EVALUATION OF DAMAGE-BASED MATERIAL MODELS FOR CARBON FIBER-REINFORCED POLYMER COMPOSITE LAMINATE UNDER MIXED-MODE BENDING

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To my beloved father, mother, brother and sister, and my lovely friend, Hengameh,
who offered me
unconditional love and support throughout the course of this thesis…

Seek the science that unties for you this knot.

Seek it as long as there's life in you still to be sought.

Leave that nothing that looks like it's something;

Seek that something that looks like it's nothing.

Rumi, Persian Poet
13th-Century

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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 necessity of investigation on 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 which creates Mode I, Mode II and Mixed Mode (I&II) of fracture. The specimen is designed and fabricated by Institute of Automotive and Transport Engineering (ISAT) and the damage development can be tracked easily on the localized interface. The Double Cantilever Beam (DCB), End Notched Flexure (ENF) and Mixed Mode Flexure (MMF) experiments and FE simulation have been used simultaneously to investigate the damage under Mode I, Mode II and Mixed Mode (I &II) of fracture loading condition. Although, Damage model used is cohesive zone model (CZM) which is developed and validated before. 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.

ABSTRAK

Bahan struktur bahan rencam mempunyai sifat kekuatan yang tinggi, ringan dan fleksibel dalam rekabentuk terutamannyaa pada orientasi gentian dan jumlah lapisan dan ianya banyak digunakan dalam aplikasi moden. Diantara jenis bahan rencam, polimer bertetulangkan gentian karbon banyak digunakan secara meluas terutama dalam industri penerbangan dan automotif di mana komponen tersebut dikenakan beban tekanan yang berbeza dan keperluan untuk menganalisis keretakan dengan menggunakan konsep *Damage Mechanics*. Kebolehpercayaan sesuatu struktur yang diperbuat daripada bahan rencam bergantung kepada proses yang berterusan terutamanya di permulaan kerosakan dan perebakannya. Dalam kajian ini, spesifik bahan rencam polimer bertetulangkan gentian karbon (CFRP) telah diuji dan kaedah simulasi kaedah unsur terhingga yang dikenakan beban tanjakan pada keadaan Mod I, Mod II dan Mod Campuran (I&II). Spesimen direka dan dibuat di Institut Kejuruteraan Automatif dan Pengangkutan, justeru perkembangan tahap kerosakan dapat dikesan dengan mudah pada antarafasa setempat.Eksperimen dan simulasi kaedah unsur terhingga pada Rasuk Berganda Julur (DCB), Lenturan Takuk Akhir (ENF) dan Lenturan Campuran Mod (MMF) telah digunakan pada masa yang sama untuk mengkaji kerosakan dalam Mod I, Mod II dan Mod Campuran (I dan II) pada keadaan beban patah. Model kerosakan yang digunakan adalah *cohesive zone model* (CZM) yang mana telah dibangunkan dan disahkan sebelum ini.Keputusan daripada simulasi model *CZM-FE* adalah berkait rapat dengan keputusan eksperimen dengan menggunakan kaedah eksperimen-perkomputeraan. Parameter CZM juga boleh diperolehi daripada *Damage Model* supaya kaedah unsur terhingga dapat disahkan. Keputusan analisis tegasan dan perubahan bentuk berdasarkan keputusan daripada kaedah unsur terhingga adalah boleh diguna pakai.

