FATIGUE FAILURE ANALYSIS OF CFRP COMPOSITE LAMINATES USING MODIFIED STIFFNESS DEGRADATION METHOD

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by

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In the name of Allah, the most beneficent and the most merciful

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LIST OF SYMBOLS

%	Percent
$\bar{E}_{1b,2b}$	Inverse moduli of elasticity
$\bar{\varphi}_4$	Deplanation function
h_i	Thickness of lamina
h_r	Thickness of the panel of the corresponding r-th panel
h_t	Thickness of laminate
B_{pq}	Stiffness coefficients in terms of the laminate
E_{x_n}	Modulus of elasticity at n^{th} load cycle
E_1	Young's modulus in longitudinal direction
E_2	Young's modulus in transverse direction
E_o	Initial or undamaged Young's modulus
E_x, G_{xy}	Stiffness component for laminate structure
G_{xy_n}	Shear modulus at n^{th} load cycle
G_{12}	Shear modulus in 1-2 plane
b_{pq}^{i}	Stiffness coefficients in terms of the lamina
ν_{12}	Poisson's ratio
φ_i	Fiber orientation angle
$<$	Less than
$=$	Equal
$\neq$	Not-equal
$>$	Greater than
$\pm$	Plus-minus

$\approx$	Almost equal
$\equiv$	Identical
$^\circ$	Degree
1,2,3	Dimensional coordinates with respect to width, height, and length of lamina
GPa	Giga pascal
MPa	Mega pascal
R	Stress ratio
γ	Gamma (shear strain)
ε	Epsilon (strain)
θ	Theta
σ	Sigma (stress)
τ	Tau (shear stress)
ω	Double of area of the analyzed contour
A	Surface area
E	Young's modulus (modulus of elasticity)
km	Kilometres
m	Meter
mm	Millimetres
n	Number of cycles
nm	Nanometres
x, y, z	Dimensional coordinates with respect to the width, height, and length of the box beam
μm	Micrometers

LIST OF ABBREVIATIONS

2D	Two-dimensional
AS4/3501-6	Carbon epoxy composite
AS4/PEEK	Polyether ether ketone
BDID	Barely detectable impact damage
BEM	Boundary element method
BVID	Barely visible impact damage
CDM	Continuum damage mechanics
CFRP	Carbon fiber-reinforced polymer
CNT	Carbon nanotube
DQM	Differential quadrature method
FDM	Finite difference method
FEA	Finite element analysis
FEM	Finite element method
FRP	Fiber-reinforced polymer
MAPLE	Multi-paradigm programming language
NDT	Non-destructive technique
RPIM	Radial point interpolation method
SDM	Simplified direct method
S-N	Stress-failure
T300/5280	Graphite epoxy composite
XFEM	Extended finite element method

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ANALISIS KEGAGALAN KELESUAN LAMINAT KOMPOSIT CFRP MENGGUNAKAN KAEDAH DEGRADASI KEANJALAN YANG DIUBAHSUAI

ABSTRAK

Struktur lamina komposit gentian karbon bertetulang polimer (CFRP) telah digunakan secara meluas dalam pelbagai aplikasi industri disebabkan oleh sifat mekanikalnya yang sangat baik. Dalam kajian ini, degradasi kekakuan pada lamina komposit CFRP yang tertakluk kepada keadaan beban kitaran telah dianalisis menggunakan dua model analitik iaitu model ubah suai Peringkat I dan model ubah suai dari Peringkat I hingga Peringkat III. Kedua-dua model ini dibangunkan berdasarkan model asal oleh Lurie dan Minhat, yang kemudiannya diubah suai dengan penambahan beberapa parameter khusus bagi meningkatkan ketepatan ramalan antara hasil analitik dan data eksperimen. Penggunaan model keanjalan linear membolehkan sifat mekanikal bahan CFRP ditentukan sebagai input kepada model ubah suai tersebut. Model ubah suai Peringkat I digunakan untuk menganalisis degradasi kekakuan semasa peringkat awal kerosakan, iaitu semasa berlakunya retakan matriks. Lengkung degradasi kekakuan yang diperoleh secara analitik kemudiannya dibandingkan dengan lengkung hasil eksperimen. Seterusnya, model ubah suai dari Peringkat I hingga Peringkat III diaplikasikan untuk menilai degradasi kekakuan yang merangkumi keseluruhan proses kerosakan bahan, iaitu daripada peringkat awal hingga ke peringkat akhir (seperti kerosakan gentian). Bagi menilai ketepatan kedua-dua model ini, peratusan perbezaan antara hasil analitik dan data eksperimen telah dikira untuk ketiga-tiga konfigurasi lamina CFRP yang dikaji, iaitu $[0,\pm45]_s$, $[0,90]_{2s}$, dan $[0,90,\pm45]_s$. Secara keseluruhan, hasil kajian menunjukkan bahawa

