INTERLAMINAR FATIGUE DAMAGE MODEL OF CARBON FIBER-REINFORCED POLYMER COMPOSITE LAMINATES

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DEDICATION

Dedicated to my father, mother (late), and wife, whose continuous support helped me reach this proud moment.

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In preparing this thesis, I contacted many people, researchers, academicians, and practitioners. They have contributed to my understanding and thoughts. In particular, I express my sincere appreciation to my supervisor, Dr Wong King Jye, for his encouragement, guidance, criticism and friendship. I am also very thankful to supervisor, Professor Dr. Mohd Nasir Tamin, for his guidance, advice and motivation. Without their continued support and interest, this thesis would not have been the same.

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ABSTRACT

Load-bearing structures made of carbon fiber-reinforced polymer (CFRP) composite laminates, such as the skin of aircraft wings, helicopter rotors, and wind turbine blades, are likely to experience time-varying loads. The fluctuating stresses could result in fatigue damage and failure of the laminates in the form of matrix cracking, fiber breakage and buckling, fiber/matrix debonding, and interface delamination. The latter is a significant damage mechanism in view of the relatively weak interlaminar bonding. In this respect, the current research has developed the interlaminar damage-based fatigue life model of fibre-reinforced polymer (FRP) composite laminates. The model incorporates the observed continuous cyclic degradation of interlaminar properties. The bi-linear traction-relative displacement softening rule for the cohesive zone model (CZM) is extended to accommodate the normalized interlaminar strength and stiffness degradation under the fatigue load cycles. The normalized fatigue life model accounts for the effect of mean stress on the observed interlaminar fatigue lives. Fatigue crack nucleation (separation) is governed by the interface's critical strain energy release rates. Hybrid finite element-experimental approach is employed to establish material parameters for the quasi static CZM. The experimental fatigue data for Mode I and Mode II of CFRP composite laminates from literature is employed to extract the residual properties. The normalized properties versus normalized fatigue life curves are then quantified based on the “wear-out” failure model. The curves are characterized by the curve fitting parameters α, β, λ, γ, μ, and ϕ for the interlaminar tensile strength, stiffness, and fracture energy. In view of the relatively large number of load cycles to capture the initiation and propagation of the interlaminar crack, the load cycle block approach is devised to improve computational efficiency. The model is coded in the UMAT Subroutine of Abaqus FE software. It is examined for interlaminar fatigue of CFRP composite laminate under Mode I , Mode II and mixed-mode loading conditions with a stress ratio, κ = 0.11, 0.15, and 0.1, respectively. The damage begins at approximately 8200 cycles and interface crack extends after accumulating 14100 applied fatigue cycles for Mode I load case. The damage begins at approximately 220000 cycles and interface crack extends after accumulating 350700 applied fatigue cycles for Mode II load case. The stress is highly concentrated at the crack front region. The FE-predicted fatigue lives are comparable with measured data and within the experimental scatter, hence validating the model. The crack tip opening and sliding displacements evolve with an initially slow rate of 2.6×10^{-9} and 1.85×10^{-10} mm/cycle respectively up to the onset of fatigue crack nucleation event at approximately 188800 cycles and then peaks at 1.5×10^{-7} and 7.1×10^{-8} mm/cycle respectively as the interface crack begins to accelerate after accumulating 284700 applied fatigue cycles for mixed mode flexure fatigue loading. The developed model will benefit various industries, including aerospace, automotive, and maritime, involved in the structural design for performance, reliability prediction, life extension and failure investigation of CFRP composite laminate structures.

