

**DETECTION AND CLASSIFICATION OF IMPACT-INDUCED  
DELAMINATION IN FIBERGLASS PRE-IMPREGNATED  
LAMINATED COMPOSITES FROM ULTRASONIC A-SCAN  
SIGNAL USING ARTIFICIAL INTELLIGENCE**

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**UNIVERSITI SAINS MALAYSIA**

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**DETECTION AND CLASSIFICATION OF IMPACT-INDUCED  
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COMPOSITES FROM ULTRASONIC A-SCAN SIGNAL USING  
ARTIFICIAL INTELLIGENCE**

**by**

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## **TABLES OF CONTENTS**

	<b>Page</b>
<b>ACKNOWLEDGEMENT</b>	ii
<b>TABLE OF CONTENTS</b>	iii
<b>LIST OF TABLES</b>	vii
<b>LIST OF FIGURES</b>	viii
<b>LIST OF ABBREVIATIONS</b>	xii
<b>LIST OF SYMBOLS</b>	xvi
<b>ABSTRAK</b>	xviii
<b>ABSTRACT</b>	xx
<b>CHAPTER ONE: INTRODUCTION</b>	
1.1 Background of study	1
1.2 Problem statement	5
1.3 Objectives	7
1.4 Scope of study	7
1.5 Research approach	8
1.6 Organization of thesis	9
<b>CHAPTER TWO: LITERATURE REVIEW</b>	
2.1 Introduction	11
2.2 Impact-induced delamination in laminated composites	15
2.3 Detection of the impact-induced delamination in laminated composites	17
2.3.1 Detection of the impact-induced delamination using static and dynamic load response method	18

2.3.2	Detection of the impact-induced delamination using laser Doppler vibrometry method	21
2.3.3	Detection of the impact-induced delamination using ultrasonic testing method	25
2.4	Wavelet function analysis	31
2.5	Feature extraction using wavelet transform approach	38
2.6	Classification of defect using neural network approach	43
2.6.1	Network generalization for for artificial neural network (ANN) method	48
2.7	Chapter summary	49

### **CHAPTER THREE: METHODOLOGY**

3.1	Introduction	51
3.2	Low-velocity impact test in fiberglass prepregs laminated composites	54
3.2.1	Experimental setup of LVI test	56
3.2.2	Grid mark on test specimen for ultrasonic scanning guide	58
3.3	Ultrasonic pulse-echo immersion testing experimental setup	60
3.3.1	Design and development of ISI i-Inspex TWO	60
3.3.2	System architecture of ISI i-InspeX TWO	62
3.3.3	Calibration of transducer before inspection	65
3.3.4	Parameter setup during inspection	69
3.4	Signal acquisition of delamination induced by impact in FGLC	72
3.5	Signal pre-processing of ultrasonic A-scan signal	74
3.5.1	Signal segmentation	75
3.5.2	Signal de-noising	76
3.6	Destructive testing after scanning inspection of FGLC plates	78
3.7	Feature extraction	79

3.7.1	Delamination features	79
3.7.2	Feature selection	81
3.8	Classification of the impact-induced delamination in fiberglass laminated composites using artificial neural network approach	84
3.8.1	Training, testing and validation the network	86
3.9	Chapter summary	88

## **CHAPTER FOUR: RESULTS AND DISCUSSIONS**

4.1	Introduction	90
4.2	Low-velocity impact test in FGLC plates	91
4.3	Calibration result of ultrasonic transducer	98
4.4	Detection of the impact-induced delamination using ultrasonic immersion testing method	100
4.4.1	Signal acquisition result	100
4.4.2	Dynamic signal segmentation result	102
4.4.3	Signal de-noising result	105
4.4.4	Visualized of delamination from re-plotted ultrasonic A-scan signals	110
4.5	Comparison of delamination measurement between destructive test and non-destructive test method	115
4.6	Feature extraction of ultrasonic A-scan signal for delamination	117
4.6.1	Feature selection result	118
4.7	Classification result of the impact-induced delamination in FGLC	125
4.8	Chapter summary	130

