



**UNIVERSITI PUTRA MALAYSIA**

***INTERNAL DEFECT DETECTION AND RECONSTRUCTION FRAMEWORK FOR  
LAMINATED GLASS FIBRE REINFORCED POLYMER COMPOSITE MATERIALS***

**NG SOK CHOO**

**ITMA 2013 1**



INTERNAL DEFECT DETECTION AND RECONSTRUCTION  
FRAMEWORK FOR LAMINATED GLASS FIBRE REINFORCED  
POLYMER COMPOSITE MATERIALS

By

NGSOKCHOO

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

May 2013

## 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 the express, prior, written permission of Universiti Putra Malaysia.

Copyright© Universiti Putra Malaysia



DEDICATION

TO MY FATHER, MY FAMILY AND CAROL BEH



© COPYRIGHT UPM

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirements for the degree of Doctor of Philosophy

**INTERNAL DEFECT DETECTION AND RECONSTRUCTION  
FRAMEWORK FOR LAMINATED GLASS FIBRE REINFORCED  
POLYMER COMPOSITE MATERIALS**

By

**NGSOKCHOO**

May 2013

**Chairman**                      **Professor Datin Napsiah Ismail, PhD**

**Faculty**                         **Institute of Advanced Technology**

The detection of internal defects in composite materials with non-destructive techniques (NDT) is crucial for both quality checks during the production phase and in-service health monitoring during maintenance operations in industrial and civil environment. Visual inspection allows only the analysis of surface characteristics of materials. If internal faults occur inside the composite structures, a deeper analysis is required. Ultrasonic testing has been a promising NDT which is based on the detection and the interpretation of the ultrasonic waves reflected by defects. However, ultrasonic data are difficult to interpret since they require the analysis of continuous signals for each point of the material under consideration. Particularly, the non-homogeneous nature of reinforced composite materials induces high dimensionality of analysis space and a very high level of structural noise that greatly complicates the interpretation task. Increasing the ultrasound system frequency can result in detection of smaller defects but the depth of penetration of the wave

decreases. Therefore, an advanced signal processing technique is necessary to manage large data sets and to extract suitable features for effective internal defect detection. The objective of the research is to design and develop a new cost-effective nondestructive evaluation (NDE) framework to detect and reconstruct the internal defects in high dimensionality environments. The proposed framework consists of four steps: (i) the relationship between the defects and the behaviour of the ultrasound is identified. (ii) Multiresolution signal decomposition technique is then applied to reduce the dimensionality of the data. (iii) The image of the defect region is reconstructed by using the attenuation of the reflected ultrasound signal (iv) Entropy-based fuzzy k-nearest neighbour classification method is used to extract the feature of the defects. Delamination was introduced as the internal defects in the experiments. The proposed framework was tested on glass fibre reinforced polymer (GFRP) composites with different thickness and fiber orientations.

The research finding showed that the position of damage has been the significant control factor to the attenuation of the ultrasound signal. Experimental results showed that the proposed framework successfully reduce the dimensionality of the analysis space. The proposed wavelet-based minimization algorithm has achieved 79.8% and 30.2% improvement of signal-to-noise ratio for the simulated and experimental noisy data respectively. This framework exhibits high accuracy of internal defect localization in high dimensionality environments. It is found out that the proposed entropy-based k-nearest neighbour classification method has shown promising performance with 94.01% accuracy in close-spaced defects detection when minimal k-nearest neighbor is used. Considering all results and the collected information, it can be concluded that the structural noise in ultrasound signals

induces low frequency. Therefore, by removing the low frequency signals, the internal defect detectability can be improved. Moreover, the classification of an input pattern based on the closest neighbours of the point of interest provides more accurate defect detection in comparison with the classification based on experience data as the defect patterns vary on circumstances in ultrasonic NDE problems.



