>Health Monitoring of Aging Aircraft Structure.</td>
</tr>
<tr>
<td>2.20</td>
<td>Systematic Study of Circular Plates with Simulated Cracks Placed at Decreasing Distance from the Sensor.</td>
</tr>
<tr>
<td>2.21</td>
<td>The Change in E/M Impedance Due to the Presence of a Crack.</td>
</tr>
<tr>
<td>2.22</td>
<td>Setting up of the SHM System to Acquire the Data from the Carbon Fiber Reinforced Plastic (CFRP) Panels.</td>
</tr>
<tr>
<td>2.23</td>
<td>Layout of PZT Actuators and the FBG Sensor on the Aluminium Plate.</td>
</tr>
<tr>
<td>2.24</td>
<td>Effect of the Sampling Frequency on Damage Predicted Locations.</td>
</tr>
<tr>
<td>2.25</td>
<td>Lay-out of Plate with Bolted Hybrid Connection with PZT.</td>
</tr>
<tr>
<td>2.26</td>
<td>Photographs of the Tower at Different Construction Stages.</td>
</tr>
<tr>
<td>2.27</td>
<td>Vertical Strains Measured vs Time.</td>
</tr>
<tr>
<td>2.28</td>
<td>The Guangzhou New TV Tower.</td>
</tr>
<tr>
<td>2.29</td>
<td>Three-Storey Wooden Frame Structure.</td>
</tr>
<tr>
<td>2.30</td>
<td>Natural Frequency of Case 1to18 Normalized to Case 1.</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------</td>
</tr>
<tr>
<td>2.31</td>
<td>Experimental Setup for Damage Identification of Steel Frame Model.</td>
</tr>
<tr>
<td>2.32</td>
<td>A Retrofitted 10-Storey Office Building.</td>
</tr>
<tr>
<td>2.33</td>
<td>Variation of RMSD with Increasing Damage Severity.</td>
</tr>
<tr>
<td>2.34</td>
<td>Conductance Signatures for Plate Y.</td>
</tr>
<tr>
<td>2.35</td>
<td>Peak Amplitude Comparison of Piezo 5 Response from Piezo 1 Excitation.</td>
</tr>
<tr>
<td>2.36</td>
<td>Active Vibration Control Truss Experimental Setup.</td>
</tr>
<tr>
<td>2.37</td>
<td>Thin Plate Specimen with PWAS Array.</td>
</tr>
<tr>
<td>2.38</td>
<td>EMI Spectrum of Aircraft Turbo-Engine Blade.</td>
</tr>
<tr>
<td>2.39</td>
<td>CFRP specimen (250 mm x 50 mm) with Piezoceramic Actuator and Sensors.</td>
</tr>
<tr>
<td>2.40</td>
<td>Thin-gage Aluminium Plate.</td>
</tr>
<tr>
<td>2.41</td>
<td>Field Test.</td>
</tr>
<tr>
<td>2.42</td>
<td>Structure used for Impedance Measurement.</td>
</tr>
<tr>
<td>2.43</td>
<td>Testing of a Composite Specimen under Four-Point Bending Load.</td>
</tr>
<tr>
<td>2.44</td>
<td>Region of the Waveform Selected Damage Detection.</td>
</tr>
<tr>
<td>2.45</td>
<td>FRFs Plot’s Comparison of a 50 J Impacted And Pristine Laminated Specimen for Range of 0 ± 10 kHz.</td>
</tr>
<tr>
<td>2.46</td>
<td>Schematic Diagram of the Primary Crack Morphology; l: Surface Crack Length; b: Subsurface Crack Length.</td>
</tr>
<tr>
<td>2.47</td>
<td>Comparison of Experimental Data and FE Result for Composite Laminate under Different Impact Energies</td>
</tr>
<tr>
<td>2.48</td>
<td>Validation of Delamination Model in Simulation of (a) DCB and (b) ENF Tests of T800S/M21 Specimens.</td>
</tr>
<tr>
<td>2.49</td>
<td>Results of X-Ray Diffraction Analysis.</td>
</tr>
<tr>
<td>2.50</td>
<td>Impact and Flexure Test Confederation.</td>
</tr>
<tr>
<td>2.51</td>
<td>TGA (curves A-D) and (Derivative) DTG (curve A’-D’) thermograms of the MPGE cured resins.</td>
</tr>
<tr>
<td>2.52</td>
<td>Tensile strength of Various Control Samples and Conditioned Samples.</td>
</tr>
<tr>
<td>3.1</td>
<td>The Research’s Flow Chart.</td>
</tr>
<tr>
<td>3.2</td>
<td>Mechanical Vibration Exciter (Shaking Table).</td>
</tr>
<tr>
<td>3.3</td>
<td>The Mechanical Vibration Exciter’s Platform (up set down) before Drilling the Holes.</td>