## **CHAPTER FIVE: CONCLUSIONS AND FUTURE RESEARCH**

5.1	Introduction	133
5.2	Conclusions	133
5.3	Contributions of study	135
5.4	Future recommendations	136

<b>REFERENCES</b>	<b>137</b>
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## **APPENDICES**

Appendix A	[Prototype development]
Appendix B	[Theoretical of material sound velocity]
Appendix C	[Coefficient of reconstruction low pass filter of different wavelet families]
Appendix D	[Cross-correlation analysis of different wavelet families]
Appendix E	[Cross-correlation analysis of different level of decomposition]
Appendix F	[Impact damage diameter against impact energy of each test specimens]
Appendix G	[Percentage different between delamination and impact damage area of each test specimens]
Appendix H	[Feature extraction of each test specimens]

## **LIST OF PUBLICATIONS**

## LIST OF TABLES

		<b>Page</b>
Table 3.1	List of initial height of impactor, impact energy and impact velocity in different impact test class	58
Table 3.2	Computer-based control setup for FGLC panels	69
Table 3.3	Manual adjustable setup for FGLC panels	71
Table 3.4	List of extracted delamination features	80
Table 4.1	Thickness measurement result of aluminium calibration block	99
Table 4.2	Sound velocity of aluminium between theory and experiment	99
Table 4.3	Correlation analysis of different wavelet families	107
Table 4.4	Correlation analysis different level of decomposition	109
Table 4.5	Comparison analysis between the size of impact damage and the size of delamination which is obtained from ultrasonic A-scan signal	113
Table 4.6	Comparison analysis between the size of horizontal delamination diameter taken from NDT and DT	116
Table 4.7	Extracted feature of the impact-induced delamination in FGLC plates from ultrasonic A-scan signal	117
Table 4.8	Classification result of the impact-induced delamination in FGLC plates	125

## LIST OF FIGURES

		<b>Page</b>
Figure 2.1	Delamination occurred between adjacent plies in laminated composites (Riccio, 2008)	12
Figure 2.2	Delamination caused by by drilling process in laminated composites (Riccio, 2008)	13
Figure 2.3	Tapered laminate geometry terminology (Leslie et al., 2016)	14
Figure 2.4	Damage pattern for thin and thick laminated composites (Riccio, 2008)	14
Figure 2.5	Typical damage caused by impact in laminated composite (Shyr and Pan, 2003)	16
Figure 2.6	Configuration of strain sensor on the laminated composites test specimen. (Watkins et al., 2007)	18
Figure 2.7	Experimental setup of laser Doppler vibrometry technique to detect delamination in laminated composites (Geetha et al., 2016)	21
Figure 2.8	Experimental setup of ultrasonic immersion testing (ASTM E1065, 2003)	25
Figure 2.9	Ultrasonic A-scan signal display (National Instruments, 2016)	26
Figure 2.10	Signal waveform (a) Sinusoid waveform (b) Wavelets waveform (Fugal, 2009)	32
Figure 2.11	The constituent of wavelets (Fugal, 2009)	32
Figure 2.12	Wavelet Decomposition Analysis (Weeks, 2007)	36
Figure 3.1	The overall process flow of this research	53
Figure 3.2	Typical failure caused by LVI in laminated composites	54
Figure 3.3	Experimental setup of LVI test for FGLC plates	56
Figure 3.4	Close-up front view of the LVI test during pre-loaded test specimen	57
Figure 3.5	Grid mark of 10 mm x 10 mm for each test specimen edge	59