model ubah suai Peringkat I memberikan ketepatan ramalan yang paling tinggi apabila dibandingkan secara langsung dengan data eksperimen, terutamanya bagi peringkat awal kerosakan. Kesederhanaan struktur model serta kesesuaiannya dengan data eksperimen menjadikan ia sangat berkesan dan boleh dipercayai untuk meramalkan kerosakan akibat keletihan pada peringkat awal hayat struktur. Walau bagaimanapun, untuk memberikan gambaran yang lebih menyeluruh terhadap tingkah laku degradasi kekakuan sepanjang hayat perkhidmatan bahan, model ubah suai dari Peringkat I hingga Peringkat III menawarkan kompromi yang baik antara ketepatan ramalan dan keupayaan menggambarkan keseluruhan proses kerosakan. Oleh itu, pemilihan model yang sesuai haruslah bergantung kepada keperluan aplikasi. Bagi tujuan penilaian jangka pendek atau pemantauan kerosakan awal, model Peringkat I adalah paling sesuai. Sebaliknya, bagi ramalan jangka panjang yang melibatkan penilaian ketahanan struktur secara keseluruhan, model dari Peringkat I hingga Peringkat III boleh digunakan kerana ia menunjukkan tahap ketepatan dan keterangkuman yang hampir menyamai data eksperimen.

FATIGUE FAILURE ANALYSIS OF CFRP COMPOSITE LAMINATES USING MODIFIED STIFFNESS DEGRADATION METHOD

ABSTRACT

Carbon fibre reinforced polymer (CFRP) composite laminates have been extensively utilised in various industrial applications due to their outstanding mechanical properties. In this study, the stiffness degradation behaviour of CFRP laminates subjected to cyclic loading conditions was analysed using two analytical models: the Modified Stage I model and the modified Stage I to Stage III model. Both models were developed based on the original model proposed by Lurie and Minhat, and subsequently enhanced through the introduction of several specific parameters to improve the predictive accuracy between analytical results and experimental data. The application of a linear elastic model facilitated the determination of the mechanical properties of the CFRP materials, which served as input parameters for the modified models. The modified Stage I model was employed to evaluate stiffness degradation during the initial damage phase, particularly matrix cracking. The resulting analytical stiffness degradation curves were compared with the experimental curves. Subsequently, the modified Stage I to Stage III model was applied to assess the full spectrum of stiffness degradation, encompassing damage evolution from the initial stage to the final stage, including fibre breakage. To evaluate the accuracy of both models, the percentage difference between the analytical model and experimental data was calculated for all three CFRP laminate configurations investigated in this study, namely $[0,\pm45]_s$, $[0,90_2]_s$, and $[0,90,\pm45]_s$. Overall, the findings indicate that the Modified Stage I model offers the highest predictive accuracy when directly compared with