</tr>
<tr>
<td>3.4</td>
<td>Drilling the Holes in the Platform using Milling Machine.</td>
</tr>
<tr>
<td>3.5</td>
<td>Aluminium Frame’s Details.</td>
</tr>
<tr>
<td>3.6</td>
<td>Three Storey’s Aluminium Frame.</td>
</tr>
<tr>
<td>3.7</td>
<td>CNC Milling Machine Model OKUMA, MX-45VA.</td>
</tr>
<tr>
<td>3.8</td>
<td>Floor Panel’s Dimensions.</td>
</tr>
<tr>
<td>3.9</td>
<td>Carbon Fibre Weave (CFW).</td>
</tr>
<tr>
<td>3.10</td>
<td>Glass Fibre Weave (GFW).</td>
</tr>
<tr>
<td>3.11</td>
<td>Glass Fiber- Chopped Strand Mats (CSM).</td>
</tr>
<tr>
<td>3.12</td>
<td>Resin.</td>
</tr>
<tr>
<td>3.13</td>
<td>Tools and Devices to Fabricate Composite’s Panels</td>
</tr>
<tr>
<td>3.14</td>
<td>Peel Ply Sheet.</td>
</tr>
<tr>
<td>3.15</td>
<td>Thin Aluminium Plate.</td>
</tr>
</tbody>
</table>
3.16 Bleeder (Breather) Layer.
3.17 Vacuums Bagging (Flexible Film).
3.18 Bagging Fitting.
3.19 The Aluminium Plate.
3.20 Steel Frames to Fabricate the Composites.
3.21 An Aluminium Plates and Steel Frames as an Open Mould.
3.22 The Flow Chart of Composite’s Fabrication Process.
3.23 Hand Lay-Up Fabrication and Vacuum Bagging Setup.
3.24 Continuous Fabrics Fibres.
3.25 Wax Applied in a Circular Motion.
3.26 The Plate Surface in a High Shine.
3.27 Using Roller Brush to Distribute the Resin.
3.28 Using a Roller to compress the Layers and Squeeze Air Bubbles and Excess Resin from the Laminates.
3.29 The Peel Ply Layer, Thin Aluminium Plate and Breather Layer, Consequently.
3.30 Base Plates for Vacuum.
3.31 Add Breather Layer to Four Sides of the Specimen Edges.
3.32 Vacuums Bagging in Process.
3.33 Curing for Composites.
3.34 Air Compressor Equipment Type BOGE KOMPRESSOREN.
3.35 CFW/ Epoxy Panels.
3.36 GFW/ Epoxy and GF (CSM)/ Epoxy Composite Panels.
3.37 Removing Composite Panels from the Frame using Pneumatic Cutter.
3.38 Cutting the Panels.
3.39 Cleaning the Frames from Remaining Resin.
3.40 Composite Panel’s Dimensions as a Floor.
3.41 Five Al 6061-T6 Specimens for Tensile Test.
3.42 INSTRON Instrument Model 3366, Data Logger, and BlueHill2 Software.
3.43 INSTRON Instrument Model 3382 with Data Logger and BlueHill2 Software.
3.44 Electrical Saw Model metabo BAS 260 Swift.
3.45 Five Composite’s Specimens before Tensile Tests.
3.46 Stress-Strain Curve Represent the Brittle and Ductile Limitation.
3.47 X-Axis in Material which Stretched in Axial Direction.
3.48 Flexural Strength Test Instrument (INSTRON 3366) and INSTRON BlueHill 2 Software.
3.49 Vickers Indenter Details.
3.51 Impact Izod Pendulum Equipments, Motorised Notchvis, and INSTRO – Model CEAST 9050.
3.52 Dimensions of Impact Izod Pendulum Test’s Specimen.
3.54 An Analytical Digital Balance Reading 0.0001g.