ABSTRAK

Struktur galas beban diperbuat daripada komposit polimer bertetulang gentian karbon (CFRP) lamina, seperti kulit sayap pesawat, rotor helikopter, dan bilah turbin angin, berkemungkinan mengalami beban yang berubah dengan masa. Tegasan turun-naik boleh mengakibatkan kerosakan lesu dan kegagalan lamina dalam bentuk keretakan matriks, pemecahan gentian dan lengkokan, penyahikatan gentian/matriks, dan pelekangan antara muka. Memandangkan ikatan antara lamina yang agak lemah, kegagalan lamina adalah mekanisme kerosakan yang penting. Oleh itu, penyelidikan semasa telah membangunkan model hayat lesu berasaskan kerosakan antara lamina bagi lamina komposit polimer bertetulang gentian (CFRP). Model ini memasukkan degradasi sifat antara lamina dalam kitaran berterusan. Peraturan pelembutan sesaran tarikan relatif dwi-linear untuk model zon kohesif (CZM) dilanjutkan untuk menampung kekuatan antara lamina ternormal dan degradasi kekakuan di bawah kitaran beban lesu. Model hayat kelesuan ternormal mengambil kira kesan tekanan min ke atas hayat lesu antara lamina yang diperhatikan. Penukleasan (pemisahan) retak lesu dikawal oleh kadar pelepasan tenaga terikan kritikal antara muka. Pendekatan hibrid eksperimen dan kaedah unsur terhingga (FE) digunakan untuk mendapatkan parameter bahan untuk CZM kuasi-statik. Data lesu dari eksperimen untuk Mod I dan Mod II komposit lamina CFRP diambil daripada literatur untuk memperolehi sifat-sifat sisa lesu. Sifat-sifat ternormal bahan berbanding lengkung-lengkung hayat lesu ternormal kemudian dikira berdasarkan model kegagalan "haus". Lengkung-lengkung itu dicirikan oleh penyuaian lengkung α, β, λ, γ, μ, dan ϕ untuk kekuatan tegangan antara lamina, kekakuan, dan tenaga patah. Memandangkan bilangan kitaran beban yang agak besar diperlukan untuk permulaan dan perambatan retakan antara lamina, pendekatan blok kitaran beban dihasilkan untuk meningkatkan kecekapan pengiraan. Model ini dikodkan dalam perisian subrutin UMAT untuk Abaqus FE. Antara lamina lesu diperiksa bagi lamina komposit CFRP di bawah Mod I, Mod II dan keadaan bebanan mod campuran dengan nisbah tegasan masing-masing, $\kappa = 0.11$, 0.15, dan 0.1. Kerosakan bermula pada kira-kira 8200 kitaran dan retak antara muka memanjang selepas 14100 kitaran lesu bagi kes beban Mod I. Bagi kes beban Mod II kerosakan bermula pada kira-kira 220000 kitaran dan retak antara muka memanjang selepas 350700 kitaran lesu bagi. Tegasan sangat tertumpu di kawasan hadapan retak. Jangka hayat lesu yang diramalkan oleh FE adalah sebanding dengan data terukur eksperimen dan didalam julat serakan data, mengesahkan model tersebut. Pembukaan hujung retak dan sesaran gelangsar berkembang dengan kadar yang pada mulanya perlahan iaitu masing-masing 2.6×10^{-9} dan 1.85×10^{-10} mm/kitaran, sehingga permulaan nukleasi retakan lesu pada kira-kira 188800 kitaran dan kemudian mencapai nilai tertinggi masing-masing pada 1.5×10^{-7} dan 7.1×10^{-8} mm/kitaran apabila retak antara muka mula menjadi semakin cepat selepas 284700 kitaran lesu bagi beban lesu lentur mod campuran. Model yang dibangunkan akan memberi manfaat kepada pelbagai industri, termasuk aeroangkasa, automotif, dan maritim, yang melibatkan reka bentuk prestasi struktur, ramalan kebolehpercayaan, lanjutan hayat dan penyiasatan kegagalan struktur lamina komposit CFRP.

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LIST OF ABBREVIATIONS

AFP	-	Automated Fiber Placement
ASTM	-	American Society for Testing and Materials
ATL	-	Automated Tape Layup
CDM	-	Continuum Damage Mechanics
CFRP	-	Carbon Fiber Reinforced Plastic
CZM	-	Cohesive Zone Model
DCB	-	Double Cantilever Beam
DM	-	Damage Mechanics
ENF	-	End Notched Flexure
FE	-	Finite Element
FRP	-	Fiber Reinforced Plastic
HLU	-	Hand Lay Up
LEFM	-	Liner Elastic Fracture Mechanics
MMF	-	Mixed Mode Flexure
RFI	-	Resin Film Infusion
RTM	-	Resin Transfer Molding
RVE	-	Representativ Volume Element
SERR	-	Strain Energy Release Rate
SIF	-	Stress Intensity Factor
UD	-	Uni-Directional
UHMW	-	Ultra-High Molecular Weight
UMAT	-	User Material
VCCT	-	Virtual Crack Closure Technique
VIP	-	Vacuum Infusion Process
X-FEM	-	Extended Finite Element Method

LIST OF SYMBOLS

a	-	Crack Length
D	-	Damage Parameter
D_f	-	Interlaminar Damage due to Property Degradationa
D_e	-	Interlaminar Damage due to Energy Dissipation
E	-	Lamina Stiffness/Elastic Modulus
k	-	Interface Penalty Stiffness
L	-	Span Length
n	-	Number of Cycles
N_f	-	Number of Cycles to Failure
S_0	-	Intermalminar Shear Strength
T_0	-	Interlaminar Tensile Strength
X_T	-	Longitudinal Tensile Strength (Lamina)
Xc	-	Longitudinal Compressive Strength (Lamina)
Y_T	-	Transverse Tensile Strength (Lamina)
Yc	-	Transverse Compresive Strength (Lamina)
σ_a	-	Amplitude Component of Normal Stress
σ_m	-	Mea Component of Normal Stress
τ_a	-	Amplitude Component of Shear Stress
τ_m	-	Mean Component of Shear Stress
τ_{res}	-	Resultant shear stress
δ	-	Relative Displacement
Θ	-	Reference Stress Term
κ	-	Stress Ratio
ν	-	Poisson Ratio
χ	-	Life Parameter

