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

by

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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
ρ_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
∞	Infinity
%	Percentage

PENGESAN DAN PENGELASAN DELAMINASI DISEBABKAN OLEH IMPAK PADA GENTIAN KACA PREPREG KOMPOSIT BERLAPIS DARIPADA ISYARAT ULTRASONIK IMBASAN-A MENGGUNAKAN 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 kebolehgunaan untuk mengelaskan perbezaan jenis delaminasi yang disebabkan oleh hentakan dalam plat GKKB.

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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 accidently 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 and strain gauges was developed to obtain force and micro strain (Watkins et al., 2007; Jang and Kim, 2017), modal characteristic of delamination growth (Valdes and Soutis, 1999; Perez et al., 2014), statistical pattern recognition (Sohn et al., 2001) and mean of Auto Regressive from time histories of the acquired response (Nardi et al., 2016). Besides, advance type of sensor, namely fiber Bragg grating sensing system (FBG) also been used by many researchers (Koh et al., 2005; Ling et al., 2005; Jang and Kim, 2017; Chandarana et al., 2017; Xu, 2014; Wu et al., 2015; Yu et al., 2016) due to its advantages of lightweight, small size, resistance electromagnetic interference and large target area. Since these technique required multiple sensor with complicated wiring installation during data acquisition, other researchers used scanning laser Doppler vibrometry (LDV) technique, where the laser beam is directly measure the vibration on the targeted surface such as delamination detection in thin laminated composites plate (Kudela et al., 2016; An, 2016) or at T-join plate (Geetha et al., 2016). The delamination image obtained from this technique is useful to locate and determine the size of the delamination.

Although most of the work reported in the literature able to monitor delamination along full life cycle of the structure, these techniques required PZT sensor to be attached on the surface of the targeted area and leaves footprint on the plate surface after removing the PZT sensor. Thus, non-contact based technique such as ultrasonic testing (UT), thermography and X-radiography were the alternative approach that meet the criteria. Several researches attempted to investigate the impact induced delamination behaviour using these techniques such as done by Mitrevski et al.(2005) and Mitrevski et al.(2006), who used UT scanned image to identify the relation between designed indenter shape and delamination area in CFRP thin plates. However, the scanned image was inadequate and difficult to identify the size of

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