3.55 Memmert Universal Oven/Furnace at Temperature 50 °C.
3.56 An Analytical Digital Balance Reading 0.001g.
3.57 Specimens before the Scanning Electron Microscopy Test.
3.58 SMITECH Instrument to Coating the Specimens.
3.60 X-Ray Diffract meter Instrument.
3.61 Mode of Oscillation (3-Point Bending) used in DMA Test.
3.62 Material Responses for Dynamic Stress.
3.64 Plastic Mould Cutter Equipment.
3.65 Diagram Standard of TGA Measurement.
3.67 A Sample of TGA Curve.
3.68 Structure Frame (Prototype) Setup.
3.69 Piezoelectric ceramic Lead Zirconate Titanate (APC 850 PZT).
3.70 NI USB-9234 Components.
3.71 NI USB-9234 Device Dimensions.
3.72 Undamaged Square Panel’s Design (Isometric).
3.73 Square Panel with Crack Length.
4.1 The Flow Chart for Investigated Material’s Characterisations.
4.2 Four Materials.
4.3 Tensile Test’s Results.
4.4 Tensile Load vs Extension.
4.5 Tensile Strength vs Extension.
4.6 Tensile Stress vs Strain.
4.7 A Comparison between the Maximum Tensile Stresses of Four Materials.
4.8 A Comparison between the Strains of Four Materials.
4.9 Comparison between the Young’s Modulus of Four Materials.
4.10 Comparison between the Poisson’s Ratios of Four Materials.
4.11 The Flexural Strength Tests.
4.12 Flexural Deflections.
4.13 Flexural Load vs Deflection.
4.14 Flexural Stress.
4.15 Flexural Strain.
4.16 Vickers Hardness Results.
4.17 Vickers Hardness Comparison.
4.18 Five Notched Specimens before Impact Test for Three Composites.
4.19 A Comparison between Impact Strength’s Results of the Three Composites.
4.20 The Comparison between Void Content % Results of Three Composites.
4.21 Tensile Fracture’s Samples of Four Investigated Materials Prepared for SEM Test.
4.22 SEM Images of Al 6061-T6 in Two Magnifications: (a) 50, and (b) 100.
4.23 SEM Images of CFW/ Epoxy Composite in Two Magnifications: (a) 50, and (b) 100.
4.24 SEM Images of GFW/ Epoxy Composite in Two Magnifications: (a) 50, and (b) 100.
4.25 SEM Images of GFW (CSM)/ Epoxy Composite in Two Magnifications as: (a) 50, and (b) 100.
4.26 Four Material’s Samples Coated by Gold in A Few Nano Meters in Thickness.
4.27 SEM Images of the Normal Surface of Al 6061-T6 in Different Magnifications: (a) 50, and (b) 100.
4.28 SEM Images of the Normal Surface of CFW/ Epoxy in Different Magnifications: (a) 50, (b) 100 and (c) 500.
4.29 SEM Images of the normal surface of GFW/ Epoxy in different magnifications: (a) 50, (b) 100 and (c) 500.
4.30 SEM Images of the normal surface of GF (CSM)/ Epoxy in different magnifications: (a) 50, (b) 100 and (c) 500.
4.31 EDS Analysis of Tensile Fracture Surfaces: (a) Al 6061-T6, (b) CFW/ Epoxy, (c) GFW/ Epoxy and (d) GF (CSM)/ Epoxy Composite.