Figure 3.6	CAD drawing of ISI i-InspeX TWO	61
Figure 3.7	System Architecture of ISI i-InspeX TWO	63
Figure 3.8	Developed GUI for motion control	63
Figure 3.9	Experimental setup of ISI i-InspeX TWO	64
Figure 3.10	Aluminium block for thickness calibration	65
Figure 3.11	Illustration of the identified point on the aluminium block	66
Figure 3.12	GUI for ultrasonic thickness measurement	67
Figure 3.13	Illustration of scanning envelop during inspecting FGLC plates on the impact area	72
Figure 3.14	Illustration of re-plotted ultrasonic A-scan signal for impact-induced delamination in FGLC plates	73
Figure 3.15	Simplified flowchart of signal pre-processing	74
Figure 3.16	ROI of overall ultrasonic A-scan signal	75
Figure 3.17	Illustration of FGLC plates with cross-section view of delamination	78
Figure 3.18	Measurement of delamination (ASTM D7136, 2012)	81
Figure 3.19	Generic example of a box plot distribution (a) different range of features, (b) similar range of features	83
Figure 3.20	Overall classification structure for detecting various type of the impact-induced delamination in FGLC using ultrasonic testing method	84
Figure 3.21	Network architecture of the proposed classification system	85
Figure 3.22	5-fold cross-validation technique	87
Figure 4.1	Impact damage of FGLC plate batch C3.1 (a) Centre of impact and virtual scanning envelop area, and (b) close-up image of specimen with impact damage area	92
Figure 4.2	Visible impact damage of FGLC plates for each LVI test class (a) specimen C1, (b) specimen C2, (c) specimen C3, (d) specimen C4, (e) specimen C5 and (f) specimen C6	94

Figure 4.3	Influence of the impact energy to the diameter of impact damage	95
Figure 4.4	Determination of impact damaged area in FGLC plates using image processing software namely 'imageJ'	96
Figure 4.5	Influence of the impact energy to the area of impact damage	97
Figure 4.6	Ultrasonic A-scan signal (a) Signal pattern of non-damage while (b) is the signal pattern of damage	101
Figure 4.7	Ultrasonic A-scan signal obtained from different gap distance. (a) 5 mm, (b) 7 mm, (c) 9 mm, (d) 10 mm, (e) 11 mm and (f) 13 mm	103
Figure 4.8	Ultrasonic A-scan signal after processed by dynamic signal segmentation system with different gap distance (a) 5 mm, (b) 7 mm, (c) 9 mm, (d) 10 mm, (e) 11 mm and (f) 13 mm	104
Figure 4.9	De-noised signal from various type of wavelet families at fourth level of decomposition for delamination. (a) Raw signal, (b) Haar, (c) Daubechies 2 and (d) Coiflets 2, (e) Symlets 2, (f) Biorthogonal 2.2 and (g) Biorthogonal 4.4	105
Figure 4.10	De-noised signal of delamination from various decomposition level. (a) raw signal, (b) first level, (c) third level, (d) fourth level, (e) fifth level and (f) sixth level	108
Figure 4.11	Illustration of the process to visualize the delamination induced by an impact for FGLC plates	110
Figure 4.12	Visualized image of delamination growth with impact energy as detected by ultrasonic A-scan signal	111
Figure 4.13	Influence of the impact energy to the area of delamination	114
Figure 4.14	Cross-section image of delamination in C2.1 FGLC plate	115
Figure 4.15	The boxplot distribution of mean features for defect points	119
Figure 4.16	The boxplot distribution of variance features for defect points	120
Figure 4.17	Boxplot distribution of standard deviation for defect points	121
Figure 4.18	Boxplot distribution for percentage of delamination area	122

Figure 4.19	Boxplot distribution for delamination diameter in horizontal direction	123
Figure 4.20	Boxplot distribution for delamination diameter in vertical direction	124
Figure 4.21	Classification performance with difference no of neurons	126
Figure 4.22	MSE vs number of epoch for different fold. (a) Network Fold-1, (b) Network Fold-2, (c) Network Fold-3, (d) Network Fold-4, (e) Network Fold-5	127

## **LIST OF ABBREVIATIONS**

1D	One dimensional
2D	Two dimensional
3D	Three dimensional
3D-SEM	3D spectral element method
A1	Approximate level one
A2	Approximate level two
A3	Approximate level three
A4	Approximate level four
ACT	Air coupled transducer
AE	Acoustic emission
AMREC	Advance materials research centre
ANN	Artificial neural network
ANOVA	Analysis of variance
AR	Auto-regressive
ASTM	American society for testing and materials
BPN	Back-propagation neural network
BVID	Barely visible impact damage
BWE	Back wall echoes
C1	Specimen class number one
C2	Specimen class number two
C3	Specimen class number three
C4	Specimen class number four
C5	Specimen class number five
C6	Specimen class number six