experimental data, particularly for early-stage damage. The simplicity of its formulation and its strong agreement with empirical results render it highly effective and reliable for predicting fatigue-induced damage in the initial service life of the structure. However, to provide a more comprehensive representation of the material's stiffness degradation behaviour throughout its service life, the modified Stage I to Stage III model presents a balanced compromise between predictive accuracy and the ability to capture the complete damage progression. Therefore, the selection of the most appropriate model should be guided by the intended application. For short-term assessments or early-stage damage monitoring, the Stage I model is the most suitable. Conversely, for long-term durability predictions involving comprehensive structural integrity evaluation, the Stage I to Stage III model is more appropriate, as it demonstrates a high level of accuracy and inclusiveness that closely aligns with experimental observations.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Heterogeneous engineering materials have existed in nature for millions of years. Composite materials are a prime example of heterogeneous engineering materials created by combining two or more different materials, which are known as the matrix and reinforcing materials, to produce a new material with good mechanical properties. Composite materials are extremely versatile materials that are formed by combining distinct constituents with different physical and chemical properties to form a new material that exhibits excellent mechanical properties compared to conventional materials. The matrix material acts as a binder and surrounds the reinforcement, providing support, protection, and transferring loads between the reinforcement materials.

Among the popular composite materials is carbon fiber reinforced polymer, known as CFRP. Carbon fiber reinforced polymer (CFRP) has emerged as a prominent material in various industries due to its exceptional mechanical properties, low weight, corrosion resistance, and fatigue endurance. This composite material is formed by combining carbon fibers as a continuous fiber reinforcement phase with a polymer matrix phase, typically epoxy resin. The carbon fibers, which constitute the reinforcement, are highly crystalline and possess a high aspect ratio (length-to-diameter ratio). This elongated structure imparts exceptional tensile strength, stiffness, and modulus to the composite. The matrix also provides the composite with its bulk properties, such as density and thermal conductivity.

The microstructure of CFRP is influenced by several factors, including fiber orientation, fiber volume fraction, and matrix properties.

Two primary configurations commonly employed in CFRP structures are sandwich and laminate structures. CFRP with the composite laminate structure typically consists of multiple layers, where each layer is composed of a combination of reinforcing fibers and a matrix material. These layers are stacked together and bonded to form a laminate structure (Hull & Clyne., 1996; Norisam & Abdullah., 2019). CFRP laminate materials are commonly used in aerospace, automotive, and marine industries for components such as aircraft wings, car body panels, boat hulls, and others. Figure 1.1 shows the Market expansion of CFRP materials in 2022 in the advanced industry, including wind turbines, sports, automotive, and others.

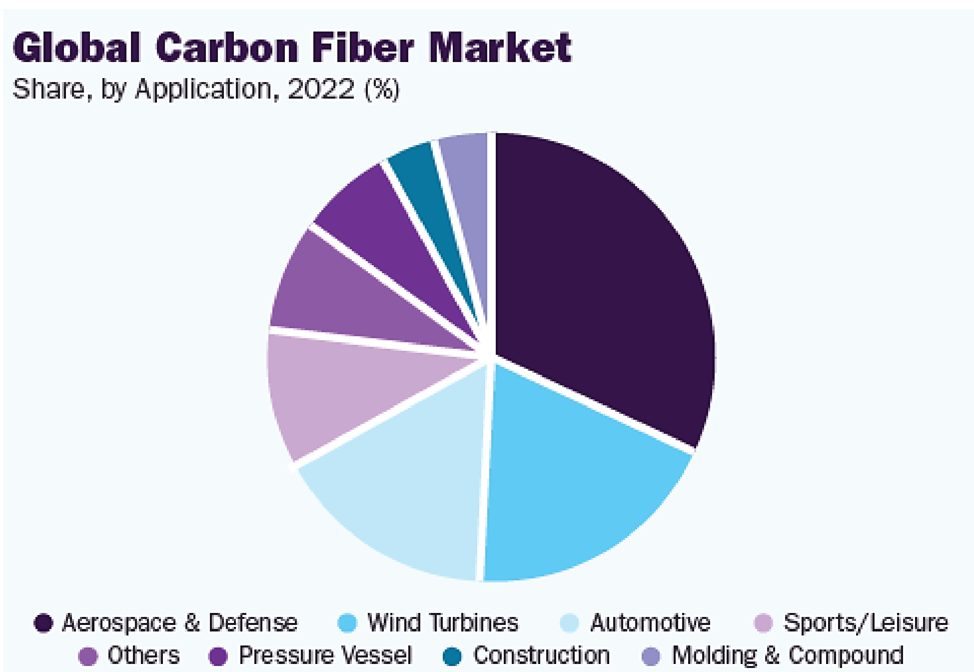

Figure 1.1. Market expansion of CFRP materials in the advanced industry (Global Carbon Fiber Market Analysis Report By Raw Material, 2022).