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

**RANGKA KERJA PENGESANAN DAN PEMBINAAN SEMULA  
KECACATAN DALAMAN BAHAN KOMPOSIT KACA BERTETULANG  
GENTIAN POLIMER BERLAMINA**

Oleh

**NGSOKCHOO**

**Mei2013**

**Pengerusi**                    **Profesor Datin Napsiah Ismail, PhD**

**Faculti**                      **Institut Teknologi Maju**

Pengesanan kecacatan dalaman dalam bahan komposit dengan teknik bukan pemusnah (NDT) adalah penting bagi kedua-dua semakan kualiti dalam fasa pengeluaran dan pemantauan kesihatan dalam layanan semasa operasi penyelenggaraan dalam bidang industri dan pembinaan awam. Pemeriksaan visual hanya membolehkan analisis ciri-ciri permukaan bahan. Jika kesilapan dalaman berlaku di dalam struktur komposit, analisis secara mendalam diperlukan. Ujian ultrasonik adalah NDT yang baik di mana kaedah ini berasaskan daripada pengesanan dan tafsiran gelombang ultrabunyi yang digambarkan oleh kecacatan.

Walau bagaimanapun, data ultrasonik adalah sukar ditafsir kerana ia memerlukan analisis isyarat berterusan bagi setiap titik dalam bahan yang dipertimbangkan.

Terutama sekali, sifat bukan homogen bahan komposit bertetulang menyebabkan ruang dimensi analisis yang tinggi dan tahap yang sangat tinggi bagi bunyi struktur yang amat merumitkan tugas tafsiran. Meningkatkan kekerapan sistem ultrabunyi



membolehkan pengesanan keadaatan yang kecil tetapi penembusan gelombang akan berkurangan. Oleh itu, teknik pemrosesan isyarat yang canggih adalah diperlukan untuk menguruskan set data yang besar dan untuk mengekstrak ciri-ciri yang sesuai bagi pengesanan keadaatan dalaman yang berkesan. Objektif kajian ini adalah untuk merekabentuk dan membangunkan satu rangka kerja penilaian tanpa musnah yang kos efektif dan murah untuk mengesan dan membina semula keadaatan dalaman dalam persekitaran dimensi tinggi. Teknik yang diadangkan terdiri daripada empat langkah: (i) hubungan antara keadaatan dan tingkah laku ultrabunyi dikenalpasti. (ii) teknik penguraian isyarat seara pelbagai resolusi kemudiannya digunakan untuk mengurangkan dimensi data. (iii) imej rantau keadaatan dibina semula dengan menggunakan pelemahan isyarat ultrabunyi yang terlantun. (iv) kaedah klasifikasi kabur k-jiran terdekat berasaskan entropi digunakan untuk mengekstrak ciri keadaatan. Nyahikatan diperkenalkan sebagai keadaatan dalaman dalam eksperimen. Rangka kerja yang diadangkan telah diuji atas komposit kasa bertetulang gentian polimer (GFRP) dengan ketebalan dan orientasi gentian yang berbeza.

Dapatan kajian menunjukkan bahawa kedudukan kerosakan telah menjadi faktor pengawal penting kepada pengesanan isyarat ultrabunyi. Keputusan eksperimen menunjukkan bahawa rangka kerja yang diadangkan berjaya mengurangkan dimensi ruang analisis. Algoritma yang diadangkan meminimumkan yang berasaskan wavelet telah mencapai peningkatan sebanyak 79.8% dan 30.2% masing-masing pada nisbah isyarat-kepada-bunyi bagi data bising simulasi dan eksperimen. Rangka kerja ini mempamerkan ketepatan yang tinggi bagi penyetempatan keadaatan dalaman dalam persekitaran dimensi tinggi. Ia adalah didapati bahawa kaedah klasifikasi kabur k-jiran terdekat berasaskan entropi telah menunjukkan prestasi

yang cemerlang dengan ketepatan 94.01% dalam pengesanan kecacatan dekat jarak apabila k-jiran terdekat minimum digunakan. Memandangkan semua keputusan dan maklumat yang dikumpul, ia boleh membuat kesimpulan bahawa bunyi struktur dalam isyarat ultrabunyi mendorong kekerapan rendah. Oleh itu, dengan mengeluarkan isyarat frekuensi rendah, pengesanan kecacatan dalaman boleh diperbaiki. Selain itu, pengelasan corak input berdasarkan jiran terdekat titik kepentingan memberi pengesanan kecacatan yang lebih tepat dalam perbandingan dengan klasifikasi berdasarkan data pengalaman sebagai corak input kerana corak kecacatan berbeza kepada keadaan dalam masalah NDE ultrasouik.