CCF	Cross-correlation function
CFRP	Carbon fiber reinforced polymer
CP	Central peak
D1	Detail level one
D2	Detail level two
D3	Detail level three
D4	Detail level four
DGT	Discrete Gabor transform
DT	Destructive test
DWE	Defect wall echoes
DWT	Discrete wavelet transform
EEG	Electroencephalogram
FBG	Fiber Bragg grating
FE	Finite element
FEM	Finite element method
FGA	Fiberglass aluminium
FGLC	Fiberglass pre-impregnated laminated composites
FSH	Full screen height
FWE	Front wall echoes
GF/EP	Glass fiber reinforced epoxy
GFRP	Glass fiber reinforced polymer
GUI	Graphical user interface
HPF	High pass filter
IID	Impact-induced delamination
ISI	Innovative system of instrumentation

LDA	Linear discriminant analysis
LDV	Laser Doppler vibrometry
LM	Levenberg-Marquardt
LPF	Low pass filter
LVI	Low-velocity impact
MATLAB	Matrix laboratory
ME	Main energy computing
MFDWC	Mel-frequency discrete wavelet coefficients
MLP	Multilayer perceptron
MSE	Mean square error
NDT	Non-destructive test
OM	Orientation map
OOA	Out-of-autoclave
PAUT	Phased array ultrasonic testing
PCA	Principle component analysis
PRF	Pulse repetition frequency
PZT	Piezoelectric
RA	Random positioning
RF	Radio frequency
ROI	Region of interest
ROIL	Region of interest line
RSGW	Redundant second generation wavelet
SEM	Scanning electron microscope
SHM	Structural health monitoring
SIRIM	Scientific and Industrial Research Institute of Malaysia

SLDV	Scanning laser Doppler vibrometry
SNR	Signal-to-noise-ratio
SO	Systematic echo capturing and preservation of original neighbouring grass
SOP	Standard of procedure
SVM	Support vector machine
SWT	Stationary wavelet transform
SZ	Systematic echo capturing method with zero-padding
US	United states
UT	Ultrasonic testing
WPT	Wavelet packet transform
WT	Wavelet transform
ZLCC	Zero-lag cross-correlation

## LIST OF SYMBOLS

$A_d$	Delamination area
$A_i$	Impact damage area
$A\%$	Percentage area of delamination over total scanning envelop size
$D_{dx}$	Horizontal delamination diameter
$D_{dy}$	Vertical delamination diameter
$D_{ix}$	Horizontal diameter of impact damage
$D_{iy}$	Vertical diameter of impact damage
$DT\_D_{dx}$	Horizontal delamination diameter from destructive test method
$E_i$	Impact energy
$g$	Acceleration due to gravity
$H_i$	Initial height of the impactor
$H_{ts}$	Gap distance between transducer and specimen
$k$	Iteration
$m$	Mean
$M_i$	Mass of impactor
$N$	Number of sample
$N_{pw}$	Numbers of pulse width
$p$	Statistical significant
$P_w$	Pulse width
$\rho_y$	Cross-correlation estimation
$r_{xy}$	Estimate of the cross-covariance
$s$	Standard deviation
$T_x$	Total thickness of specimen
$v$	Variance

$V_{al}$	Theoretical of aluminium sound velocity
$V_i$	Impact velocity
$x_k$	Data in sequence
$\bar{x}$	Data in average
$\infty$	Infinity
%	Percentage

**PENGESAN DAN PENGELASAN DELAMINASI DISEBABKAN OLEH  
IMPAK PADA GENTIAN KACA PREPREG KOMPOSIT BERLAPIS  
DARIPADA ISYARAT ULTRASONIK IMBASAN-A  
MENGUNAKAN KECERDASAN BUATAN**