The orientation of the fibers within each ply has a crucial impact on the mechanical behavior of CFRP composite laminates. Due to their different fiber orientation, a number of typical laminate structures, including angle ply, cross-ply, balanced, symmetric, and asymmetric, exhibit different mechanical properties. Different fiber orientations can result in varied mechanical properties in CFRP composite laminate materials. The common configurations used in composite laminate lay-ups for aircraft component manufacturing, as well as in other engineering applications, are [0/+45/-45/90] and [0,90]. These configurations are commonly used in aerospace applications because they offer good mechanical properties, such as stiffness and strength (Mouritz., 2012). The selection of the orientation of the fiber in CFRP composite laminate structure lay-ups for aircraft applications is a critical aspect of the design process. Engineers carefully consider various factors such as the specific requirements of the component, anticipated load conditions, desired mechanical properties, weight constraints, manufacturing feasibility, and cost-effectiveness. Figure 1.2 shows an example of CFRP composite laminate materials applied in the part of the aerospace body in the aerospace industry.

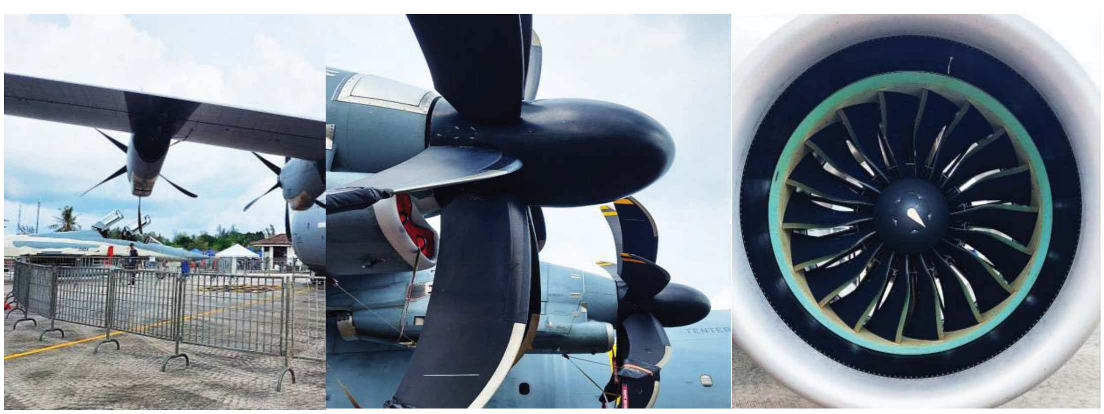

Figure 1.2. Application of composite materials in the aerospace industry.

However, under various loading conditions, such as fatigue loading, the mechanical properties of the CFRP composite laminate materials, including strength and stiffness, can be reduced and affect the mechanical properties of these materials. Fatigue loading is an important factor to consider when developing and applying composite laminate materials since it has a substantial impact on the performance and lifespan of the composite laminate materials, including the CFRP materials. This load is known as a repeated application of stress to a material, which can lead to failure even if the maximum stress is below the ultimate tensile strength of the material. In CFRP composite laminate materials, fatigue loading can be particularly problematic to the mechanical properties of the composite laminate materials, which is it can reduce the strength, stiffness and damage accumulation process of the CFRP composite laminate materials. Fatigue loading can lead to a decrease in the stiffness of these types of materials, making them more susceptible to deformation under load and increasing the risk of failure in the CFRP composite materials structure. The repeated stress cycles can cause damage to accumulate in the composite laminate material, leading to progressive degradation of its mechanical properties.