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Fiber-reinforced polymers (FRP) composite laminates are widely used in advanced structural load-bearing applications where a high strength-to-weight ratio, and high stiffness are desirable. In addition, the laminates offer design flexibility in achieving optimum directional properties. Example of the applications include aerostructures such as fuselage and spoilers, skin of wind turbine blades, automobile body and floor structures, and pressure vessels. Typical operating load of these structures consists of both quasi static and fatigue loading conditions. The applied load of these structures is carried by the laminas and transferred across the interfaces of the laminates. The relatively low interlaminar strength and toughness have been observed to cause interface delamination, particularly under the fluctuating stresses [1]. The presence of harsh operating environment, such as high humidity and temperature further accelerates the damage and failure process of the material.

Such damaging scenarios of the operating conditions affect the reliability of the FRP composite laminate structures. Consequently, a robust, yet accurate interlaminar fatigue damage model is indispensable as tool for thorough understanding of the mechanics of deformation and failure of the material, and for the reliability assessment exercises and fatigue life prediction of the laminated composite structures. FRP composite laminate structures, such as aircraft fuselage and spoilers, and wind turbine blades, are constantly subjected to fluctuating load, in addition to sustaining their own mass. The fluctuating load cycles induce fatigue damage that evolves over the operating lifetime of the structure. The different types of fatigue damage, including interlaminar fatigue, and laminar tensile fatigue contributes to the damage leading to premature failure of the material. Static damage only occurs when the stress exceeded the threshold level for damage initiation. In addition, the static part of the fluctuating stress influences the resulting material damage evolution process through the mean stress effect. Consequently, the fatigue damage and its predictive model is more significant than the static counterpart.

The relatively high amplitude and mean stress components of the fatigue load cycles have contributed to different modes of failure of FRP composite laminates. These include matrix yielding and cracking, fiber/matrix interface debonding, fiber pulled-out, fiber buckling and fracture, and interface delamination [2]. Interface delamination is the prominent failure mechanism owing to the relatively low interlaminar strength and toughness [3,4]. Matrix cracking in the adjacent lamina has also been observed to cause interface delamination [5,6]. The occurrence of interface delamination has been shown to cause significant degradation in stiffness of the material [7,8]. A 27% drop in the stiffness of carbon fiber-reinforced polymer (CFRP) composite laminates with interface crack has been reported [8].

In addition, a 9% reduction of the flexural modulus is reported for the CFRP composite laminate specimen with a pre-existing interface crack with a length-to-span ratio of 0.25 after enduring 50,000 flexural load cycles [9]. In Mode I crack loading, the growth behavior of the near-threshold interface fatigue cracks in CFRP composite laminates is dominated by matrix cracking and interface delamination [10]. These observations suggest significant susceptibility to failure of the composite structural member resulting from interface delamination. Again, this calls for accurate interlaminar fatigue damage and failure models for structural reliability assessment of FRP composite laminates. To anticipate damage development in the laminated composite structure during service lifetime, fatigue damage models must be adequately developed by adapting the damage mechanics approach.

The degradation of material properties represents the progression of interlaminar damage in FRP composite laminates. However, because of the wide range of FRP laminate design configurations, determining degrading properties alone through testing is impractical. Therefore, modelling behavior in response to the applied load is preferable to predicting material performance during fatigue loading conditions. An accurate interlaminar fatigue damage model can aid in the improvement of FRP composite structure design. Consequently, a robust yet accurate interlaminar fatigue damage model is indispensable for a thorough understanding of the mechanics of deformation and failure of the material and the reliability assessment exercises and fatigue life prediction of the laminated composite structures.

The focus of this study is on representing the interlaminar fatigue damage in the damage-based failure model. This research contributes to developing a damage-based model for interlaminar fatigue of FRP composite laminate structures. The damage-based failure model is integrated into a commercial finite element analysis (FEA) software and employed to examine the interlaminar fatigue damage and failure processes for the reliability assessment in CFRP composite laminates under individual and mixed-mode interface loading conditions.

1.2 Statement of the Research Problem

The damage development in an FRP composite interface during fatigue loading conditions is anticipated in this study using a damage model based on the degradation of material properties. The laminate's weaker interface influences the primary failure mechanism in an FRP composite laminate, the weakest link in FRP composite laminates. Therefore, it is essential to deal with this issue. This research addresses the central question of "*How to develop a validated damage-based interlaminar fatigue model of FRP composite laminates for reliability assessment of the composite structures under the general load conditions*".