4.32 EDS Analysis of the Surfaces: (a) Al 6061-T6, (b) CFW/ Epoxy, (c) GFW/ Epoxy, and (d) GF (CSM)/ Epoxy Composites.
4.34 X-Ray Diffraction Pattern: (a) CFW, (b) GFW and (c) GF (CSM)/ Epoxy Composites.
4.35 A Comparison between X-Ray Diffraction Patterns of CFW, GFW and GF (CSM) Fibers/ Epoxy Composites.
4.36 Dynamic Mechanical Analysis.
4.37 Storage Modulus vs. Temperature of Three Composites.
4.38 Loss Modulus vs. Temperature of Three Composites.
4.39 Loss Factor (Tan Delta) vs. Temperature of Three Composites.
4.40 Thermo Gravimetric Analysis (TGA) of: (a) CFW, (b) GFW and (c) GF (CSM)/Epoxy Composites.
4.41 Comparison between Weight Losses of the Three Composites.
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.42</td>
<td>Comparison between Derivative Weights of the Three Composites</td>
<td>147</td>
</tr>
<tr>
<td>5.1</td>
<td>The Flow Chart of Acquired Signals</td>
<td>150</td>
</tr>
<tr>
<td>5.2</td>
<td>Three Panels of Four Investigated Materials</td>
<td>151</td>
</tr>
<tr>
<td>5.3</td>
<td>Structural Health Monitoring System</td>
<td>153</td>
</tr>
<tr>
<td>5.4</td>
<td>LabView SignalExpress Windows</td>
<td>156</td>
</tr>
<tr>
<td>5.5</td>
<td>Filtered Signals of Four Investigated Material’s Panels (Undamaged)</td>
<td>160</td>
</tr>
<tr>
<td>5.6</td>
<td>Power Spectrum of Four Investigated Material’s Panels (Undamaged)</td>
<td>161</td>
</tr>
<tr>
<td>5.7</td>
<td>Zoom Power Spectrum of Four Investigated Material’s Panels (Undamaged)</td>
<td>162</td>
</tr>
<tr>
<td>5.8</td>
<td>Coherence of Four Investigated Material’s Panels (Undamaged)</td>
<td>164</td>
</tr>
<tr>
<td>5.9</td>
<td>Filtered Signals of Four Investigated Material’s Panels (Crack 10 mm)</td>
<td>165</td>
</tr>
<tr>
<td>5.10</td>
<td>Zoom Power Spectrum of Four Investigated Material’s Panels (Crack 10 mm)</td>
<td>167</td>
</tr>
<tr>
<td>5.11</td>
<td>Filtered Signals of Four Investigated Material’s Panels (Crack 15 mm)</td>
<td>168</td>
</tr>
<tr>
<td>5.12</td>
<td>Zoom Power Spectrum of Four Investigated Material’s Panels (Crack 15 mm)</td>
<td>170</td>
</tr>
<tr>
<td>5.13</td>
<td>Filtered Signals of Four Investigated Material’s Panels (Crack 20 mm)</td>
<td>171</td>
</tr>
<tr>
<td>5.14</td>
<td>Zoom Power Spectrum of Four Investigated Material’s Panels (Crack 20 mm)</td>
<td>173</td>
</tr>
<tr>
<td>5.15</td>
<td>Zoom Power Spectrum of Four Material’s Panels (Undamaged)</td>
<td>173</td>
</tr>
<tr>
<td>5.16</td>
<td>Zoom Power Spectrum of Four Material’s Panel (Crack 10 mm)</td>
<td>174</td>
</tr>
<tr>
<td>5.17</td>
<td>Zoom Power Spectrum of Four Material’s Panel (Crack 15 mm)</td>
<td>174</td>
</tr>
<tr>
<td>5.18</td>
<td>Zoom Power Spectrum of Four Material’s Panel (Crack 20 mm)</td>
<td>175</td>
</tr>
<tr>
<td>5.19</td>
<td>Comparisons between the Four Cases of Four Investigated Material’s Panels</td>
<td>176</td>
</tr>
<tr>
<td>5.20</td>
<td>RMSD Values of Four Investigated Material’s Specimens</td>
<td>180</td>
</tr>
<tr>
<td>5.21</td>
<td>RMSD Values of Four Investigated Material’s Panels in Four Cases</td>