Fatigue damage in CFRP composite laminate materials is a progressive process that can lead to material degradation and failure under repeated cyclic loading. This process can be divided into three primary stages, namely matrix cracking (stage I), delamination (stage II), and fiber fracture (stage III). These three types of damage can occur individually or in combination, and their severity can vary depending on the specific material, loading conditions, and environmental factors. To obtain a comprehensive understanding of damage evolution in CFRP composite laminates, it is often necessary to combine multiple methods. Experimental methods can provide valuable data on damage initiation and propagation, while analytical and numerical methods can help to interpret and predict damage behavior. As is known, CFRP fatigue damage is a gradual process that triggers material weakening and ultimately destruction when subjected to fatigue loads. The development of damage mechanisms in CFRP composite laminate materials is a complicated process. One of the factors contributing to this complexity is the heterogeneity and anisotropy of the fiber-reinforced composite laminate materials. Figure 1.3 shows the damage mechanism of CFRP composite materials under fatigue loading conditions. This figure (Blythe et al., 2022) shows the three stages of the damage evolution process under fatigue load for the CFRP composite materials.

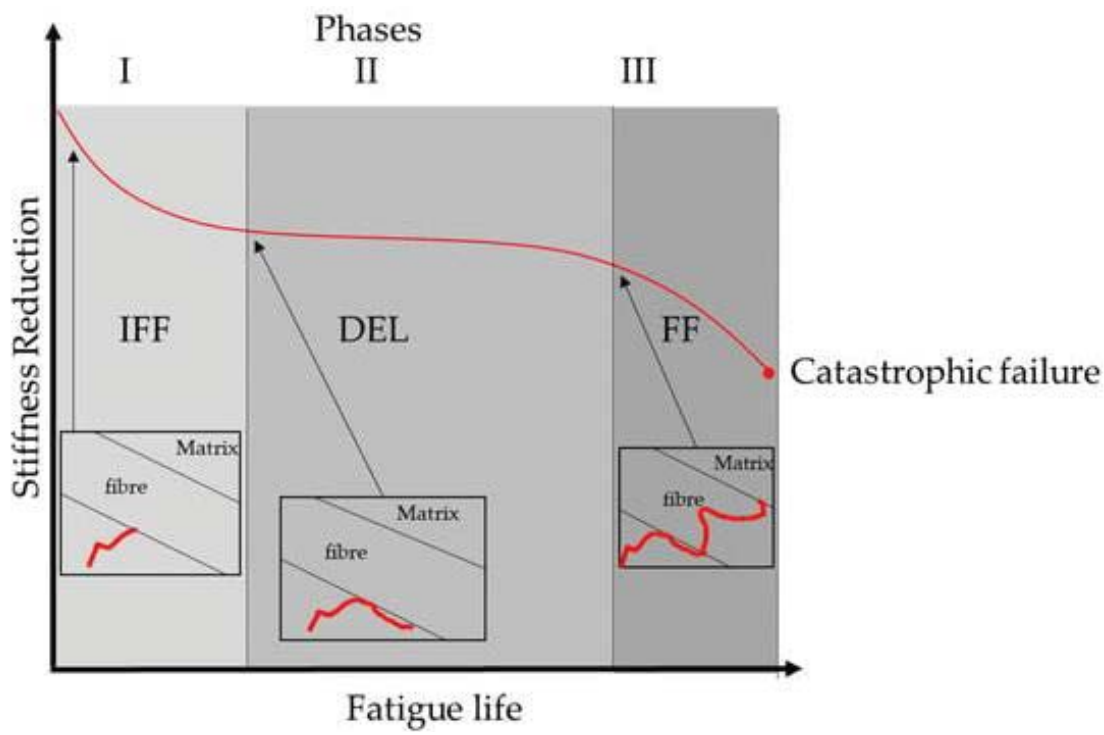

Figure 1.3 Damage mechanism of CFRP composite materials under fatigue loading conditions (Blythe et al., 2022).