DAMAGE EVOLUTION IN CARBON FIBER-REINFORCED POLYMER (CFRP) COMPOSITES UNDER SHEAR FATIGUE LOADING

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To my beloved mom, dad, my brothers, and my lovely fiancée, Sara, who offered me unconditional love and support throughout the course of this thesis

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ABSTRACT

Composite structures present high strength, low weight and design flexibility in terms of fiber orientation and number of plies and used vastly in advanced and modern applications. Among them, carbon fiber-reinforced polymer composites (CFRP) are used widely in aeronautic and automotive industries in which components are subjected to different loading types and this will double the necessity of investigation on fatigue and fracture analysis using damage mechanics concepts. The reliability of structures made of composites, depends on continual process of damage initiation and propagation. In the current research, a specific CFRP composite is being tested and finite element simulated under monotonic loading and subsequent cyclic loading with dominant shear stress along its length. The specimen is designed so that the damage development can be tracked easily on the localized interface. The 3ENF experiments and FE simulation have been used simultaneously to investigate the damage under mode II fracture loading condition. Damage model used is cohesive zone model (CZM) which is developed and validated before. The key contribution of the current research is to present and describe a concept to extend current damage model to account for material behavior in cyclic loading in terms of development of damage. Damage is interpreted as degradation of penalty stiffness in normal and shear directions. Monotonic results showed that the CZM-based FE model is correlated well with experimental results and based on the experimental-computational approach, CZM parameters can be obtained and damage model will be characterized so that finite element method can be validated and stress and deformation analyses using FE results are feasible. The cyclic tests are also conducted for different load amplitude and number of cycles and necessary results are extracted to monitor and investigation on degradation in material stiffness and fracture energy as an effect of fatigue phenomenon and also being utilized to obtain presented fatigue damage model and as guidance and useful resource for future finite element simulation applying proper user-written subroutine into FE package.

ABSTRAK

Struktur komposit memberikan kekuatan yang tinggi, berat yang rendah dan reka bentuk yang fleksibel terutamanya dari segi orientasi gentian dan bilangan lapisan gentian dan digunakan secara meluas dalam aplikasi maju dan moden. Di antara kebanyakkan komposit, komposit polimer bertetulang gentian karbon (CFRP) digunakan secara meluas dalam industri aeronotik dan automotif. Di mana, komponen ini dikenakan beban yang berbeza-beza dan ini akan menggandakan keperluan dalam analisis kelesuan dan analisis patah menggunakan konsep mekanik kerosakan. Kebolehpercayaan struktur yang diperbuat daripada komposit ini bergantung kepada proses pemulaan dan perebakan kerosakan. Kajian pada masa kini, komposit CFRP tertentu telah diuji dan simulasi finite element telah dijalankan di bawah beban monotonik dan beban kitaran berikut dengan tegasan ricih mendominasi panjangnya. Spesimen yang digunakan direka supaya kerosakan dapat dikesan dengan mudah pada antara muka setempat. Eksperimen 3ENF dan simulasi FE telah digunakan secara serentak untuk memeriksa kerosakan di bawah beban keadaan patah pada mod II. Model kerosakan yang digunakan ialah cohesive zone model (CZM) yang telah dibangunkan dan telah disahkan. Sumbangan utama penyelidikan ini adalah untuk menerangkan satu konsep untuk melanjutkan kerosakan model semasa dengan mengambil kira perilaku bahan di dalam beban berkitar dari segi pembangunan kerosakan. Kerosakan ditafsirkan sebagai penurunan kekakuan penalti pada arah normal dan ricihan. Keputusan monotonik menunjukkan model CZM berasaskan FE berhubung baik dengan keputusan eksperimen. Berdasarkan pendekatan eksperimen-pengiraan, parameter CZM boleh diperolehi dan model kerosakan boleh dikenalpasti. Oleh itu, kaedah FE boleh disahkan, tegasan dan pembentukan analisis menggunakan keputusan FE dapat dilakasanakan. Ujian kitaran dilaksanakan untuk beban amplitude yang berlainan dan bilangan kitaran dan keputusan yang diperlukan untuk memantau dan memeriksa penurunan di dalam kekakuan bahan dan tenaga patah sebagai kesan fenomena lesu dan juga digunakan untuk mendapatkan model kelesuan sebagai panduan dan sumber yang diperlukan untuk simulasi FE akan datang dengan menggunakan subrutin FE yang sesuai ke dalam perisian FE.