<td>181</td>
</tr>
<tr>
<td>5.22</td>
<td>Comparison of RMSD % Results of Four Investigated Material’s in Four Cases</td>
<td>182</td>
</tr>
<tr>
<td>5.23</td>
<td>Comparison between FRI Results of Four Investigated Material’s in Four Cases</td>
<td>183</td>
</tr>
<tr>
<td>5.24</td>
<td>Comparison between the FRI % of Four Investigated Material’s in Four Cases</td>
<td>183</td>
</tr>
<tr>
<td>A.1</td>
<td>Filtered Signals of Four Investigated Material’s Panels</td>
<td>211</td>
</tr>
<tr>
<td>A.2</td>
<td>The Natural Frequencies of Four Investigated Material’s Panels</td>
<td>215</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>A.3</td>
<td>Power Spectrum of Four Investigated Material’s Panels (Crack 10 mm).</td>
<td>216</td>
</tr>
<tr>
<td>A.4</td>
<td>Coherence of Four Investigated Material’s Panels (Crack 10 mm).</td>
<td>217</td>
</tr>
<tr>
<td>A.5</td>
<td>Power Spectrum of Four Investigated Material’s Panels (Crack 15 mm).</td>
<td>218</td>
</tr>
<tr>
<td>A.6</td>
<td>Coherence of Four Investigated Material’s Panels (Crack 15 mm).</td>
<td>219</td>
</tr>
<tr>
<td>A.7</td>
<td>Power Spectrum of Four Investigated Material’s Panels (Crack 20 mm).</td>
<td>220</td>
</tr>
<tr>
<td>A.8</td>
<td>Coherence of Four Investigated Material’s Panels (Crack 20 mm).</td>
<td>221</td>
</tr>
<tr>
<td>A.9</td>
<td>Peak Frequency of Four Investigated Material’s Panels (Undamaged Panels).</td>
<td>222</td>
</tr>
<tr>
<td>A.10</td>
<td>Peak Frequency of Four Investigated Material’s Panels (Crack 10 mm).</td>
<td>223</td>
</tr>
<tr>
<td>A.11</td>
<td>Peak Frequency of Four Investigated Material’s Panels (Crack 15 mm).</td>
<td>224</td>
</tr>
<tr>
<td>A.12</td>
<td>Coherence of Four Investigated of Four Investigated Material’s Panels (Crack 20 mm).</td>
<td>225</td>
</tr>
<tr>
<td>B.1</td>
<td>Dimensions of Al 6061-T6 Specimen for Tensile Test.</td>
<td>226</td>
</tr>
<tr>
<td>C.1</td>
<td>Data Sheet of EpoxyAmite®100 and Hardener (103 Slow Type B).</td>
<td>227</td>
</tr>
<tr>
<td>D.1</td>
<td>Shaker Equipment in Structural Lab- UPM.</td>
<td>228</td>
</tr>
<tr>
<td>D.2</td>
<td>Cutting and Drilling the Steel and Aluminium of the Frame Prototype Setup.</td>
<td>229</td>
</tr>
<tr>
<td>D.3</td>
<td>Cutting the GF (CSM) Fabric’s Fibre.</td>
<td>230</td>
</tr>
<tr>
<td>D.4</td>
<td>Composites Fabrication in Vacuum Bagging Process.</td>
<td>231</td>
</tr>
<tr>
<td>D.5</td>
<td>Take out the Composite Panel from the Steel Frame.</td>
<td>231</td>
</tr>
<tr>
<td>D.6</td>
<td>CNC Machine to Cut the Panels According to the Dimensions.</td>
<td>231</td>
</tr>
<tr>
<td>D.7</td>
<td>Aluminium Frame Setup with AL 6061-T6 Floor’ Panels, and GFW/Epoxy Floor’ Panels.</td>
<td>232</td>
</tr>
<tr>
<td>D.8</td>
<td>Aluminium Frame Setup with GFW/Epoxy Floor’ Panels.</td>
<td>232</td>
</tr>
</tbody>
</table>
LIST OF ABBREVIATIONS

AE Acoustic Emission
Al 6061-T6 Aluminium Alloy Type 6061-T6
CFRP Carbon Fibre Reinforced Plastic
CFW Twill Weave 240 g/m² 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/m² Glass Fibre