**ABSTRAK**

Delaminasi disebabkan oleh impak pada gentian kaca komposit berlapis (GKKB) merupakan mod kegagalan yang penting. Selain memberi kesan terhadap kekuatan bahan dan kebolehpercayaan struktur, mod kegagalan ini biasanya memaparkan kerosakan yang kecil pada bahagian permukaan tetapi mungkin merebak pada kerosakan bahagian dalam. Kaedah pengesanan yang sedia ada menggunakan tindak balas beban statik dan dinamik mempunyai batasan yang dianggap pemantauan tidak boleh-alih dan memerlukan penderia yang dilekatkan pada permukaan bahan ujikaji. Teknik ini tidak sesuai kerana kerosakan yang disebabkan oleh hentakan yang biasanya berlaku secara tidak sengaja di kawasan tertentu secara rawak. Oleh itu, pengesan dan pengelasan delaminasi disebabkan oleh hentakan dengan menggunakan rangkaian saraf buatan daripada isyarat ultrasonik mempunyai potensi yang baik untuk digunakan, namun tiada percubaan dibuat untuk mengesan and mengelaskan mod kegagalan ini pada bahan GKKB. Pengelasan delaminasi terhadap hentakan bukan sahaja boleh diaplikasikan sebagai alat ramalan untuk mencirikan delaminasi, ia juga boleh digunakan sebagai rujukan semasa memeriksa bahan GKKB di dalam keadaan tertentu. Dalam kajian ini, potensi menggunakan ujian ultrasonik secara rendaman untuk mengesan delaminasi akibat hentakan pada bahan GKKB jenis kain 7781 E-Kaca dikaji. Beberapa penemuan dan pembangunan telah dicapai dalam kajian ini seperti hubungan di antara kawasan delaminasi dan peningkatan tenaga hentakan, di mana kadarnya adalah di antara 23 ke 45 peratus. Selain itu, diameter bagi kerosakan yang disebabkan oleh hentakan meningkat secara langsung terhadap peningkatan

tenaga hentakan iaitu dalam lingkungan 21 hingga 46 peratus manakala bagi kawasan kerosakan yang disebabkan oleh hentakan pula adalah di antara 24 hingga 42 peratus. Di samping itu, algoritma pembahagian yang dinamik telah berjaya dibangunkan di dalam kajian ini untuk membahagi isyarat ultrasonik imbasan-A secara automatik tanpa mengira perbezaan jarak jurang antara penderia dan permukaan bahan ujikaji. Berdasarkan hasil pemeriksaan ultrasonik, didapati bahawa delaminasi merebak sehingga 35.90 peratus di bahagian dalam dan purata peratus berbezaan hasil pengukuran yang diambil dari ujian musnah dan ujian tanpa musnah adalah hanya 4.72 peratus dan boleh diterima. Oleh kerana keputusan pengelasan yang dicapai adalah sangat tepat, iaitu melebihi 99.29 peratus, dapat disimpulkan bahawa ciri-ciri yang dipilih sebagai input pengelasan telah berjaya dan penggunaan rangkaian saraf buatan dari isyarat A-scan ultrasonik telah menunjukkan kebolegunaan untuk mengelaskan perbezaan jenis delaminasi yang disebabkan oleh hentakan dalam plat GKKB.

# **DETECTION AND CLASSIFICATION OF IMPACT-INDUCED DELAMINATION IN FIBERGLASS PRE-IMPREGNATED LAMINATED COMPOSITES FROM ULTRASONIC A-SCAN SIGNAL USING ARTIFICIAL INTELLIGENCE**