## ACKNOWLEDGEMENTS

I would like to thank many people who assisted me to finish the research. My appreciation and thanks to my supervisor, Professor Datin Dr. Napsiah Ismail, for her generous support and guidance throughout the duration of carrying out my research. I would like to thank Associate Professor Dr. Aidy Ali and Professor Ir. Dr. Barkawi Bin Sahari for the support and assistance that made this research possible.

I take this opportunity to formally thank my fellow course mates and friends, for their help and support throughout the whole project. Great appreciation is expressed to the Institute of Advanced Technology for providing the facilities required for undertaking this study.

I would also especially like to thank my family who has always believed in me, also, Carol Beh, whom I believe in and who have the potential to surpass my efforts.

Ng Sok Choo

May 2013

I certify that a Thesis Examination Committee has met on **9 May 2013** to conduct the final examination of **NG SOK CHOO** on her thesis entitled " Internal defect detection and reconstruction framework for laminated glass fibre reinforced polymer composite materials" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee Tecommends that the student be awarded the degree of Doctor of Philosophy.

Members of the Examination Committee were as follows:

**Mohd Sapuan b. Salit, PhD, Ir.**

Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Tang Sai Hong, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Mohd Khairol Anuar b. Mohd Arifin, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Mohammad Hameedullah, PhD**

Professor  
Aligard Muslim University  
India  
(Independent Examiner)

**NORITAH OMAR, PhD**

Assoc. Professor and Deputy Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date:

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirements for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

**Datin Napsiah Ismail, PhD**

Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Aidy Ali, PhD**

Associate Professor  
Department of Mechanical Engineering  
Universiti Pertahanan Nasional Malaysia  
(Member)

**Barkawi Bin Sahari, PhD, Ir.**

Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**BUJANG BIN KIM HUAT, PhD**

Professor and Dean  
School of Graduate Studies  
Universiti Putra Malaysia

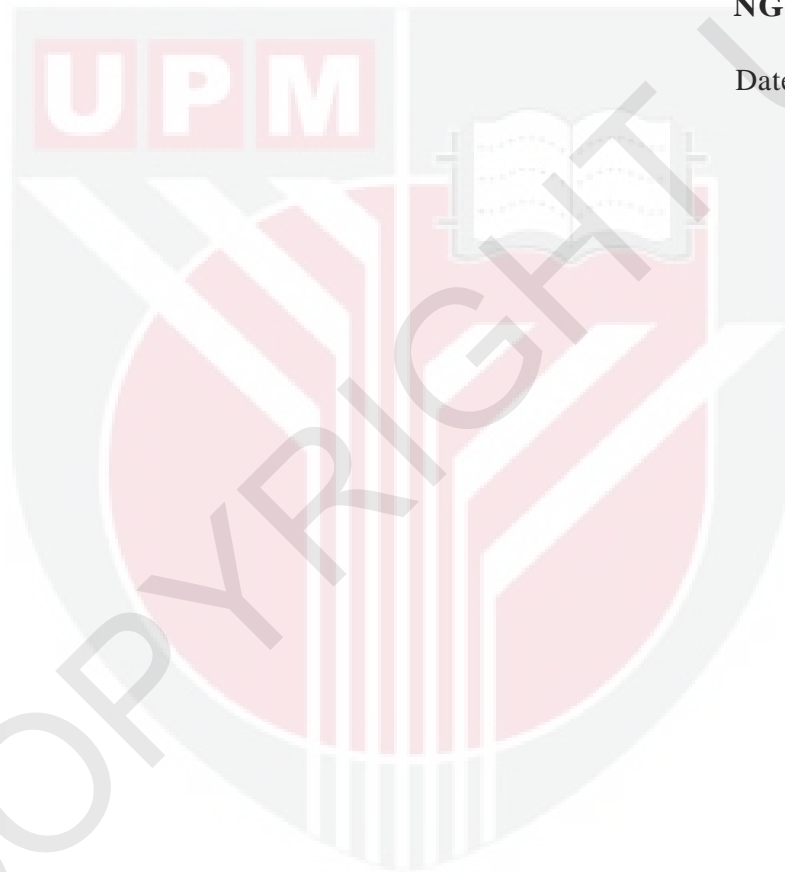
Date:

## DECLARATION

I hereby declare that the thesis is my original work except for quotations and citations, which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Putra Malaysia or other institutions.