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LIST OF SYMBOLS

a - Crack length

A - Area

b - width

D - Damage variable

E - Young`s modulus of elasticity

f - frequency

G - Shear modulus

G_c - Critical energy release rate

K_n - Penalty stiffness in normal direction

K_s - Penalty stiffness in shear direction

K_s^f - Penalty stiffness in shear direction, fatigue loading

L - length

N - Number of cycles

N_f - Fatigue life

N_0 - Nominal stress in normal mode

P - Load

R - Load ratio

S - Maximum interfacial strength in shear mode

S_0 - Nominal stress in shear mode

S_a - Alternating stress

S_m - Mean stress

S_{max} - Maximum cyclic load

S_{min} - Minimum cyclic load

t - thickness

V_f - Fiber volume fraction

α - Delamination length

β - Mode mixity

δ - Deflection , separation

δ_0 - Relative displacement at damage onset

δ_f - Relative displacement at fracture

δ_m - Total mixed-mode relative displacement

δ_{shear} - Tangential displacement

ΔS - Stress range

ϕ - Diameter

η - Power at B-K criterion

ν - Poisson ratio

σ_c - Composite normal strength

σ_R - Residual strength

τ - Shear stress, traction force

CHAPTER 1

INTRODUCTION

1.1 Introduction

In this chapter, the background of the study and some discussions on key issues relating to damage mechanics of advanced composite structures, under cyclic loading condition will be presented and briefly described. Moreover, the finite element method as a key numerical procedure to study the behavior of material during evolution of damage under shear stress will be shortly discussed. Subsequently, the objectives of the study will be either presented or followed by a discussion on the scope and significance of the study. The chapter ends with a description of the framework and supports exploited in this study and the operational definition.

The current research will focus on modeling and finite element (FE) simulation of a specific carbon fiber reinforced polymer (CFRP) with specific number of plies and fiber orientation with pre-existing crack and in three point flexural cyclic loading condition and tries to predict the dominant damage mechanisms and evolution of damage in such situations. The FE simulation should then validated with real-world conditions, therefore a systematic experimental procedure will be conducted and the results of both numerical modeling and simulation and also experimental data will be compared with each other to investigate on accuracy and reliability of numerical method.

1.2 Background of the study

The increasing use of fiber-reinforced materials, especially carbon fiber-reinforced plastics, for load-bearing components which may be subjected to vibratory conditions, such as in aerospace applications, necessitates knowledge of the fatigue behavior of these materials. Research into the fatigue response of fiber composites has been carried out since the materials themselves first began to be a subject of serious study. Some of the first papers on the fatigue behavior of glass-reinforced plastics, for example, were published in the USA by Boller in the 1950s and 60s, and shortly after this Owen and his collaborators at Nottingham University in the UK were reporting the results of work on early carbon-fiber reinforced plastics (CFRPs).[1]

Unlike metals, composite materials are inhomogeneous (on a gross scale) and anisotropic. They accumulate damage in a general rather than a localized fashion, and failure does not always occur by the propagation of a single macroscopic crack. The micro-structural mechanisms of damage accumulation, including fiber breakage and matrix cracking, debonding, transverse-ply cracking, and delamination, occur sometimes independently and sometimes interactively, and the predominance of one or the other may be strongly affected by both materials variables and testing conditions.

1.2.1 Cohesive zone model

The Cohesive zone Model (CZM) offers an alternative way to view failure in materials or along material interfaces. It is a phenomenological model instead of an exact physical representation of material behavior in the fracture process zone, where distributed micro cracking or void formation takes place (Atkinson [2]). The original proposal of the strip yield zone model of Dugdale [2] idealized the plastic region as a narrow strip extending ahead of the crack tip, and a relation is obtained between the extent of plastic yielding and external load applied. This concept has been regarded as a cohesive zone type model with the strip yield zone treated as a cohesive zone. Based on the underlying atomic nature of the fracture process, Barenblatt [2] assumes a nonlinear cohesive force to be distributed over a sufficiently large zone (relative to atomic dimensions) along the crack plane instead of infinitesimally concentrated along a line. Later applications have related the cohesive zone to the plastic zone or the process zone. Despite various definitions of the cohesive zone, the physical meaning is still up to individual understanding.

1.2.2 Composite material

According to the definition a composite consists of two or more chemically distinct materials which when combined have improved properties over the individual materials. Composite materials have advantageous over metals such as high strength, light weight, design flexibility, consolidation of parts etc. Advanced composite materials are finding increasing application in aerospace, automotive, marine and many other industries due to the advantages in performance, structural efficiency and cost they provide. Composite structures have different classifications, such as Particle-Reinforced, Fiber-Reinforced and Structural composites. Form these categories; fiber-reinforced composites have wide range of application in modern and advanced structures. Carbon Fiber-Reinforced Polymer (CFRP) composites are commonly employed in modern structural application such as aircraft wing, rotor blades, and automobile chassis.

