MODE-I LOW CYCLE FATIGUE DELAMINATION OF WOVEN GLASS FIBRE REINFORCED POLYMER MATRIX COMPOSITE

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DECLARATION

I hereby declare that the material in this thesis is my own except for quotations, excerpts, equations, summaries and references, which have been duly acknowledged.

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CERTIFICATION

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DEGREE : **MASTER OF ENGINEERING (COMPOSITE MATERIALS)**

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ABSTRACT

MODE-I LOW CYCLE FATIGUE DELAMINATION OF WOVEN GLASS FIBRE REINFORCED POLYMER MATRIX COMPOSITE

Most parts of the failures in structural elements in use were consequences of mechanical fatigue. Therefore, fatigue had been a critical factor in designing durable mechanical elements. In laminated woven GFRP composite material, the fatigue process involves different damage mechanism that results in the degradation of the materials. One of the most important damage mechanisms was the delamination between plies of the laminates. Outstanding performance woven E-glass/Polyester composites, which were increasingly used for various applications were susceptible to delamination. In response to this problem, the mode-I interlaminar fracture and fatigue delamination toughness of woven E-glass/Polyester laminates had been studied under tensile loading by using a double cantilever beam (DCB) specimen. Results were presented from an experimental study to determine the mode-I quasi-static and fatigue delamination toughness of a reinforced laminated composite. Mode-I double cantilever beam (DCB) tests had been performed on woven GFRP unsaturated polyester composite, E-Glass EWR 600 NISER, specimens. Static delamination had been first obtained. The specimen design and test procedure were performed with reference to the BS ISO 15024 and ASTM D5528. Specimens were then cycled at low cycle fatigue with 2Hz, 5Hz and 9Hz frequencies at constant amplitude of 1.5mm. These data used to determine the fatigue delamination growth onset characteristic. The results from this investigation were used to generate a surface plot relating fracture toughness to mode-I and the number of cycles achieved before the onset of fracture. This plot characterizes the behaviour of the material under all static and fatigue conditions, thus providing a valuable tool for the design of composite structures in those applications where delamination growth had been of concern. Fatigue delamination growth onset test was carried out according to the ASTM D6115. The experimental results of mode-I fracture toughness, as a function of crack length had been obtained. Experimental data obtained were analyzed using the modified beam theory, MBT method. The delamination-resistance curve or the R-curve effect had been found as the general characteristics of the laminate system. Constant amplitude cyclic opening displacement fatigue test was also conducted to establish the delamination growth rate (da/dN) as a function of maximum cyclic energy release rate (G_{Imax}). The test then continues to identify the fatigue life characteristic. Fracture mechanic based total life model for delaminated woven GFRP composite was then established. The model includes the delamination growth predominant in the linear domain. Fibre bridging phenomenon with slow and stable crack propagation and extensive half-arm fiber bridged were also observed and identified from the fractographic analysis, with lower curing pressure was found to produce higher G_{IC} and G_{Imax} propagation toughness values.

ABSTRAK

Kebanyakan kegagalan pada bahagian komponen di dalam struktur elemen yang digunakan adalah akibat daripada kelesuan mekanikal. Oleh yang demikian, kelesuan adalah faktor kritikal di dalam merekabentuk elemen-elemen mekanikal yang tahan lasak. Bagi bahan komposit berlamina, proses kelesuan yang mengakibatkan keaiban pada bahan ini adalah merangkumi pelbagai mekanisma kerosakan yang berbeza-beza. Salah satu mekanisma kerosakan yang terpenting adalah delaminasi (delamination) di antara lapisan-lapisan bahan berlamina tersebut. Keupayaan yang sangat baik dari anyaman gentian kaca jenis-E/Polyester berlamina, yang mana kini banyak digunakan pada pelbagai aplikasi adalah turut berisiko mengalami delaminasi. Sebagai respon keadaan masalah ini, kajian kepada keupayaan dalam mod-I keretakan antara lamina dan kelesuan delaminasi telah dilakukan dengan menggunakan spesimen penyanggar alang berpasangan (DCB). Semua hasil keputusan diterjemahkan dalam bentuk eksperimen bagi ujikaji statik dan kelesuan untuk keupayaan bahan komposit peneguhan berlamina. Ujikaji dijalankan dengan menggunakan spesimen bahan komposit gentian kaca EWR 600 NISER. Ujikaji delaminasi statik merupakan hasil yang pertama sekali diperolehi. Ujikaji ini dilakukan berdasar dan berlandaskan pada rujukan piawaian BS ISO 15024 dan ASTM D5528. Seterusnya spesimen ini dikitarkan pada kitaran frekunsi rendah 2Hz, 5Hz dan 9Hz pada amplitud malar 1.5mm. Data-data dari ujikaji ini kemudiannya digunakan dalam memperincikan titik awalan kelesuan delaminasi. Ianya juga dijelaskan dengan memplot graf yang berkaitan dengan keupayaan keretakan dan bilangan kitaran yang dicapai sebelum berlakunya titik awalan kelesuan. Plot ini juga memperincikan bahan tersebut dari segi ciri-ciri statik dan kelesuan yang mana ianya amat berguna bagi merekabentuk struktur bahan komposit dalam situasi ciri kegagalan seperti ini dititikberatkan. Bagi ujikaji sebaran kelesuan delaminasi, ianya dilakukan dengan rujukan piawai ASTM D6115. Seterusnya keputusan ujikaji yang diperolehi adalah dalam bentuk mod-I keupayaan keretakan bagi fungsi kadar panjang keretakan. Semua data yang diperolehi diproses menggunakan teori pegubahsuaian alang (MBT). Lengkungan rintangan-delaminasi atau lengkuk-R telah dikenalpasti sebagai ciri umum bagi sistem berlamina. Pembukaan berkitar bagi ujikaji kelesuan pada amplitut malar telah dijalankan bagi memenuhi keperluan kadar pertambahan delaminasi (da/dN) bagi fungsi kitaran maksimum kadar pelepasan tenaga (G_{Imax}). Seterusnya, ujikaji dilakukan untuk mengenalpasti ciri putaran hidup kelesuan. Mekanik keretakan berasakan model putaran hidup keseluruhan bagi pertambahan delaminasi pada bahagian (domain) linear. Melalui analisis fraktografy, fenomena penghubungan gentian dengan penyebaran keretakan yang stabil serta tokokan penghubungan gentian pada sebelah lengan spesimen telah diperhatikan. Spesimen lamina komposit yang difabrikasi dengan tekanan rendah dikenalpasti sebagai sesuatu yang memberikan nilai penyebaran tertinggi bagi G_{IC} and G_{Imax} .