**NGSOKCHOO**

Date:



## TABLE OF CONTENTS

	<b>Page</b>
<b>DEDICATION</b>	ii
<b>ABSTRACT</b>	iii
<b>ABSTRAK</b>	vi
<b>ACKNOWLEDGEMENTS</b>	ix
<b>APPROVAL</b>	x
<b>DECLARATION</b>	xii
<b>LIST OF TABLES</b>	xv
<b>LIST OF FIGURES</b>	xvi
<b>LIST OF ABBREVIATIONS AND NOTATIONS</b>	xx
<b>CHAPTER</b>	
<b>1 INTRODUCTION</b>	
1.1 Backgr01111d	1
1.2 Problem Statement	4
1.3 Objective of the Research	7
1.4 Scope of Research	9
1.5 Research Hypotheses	10
1.6 Contributions of the Research	11
1.7 Organization of the Thesis	12
<b>2 LITERATURE REVIEW</b>	
2.1 Introduction	14
2.2 Laminated GFRP Composite Materials	15
2.2.1 Mechanical and Environmental Loads of Laminate	18
2.3 Failure Modes in Laminated Composite Materials	22
2.3.1 Manufacturing Process and Defects	25
2.4 Non-Destructive Testing and Evaluation Method	30
2.4.1 Ultrasound	31
2.4.2 Radiography	37
2.4.3 Acoustic Emission.	40
2.5 Ultrasonic Signal Processing	43
2.5.1 Filter Methods	44
2.5.2 Wrapper Methods	57
2.6 Summary	66
<b>3 MATERIALS AND METHODS</b>	
3.1 Introduction	69
3.2 Research Methodology	70
3.3 Physical Experimental Set Up of Ultrasonic Testing System	76
3.3.1 U-WaveTech	79
3.4 Material Preparation	82
3.4.1 Data Acquisition	83
3.4.2 Data Preprocessing	84
3.5 Experimental Design	85

3.6	Summary	97
<b>4</b>	<b>DEVELOPMENT OF AN ADVANCED NONDESTRUCTIVE EVALUATION FRAMEWORK</b>	
4.1	Introduction	99
4.2	Overview of Automated NDE Framework	100
4.3	Taguchi Experimental Design to Identify Delamination in GFRP	103
4.4	Multiresolution Signal Decomposition	113
4.4.1	Orthogonal Wavelet Analysis	116
4.4.2	Wavelet-based Minimization	118
4.5	3D Volume Visualization of Delamination Region in GFRP	125
4.5.1	Ultrasound Imaging of Multi-layered Composites Structure	128
4.5.2	Gating Procedures	129
4.5.3	C-Scan Image Generation	130
4.6	Entropy-based Fuzzy k-Nearest Neighbour Classification	132
4.6.1	Fuzzy Sets	137
4.6.2	Entropy-based Fuzzy <i>K-NN</i> Classifier	139
4.7	Summary	142
<b>5</b>	<b>RESULTS AND DISCUSSIONS</b>	
5.1	Introduction	145
5.2	Impact of Each Control Factor on the Characteristics of Ultrasound Signals	146
5.3	Performance of Wavelet-based Minimization on Data Dimensionality Reduction	152
5.3.1	Results from Simulated Data	153
5.3.2	Results from Experimental Data	158
5.4	Performance of Delamination Region Visualization in GFRP	163
5.5	Performance of Entropy-based Fuzzy k-Nearest Neighbour Classification	170
5.6	Summary	176
<b>6</b>	<b>CONCLUSIONS AND RECOMMENDATION FOR FUTURE WORK</b>	
6.1	Introduction	180
6.2	Concluding Remarks	183
6.3	Future Work and Extensions	185
	<b>REFERENCES</b>	187
	<b>APPENDIX A</b>	200
	<b>APPENDIX B</b>	201
	<b>APPENDIX C</b>	202
	<b>BIODATA OF STUDENT</b>	225
	<b>LIST OF PUBLICATIONS</b>	226