1.2.3 Finite element method

The finite element method (FEM) is a numerical method seeking an approximated solution of the distribution of field variables in the problem domain that is difficult to obtain analytically. It is done by dividing the problem domain into several elements. Known physical laws are then applied to each small element, each of which usually has a very simple geometry. A continuous function of an unknown field variable is approximated using piecewise linear functions in each sub-domain, called an element formed by nodes. The unknowns are then the discrete values of the field variable at the nodes. Next, proper principles are followed to establish equations for the elements, after which the elements are ‘tied’ to one another. This process leads to a set of linear algebraic simultaneous equations for the entire system that can be solved easily to yield the required field variable.[3]

1.3 Statement of the problem

Simply supported laminated composite specimen under three point flexural cyclic loading is considered. This laminate can be generally in any type of angle-plies or cross-plies. The task is to investigate the process of damage first in static and then under cyclic flexural loading. The investigation should be done on how the damage initiates and will propagate in composite laminas under fatigue loading condition. The method which is applied is finite element method (FEM). Moreover, simulation on the damage mechanism of specimen will be done with one of the commercial CAE packages, namely, ABAQUS. The method of monitoring damage in composite laminate and its reliability should also be investigated.

1.4 Research Question

- What are the damage mechanisms in CFRP composites under cyclic loading?
- What are the current models for deformation and failure of CFRP under shear fatigue loading condition?
- How can these models be used effectively to result in life prediction of composite part under mentioned load?
- What is the suitable testing procedure for establishing model parameters and damage evolution characteristics?
- How could the FEA be validated for damage tolerance and reliability of CFRP composite component?

1.5 Objective of study

Main research objectives are briefly as below:

- To identify dominant damage mechanisms and their interactions during failure process of CFRP laminates.
- To study and determine damage evolution characteristics of CFRP composites under shear cyclic loading.

- To demonstrate a model for fatigue life prediction of CFRP composites under cyclic loading using finite element method (FEM).
- To validate damage mechanics model for the composite laminate failure.

1.6 Scopes of the study

- Carbon fiber-reinforced polymer (CFRP) composite laminates with specific lay-up will be used as representative material.
- Testing procedure and specimen preparation will be according to ASTM standard (D709-07).
- Damage Model of material will be based on existing damage-based formulations, with some modifications when needed.
- Damage model will be validated using data from standard test procedure on cyclic loading.
- Finite Element software, ABAQUS ver. 6.9 EF will be used for simulation and analysis.

1.7 Importance of the study

Considering that fatigue is the main failure mechanism under cyclic loading and difficulties in fatigue analysis and consequent life prediction since the difference between material properties of constituents and possible fatigue behavior affection of one constituent by the presence of other constituents and also the interfacial regions between the fibers and matrix, it can easily be understood that study in this field is of prime importance and necessary. Many composites are far more sensitive to being loaded in shear than in tension, since their ratio of tensile to shear strength is high (20 is typical for CFRP). Therefore a unified approach should account for various damage and fracture modes in the design phase with the aid of numerical modeling and validation testing of the composite sample coupons.

This project proposes the development of a framework for establishing CFRP composite laminates behavior under cyclic loading conditions. The benefit of the extended framework is visible in providing guidelines on interpretation of data for conditions other than those under which they were obtained. Reliability test data generated through the proposed experimental program is indispensable during both initial material selection and detailed engineering design stage of CFRP composite structures. The outcome of the proposed research; a validated unified methodology for assessing composite fatigue failure process by the various damage mechanisms could be directly employed for predicting structural integrity of composite parts in service and under cyclic loading. This proposed project is in-line with industry-led R&D theme in aero composite structural design and development under university-industry collaboration with the establishment of Aero structure Manufacturing Innovation Center (AMIC) in Malaysia. The significance of composite research is reflected in a continual increase of EADS/Airbus average annual sourcing in Malaysia from USD 50m in 2004-2007 to USD 120m in 2010-2012.

1.8 Research approach

After that the problem is defined and the research questions, objectives, and project scope are well understood, the research will begin by referring to and exploring in previous works and other researchers` findings, firstly to get sufficient information and data about the peer works and also finding the less considered aspects of our interest.

Next, the research will be continued by establishing a systematic methodology for solving the research problem which needs to be evaluated and after that being validated.

Based on the specified methodology, the experimental and finite element simulation and analysis will be conducted and when the numerical study is validated and its accuracy is sufficient for our purpose, the results will be presented with deep analysis.

1.9 Structure of research

In chapter 1, the background of the study, statement of the problem, objectives, research questions, significant of study, scope of project and research approach are described.

In chapter 2 review of the literature related to damage mechanics of composite structures and also fatigue in fiber reinforced composites as well as introduction to cohesive zone model will be covered with more details.

In Chapter 3 the author will present and evaluate the methodology used within the research. The used material, experimental and numerical techniques, specimen geometry, data acquisition approaches, theoretical frameworks used in the study, preliminary results and many more will be covered and discussed.

Chapter 4 will cover the key research findings and present detailed discussions on results with the aid of description and interpretation of acquired data, comparison and data analysis that can come to main research conclusions.

Finally, in chapter 5 conclusion and summary of resultswill be presented briefly

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