GFW Plain Weave 300 g/m² 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
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>UBC</td>
<td>University of British Columbia</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>VI</td>
<td>Virtual Instrument</td>
</tr>
<tr>
<td>XRD</td>
<td>X-Ray Diffraction</td>
</tr>
</tbody>
</table>
## LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>cross-sectional area of specimen, mm²,</td>
</tr>
<tr>
<td>$A_o$</td>
<td>the original cross sectional area of specimen through which the force is applied,</td>
</tr>
<tr>
<td>b</td>
<td>width of beam tested, mm,</td>
</tr>
<tr>
<td>d</td>
<td>depth of beam tested, mm,</td>
</tr>
<tr>
<td>$d\varepsilon_{axial}$</td>
<td>axial strain, positive for axial tension and negative for axial compression,</td>
</tr>
<tr>
<td>$d\varepsilon_{trans}$</td>
<td>transverse strain, negative value for axial tension(stretching) and positive for axial compression,</td>
</tr>
<tr>
<td>$D_f$</td>
<td>maximum deflection of the centre of the beam, mm</td>
</tr>
<tr>
<td>$E$</td>
<td>Young’s modulus,</td>
</tr>
<tr>
<td>F</td>
<td>the force applied on specimen under tensile,</td>
</tr>
<tr>
<td>$F_{tu}$</td>
<td>ultimate tensile strength, MPa,</td>
</tr>
<tr>
<td>L</td>
<td>support span, mm,</td>
</tr>
<tr>
<td>$L_o$</td>
<td>the original length of the specimen,</td>
</tr>
<tr>
<td>$\Delta L$</td>
<td>the amount by which the length of the object changes,</td>
</tr>
<tr>
<td>$M_d$</td>
<td>Measured composite density, g/cm³.</td>
</tr>
<tr>
<td>P</td>
<td>load at a given point on the load deflection curve, N</td>
</tr>
<tr>
<td>$P_i$</td>
<td>load at $i$th data point, N,</td>
</tr>
<tr>
<td>$P_{max}$</td>
<td>maximum load before failure, N,</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density,</td>
</tr>
<tr>
<td>$\rho_r$</td>
<td>density of resin,</td>
</tr>
<tr>
<td>$\rho_{reinf}$</td>
<td>density of reinforcement</td>
</tr>
<tr>
<td>r</td>
<td>resin, weight%,</td>
</tr>
<tr>
<td>R</td>
<td>resin in Composite, weight %,</td>
</tr>
<tr>
<td>$S_p$</td>
<td>specific gravity,</td>
</tr>
<tr>
<td>$T_d$</td>
<td>theoretical composite density, g/cm³,</td>
</tr>
<tr>
<td>$v$</td>
<td>Poisson’s ratio,</td>
</tr>
<tr>
<td>V</td>
<td>void content, volume %,</td>
</tr>
<tr>
<td>$W_c$</td>
<td>conditioned weight, (g),</td>
</tr>
<tr>
<td>$W_w$</td>
<td>wet weight, (g),</td>
</tr>
<tr>
<td>$w_{reinf}$</td>
<td>reinforcement, weight%</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>stress,</td>
</tr>
<tr>
<td>$\sigma_i$</td>
<td>tensile stress at $i$th data point, MPa,</td>
</tr>
<tr>
<td>$\sigma_o$</td>
<td>stress in the outer fibers at midpoint, MPa,</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>strain, and</td>
</tr>
<tr>
<td>$\varepsilon_o$</td>
<td>strain in the outer surface, mm/mm.</td>
</tr>
</tbody>
</table>
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).
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 computing 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


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