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a	-	Crack length
A	-	Area
b	-	Width
D	-	Damage variable
E	-	Young`s modulus of elasticity
G	-	Shear modulus
G_c	-	Critical energy release rate
L	-	length
P	-	Load
S	-	Maximum interfacial strength in shear mode
t	-	Thickness
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
Φ	-	Diameter
η	-	Power at B-K criterion
ϑ	-	Poisson ratio
τ	-	Shear stress, traction force

CHAPTER 1.0

INTRUDUCTION

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 Mixed-mode bending 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 tension and 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 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 Mixed-mode loading condition. 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

Carbon-fiber-reinforced polymer, carbon-fiber-reinforced plastic or carbon fiber reinforced thermoplastic (CFRP, CRP, CFRTP or often simply carbon fiber, or even carbon), is an extremely strong and light fiber-reinforced polymer which contains carbon fibers. it has many applications in aerospace and automotive fields, such as Formula One racing. The compound is also used in sailboats, rowing shells, modern bicycles, and motorcycles because of its high strength-to-weight ratio and very good rigidity. Improved manufacturing techniques are reducing the costs and time to manufacture, making it increasingly common in small consumer goods as well, such as fishing rods, hockey sticks, paintball equipment, archery equipment, tent poles, racquet frames, stringed instrument bodies, drum shells, golf clubs, helmets used as a paragliding accessory and pool/billiards/snooker cues (Koloor et al.).

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 Composite Material

Composite materials (also called composition materials) are materials made from two or more constituent materials with significantly different physical or chemical properties, that when combined, produce a material with characteristics different from the individual components. 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.

1.2.2 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 (Quek and Liu, 2003).

1.2.3 Cohesive Zone Model

The cohesive zone model (CZM) is one of the most modern evolutions in the area of fracture mechanics in which fracture formation is regarded as a gradual phenomenon in which the separation of the surfaces involving in the crack takes place across an extended crack tip, or cohesive zone, and is resisted by cohesive tractions. This method has several advantages in comparison with the conventional methods in fracture mechanics. For illustration, It is able to adequately predict the behavior of uncracked structures, including those with blunt notches or Size of non-linear zone need not be negligible in comparison with other dimensions of the cracked geometry in CZM, while in other conventional methods, it is not so, and, Even for brittle materials, the presence of an initial crack is needed for LEFM to be applicable.

The cohesive zone model (CZM) is widely used in modeling fracture and other failure phenomena in different types of materials. Applications can be found in homogeneous as well as composite materials (Zreid et al., 2013).

1.3 Research Objectives

- To develop finite element (FE) model of carbon fiber-reinforced polymer (CFRP) composite laminates with initial defect under mixed-mode bending (MMB) load.

- To validate and examine available damage-based models for the mixed-mode bending.

1.4 Problem Statement

How an appropriate available damage based can be evaluated to respect the initial defect under Mixed-Mode bending for CFRP?

1.5 Research Scopes

- Review of Finite Element (FE) formation for solid (8-node) element, FE modeling of CFRP composite laminates, continuum damage models, cohesive behavior of interface.

- Review the current status FE simulation of CFRP composite laminates based on damage mechanics approach. This work that composite of Mode I and Mode II loading case was performed by a doctoral candidate at CSMLab.

- Develop FE model of the CFRP composite beam $[0]_8$ with initial interface crack for mixed mode bending test setup. Established characteristic load-deflection curve.

- Perform flexural test on the composite beam specimen using mixed-mode bending (MMB) test setup in accordance to the test standard.

- Validate the FE model with measured load-deflection data. Analysis internal states of displacement, strain and stress in the laminates with respect to damage initiation, propagation and localized fracture.

1.6 Research Questions

- Is it possible to simulate the real Carbon Fiber-Reinforced Polymer (CFRP) in virtual space for predicting the behavior of this material under complex loading?

- How an appropriate available damage based can be evaluated to respect the initial defect under Mixed-Mode bending for CFRP?

1.7 Structure of Research

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

In chapter 2, review of the literature related to damage mechanics of composite structures and also some review on kind of fracture modes in mechanics, especially mixed mode as well as introduction to cohesive zone model will be covered with more details.

In chapter 3, the evaluation of methodology will present. Moreover, the used material, experimental and numerical techniques will be covered.

In chapter 4, the preliminary results and dissection on the results will be discussed.

Finally, in chapter 5 conclusion and summary of preliminary results will be presented briefly.

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