KEYWORDS

Woven GFRP, Mode-I, Double Cantilever Beam, Interlaminar, Fatigue Delamination.

THESIS CONTENT

LIST OF TABLES

LIST OF FIGURES

Page

Page

Page

Page

Page

LIST OF ABBREVIATION

ASTM	American Society for Testing and Materials
Bhd.	Berhad
BPA	bisphenol A
BS	British Standard
BT	Beam Theory
CC	Compliance Calibration
CLS	crack-lap shear
CT	Compact Tension
DCB	Double Cantilever Beam
DEN	double-edge-notch
DENF	double-end-notch flexure
e.g.	For example
ELS	end-loaded split
EN	European Norm
ENF	end-notched flexure
EPFM	Elastic Plastic Fracture Mechanic
etc.	Etcetera
EWR	E-glass Woven Roving
FRP	Fibre Reinforced Polymer
GFRP	Glass Fibre Reinforced Polymer
i.e.	That is to say
ISO	International Organization for Standardization
LEFM	Linear Elastic Fracture Mechanic
M	Malaysia
MBT	Modified Beam Theory
MCC	Modified Compliance Calibration
MMB	Mixed-mode bending
MMF	mixed-mode flexure
MOU	Memorandum Of Understanding
MT	Middle Tension
RM	Ringgit Malaysia
SC	surface-cracked

SCB	single cantilever beam
Sdn.	Sendirian
SEM	Scanning Electron Microscope
SENB	Single Edge Notch Bend
SHCP	Singapore Highpolymer Chemical Products
VIC	Vickers indentation crack
WIF	wedge-insert-fracture
XWB	Extra Wide Body

LIST OF SYMBOLS

δ	Load point deflection
Δ	Effective delamination extension to correct for rotation of DCB arms a delamination front
π	Pie
σ	Remotely applied stress
τ	interfacial shear stress constantly along the length of the fibre
ρ	Density
γ	surface energy of the material
ε	Strain
θ	Angle within centre
δ_{cr}	Value of displacement at the onset of delamination growth from the insert in a quasi-static test
ΔG	Energy release rate range
ΔL_o	Increase in the specimen length between the gauge mark
δ_{max}	Maximum value of cyclic displacement
δ_{mean}	Mean value of cyclic displacement
δ_{min}	Minimum value of cyclic displacement
Δ_x	Incremental change in Log a
Δ_y	Incremental change in Log C
$[\Delta]_{av}$	Average value of Δ from the quasi-static tests
$[G_{IC}]_{av}$	Average value of GIC from the quasi-static tests
$2R$	Closest centre to centre spacing of the fibres
a	Delamination length
A	Material constant in fatigue condition
A_o	Insert length
A_i	Initial cross-sectional of the specimen

A_1	Slope of plot of a/b versus C1/3
a_o	Initial delamination length
b	Width of DCB specimen
B	Material constant in fatigue condition
b_f	Material constant in fatigue condition
C	Compliance, δ/P, of DCB specimen
C_f	Constant in fatigue condition
D	Density of resin
d	Density of reinforcement
da	Infinitesimal increase in delamination length
dt	Time increment
dU	Infinitesimal increase in strain energy
E'	Young Modulus for plane stress
E_{II}	Modulus of elasticity in the fibre direction
F_{cor}	Large displacement correction factor
F	Force
G	Strain energy release rate
G_{IC}	Opening mode-I interlaminar fracture toughness
G_{IIC}	Opening mode-II interlaminar fracture toughness
G_{IIIC}	Opening mode-III interlaminar fracture toughness
G_{Imax}	Maximum or peak cyclic mode-I strain energy release rate
G_{IR}	Mode-I Interlaminar fracture resistance
G-N	Relationship between the cyclic stain energy release rate and the number of cycles to onset of delamination growth
G_{TH}	Threshold strain energy release rate
h	Thickness of DCB specimen
h_{sf}	Separation of the fibre

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