## **ABSTRACT**

Impact-induced delamination (IID) in fiberglass pre-impregnated laminated composites (FGLC) is an important failure mode. Besides affected the material strength and structural reliability, this failure mode normally present minor damage on the surface but the internal damage may extensive. Existing detection method using static and dynamic load response have limitations that are considered static based monitoring and require the sensor to be attached to the test specimen surface. This technique is not suitable as the damage caused by the impact normally occurred by accident at random location. Thus, detection and classification of IID using artificial neural network from ultrasonic signal has great potential to be applied, but no attempt has been made to detect and classify this failure mode in FGLC material. The classification of delamination against impact not only applicable as prediction tool to characterise the delamination, it also can be used as reference during inspecting the FGLC under specific conditions. In this study, the potential of using ultrasonic immersion testing for detecting the IID in FGLC type 7781 E-Glass fabric is studied. Several findings and development have been achieved in this study such as the relationship between delamination area and the increasing of an impact energy, where the rate is between 23 to 45 percent. Besides, it was found that the diameter of the impact damage is directly increase with the increasing of the impact energy in the range of 21 until 46 percent while for the impact damage area is between 24 until 42 percent. In addition, the dynamic segmentation algorithm has been successfully developed in this study to automatically segment the A-scan signal with regardless the

variation of gap distance between transducer and specimen surface. Based on the ultrasonic inspection result, it was found that the delamination is extend internally up to 35.90 percent and the average percentage different of the measurement result which is taken from DT and NDT is just 4.72 percent and acceptable. Since the achieved classification result is highly accurate, which is exceeded 99.29 percent, it can be concluded that the selected features for the classification input is successful and the use of artificial neural network from ultrasonic A-scan signal has shown its applicability to classify the different type of the impact-induced delamination in FGLC plates.

## **CHAPTER ONE**

### **INTRODUCTION**

#### **1.1 Background of study**

Fiberglass pre-impregnated laminated composites (FGLC) is the reinforced glass fabric which has been pre-impregnated with a resin system, typically ready for lay into the mold and require pressure and heat during curing process (FAA, 2012). FGLC structures have been developed and widely implemented in manufacturing and advanced industries including automotive, military, sport and aerospace over the decades. The advantages of FGLC prepregs over other hand lay-up laminated composites are higher the strength properties by minimizing the excess resin problem and balance the distribution of resin which is significantly reduced the damage from resin problem; either resin-rich area or dry spot area. Also, it required less curing time, whose allow the part for service once the curing time has completed (Hubert et al., 2017). Although advances in the FGLC manufacturing technology has improved much on the strength properties and manufacturing time, recent studies have found that delamination, fiber breakage and matric crack are typically occurred in laminated composites (Perez et al., 2014; Ambu et al., 2006). However, based on these failure modes, delamination is the most commonly found in laminated composites by separated layer parallel to the surface of the structure (Adam and Cawley, 1989). In the recent years, delamination growth and structural integrity behaviour in laminated composites has receive much attention in the research community. According to Ng et al. (2012), there are three main factors can cause the presence of delamination in laminated composites which are, (i) trapped air due to poor lay-up procedures,

(ii) unremoved prepreg backing film during stacking process, and (iii) external force during in-service. However, the first and second factor of delamination can be avoided throughout robust standard of procedure (SOP) with help in-process quality control. In contrast, the delamination which is caused by an external force such as an impact that has been occurred when the tool accidentally drop to the structural surface during maintenance is difficult to prevent (Nikfar and Njuguna, 2014). The delamination induced by low-velocity impact (LVI) during manufacturing or in-service cause severe stiffness and reduction of compressive strength that potentially lead to catastrophic failure for the whole structures (Perez et al., 2014; Lin and Chang, 2002). LVI has been determined based on an impact velocity in the range of 1 to 10 m/s depending on the material properties, the projectile mass and the target stiffness (Sjoblom et al., 1988).

The detection of delamination are quit challenging since this failure mode cannot be observed by naked eyes on the surface. Thus, several researches have been carried out in developing extensive method of detection the delamination induced by impact for laminated composites. Although delamination cannot be observed by naked eyes, Sayer et al. (2012) applied high end vision system to investigate the effect of temperature in hybrid laminated composites to the impact induced delamination area. The similar experiment has been conducted later by Liu et al. (2014) but using different type of laminated composites, namely pyramidal truss core sandwich. Moreover, detailed result from cross section view image of delamination area was captured using scanning electron microscope (SEM) equipment. However, this technique will damage the structure and not applicable to detect delamination on working parts. Alternatively, another non-destructive testing (NDT) technique based on static and dynamic force response for various geometric boundary condition using piezoelectric (PZT) sensor