1.3 Research Objectives

This study aims to develop a new damage-based interlaminar fatigue life model for FRP composite laminates. The specific objectives are:

1. To establish interlaminar quasi static and residual properties and damage model parameters for CFRP composite laminates through combined experimental-FE approach.

2. To develop a validated damage-based interlaminar fatigue life model for fiber-reinforced polymer (FRP) composite laminates.

3. To quantify the mechanics of brittle interfaces and establish the reliability of CFRP composite laminates in mixed mode fatigue loading conditions.

1.4 Scope of Study

The present study focused on quantifying the mechanics of interlaminar damage process and reliability assessment of CFRP composite laminates and adhered to following scope:

i. The interlaminar fatigue damage model is developed based on UD laminates at the mesoscale. For the extraction of residual properties, data from literature is employed for cyclic loading conditions.

ii. The quasi static tests are conducted in accordance with the ASTM D5528 and ASTM D7905 for Mode I and Mode II respectively, at room temperature and in laboratory air conditions. Only load-displacement data and fracture energy can be obtained from these static tests.

iii. Constant amplitude fatigue loading is assumed for the development of the model. The load cycle-block technique is used to calculate cumulative fatigue damage.

iv. The damage-based model is implemented in the FE software ABAQUS 2017 through a user-written subroutine UMAT to validate the model.

v. 3D elements are used in the FE Model preparation.

1.5 Significance of Study

The degradation of residual fatigue properties dictates the accumulation of interlaminar fatigue damage in the FRP composite laminates. The residual properties are normalized to the quasi static properties to obtain normalized degradations of properties. As a result, without large campaigns of experimental testing, the developed methodology may be generalized to any set of properties for carbon-based FRP composites under varied stress ratios. Furthermore, the methodology can be used for any FRP composite laminate configuration. Developing such a methodology and prediction model will meet industry needs, particularly in lowering the number of experimental tests. Therefore, the developed model will benefit various industries, including aerospace, automotive, and maritime, involved in the structural design for performance, reliability prediction, life extension and failure investigation of FRP composite laminate structures.

1.6 Thesis Layout

Chapter 1 provides an overview of composite laminates and the issues of simulating and analysing them for the industrial sector. The problem statement, scope, and objectives are then defined. The limitations of this study's scope are being highlighted.

The existing knowledge on general loading of interfaces, cohesive zone model, failure modes of composite laminates and failure process of interfaces under monotonic and fatigue loading, are all covered in Chapter 2.

Chapter 3 elaborates on the research methodology for the current work. A novel interlaminar damage-based fatigue life model based on fatigue properties degradation has been introduced. The basis for obtaining fatigue degradation properties via interrupted fatigue tests is elaborated. A methodology based on a hybrid experimental-computational approach is adopted to determine the interface properties and damage model parameters under quasi static and cyclic loading. The methodology for implementing the damage model into FE software and its validation through case studies is introduced.

The explanation for the development of the interlaminar fatigue damage model and results for monotonic loading of interface are presented in Chapter 4. The load cycle block approach and its associated features are explained in this chapter.

The validation outcomes of the model, which were demonstrated in the FE simulation for selected cases, are detailed in Chapter 5. The model is validated for individual Mode I and Mode II loading conditions.

Chapter 6 elaborates on the capabilities of the newly developed interlaminar fatigue damage model to quantify the mechanics of interlaminar damage process of CFRP composite laminates in mixed mode loading conditions.

The key conclusions related to the methodology and damage model are detailed in Chapter 7. In this chapter, additional work was suggested to expand the knowledge base in this research area.

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LIST OF PUBLICATIONS

1. Khan, S.A., Wong, K.J., Sung, A.N., Johar, M. and Tamin, M.N., 2022, October. Characterization of Interface Damage of Fiber-Reinforced Polymer Composite Laminates Under Mode I Loading. In *AIP Conference Proceedings* (Vol. 2676, No. 1, p. 050003). AIP Publishing LLC, **https://doi.org/10.1063/5.0112714**

2. Khan, S.A., Wong, K.J., Koloor, S.S.R., Yidris, N., Yusof, A.A.M., Januddi, M.A.F.M.S., Tamin, M.N., and Johar, M., 2022, December. Strain Rate Effect on Mode I Debonding Characterization of Adhesively Bonded Aluminum Joints. Journal of Processes, **https://doi.org/10.3390/pr11010081.**

3. Khan, S.A., Wong, K.J., Koloor, S.S.R., Siebert, G., and Tamin, M.N., 2023, January. A Fatigue Model to Predict Interlaminar Damage of FRP Composite Laminates Subjected to Mode I Load, Journal of polymers, **https://doi.org/10.3390/polym15030527**