SIMULATION METHODOLOGY FOR FRACTURE PROCESSES OF COMPOSITE LAMINATES USING DAMAGE-BASED MODELS

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To my beloved

Prof. Mohd Nasir, Dad and Mom, my wonderful wife Atefeh, my brother Mustafa, and my sisters Maryam and Masoomeh.

To my friends for their endless love and supports…

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ABSTRACT

Fiber-reinforced polymer composite (FRP) laminates have found increasing use in advanced industrial applications. However, the limited knowledge and validated material models of the failure processes of the laminated composites continue to pose challenges in ensuring reliability and integrity of the structures. This research aims at establishing a validated simulation methodology for fracture assessment of FRP composite laminates. The approach accounts for the failure processes and the associated damage mechanisms through finite element (FE) simulations. The FE model development considers the existence of the physical interfaces between the laminas due to the manufacturing processes. A hybrid experimental-computational approach is developed for systematic implementation of the simulation methodology. Different combinations of the failure modes were observed, including matrix cracking-crushing, fiber/matrix interface debonding, interface multi-delamination, and fiber fracture-buckling. Local material failure is modeled by a damage initiation event followed by the evolution of the damage to fracture. Two types of damage-based models are investigated; the continuum damage model encompassing the multi-damage criteria for the FRP composite lamina and the cohesive zone model for interface delamination. A full derivation of the continuum damage model for the anisotropic material is given and employed for prediction of the damage evolution in the lamina. A series of experiments on CFRP and GFRP composite laminate specimens are conducted to establish the flexural and fracture behaviors of the materials. Complementary 3D FE models of the specimens and test setups are developed. Two different FE-based models, namely the *conventional* and *Prepreg* model, are developed and examined for GFRP and CFRP composites. Results show that accurate prediction of elastic-damage behavior and the progressive damage process in FRP composites depend on the chosen FE-based model of the FRP composite laminates and the damage-based material model used. The flexural test of a 12-ply antisymmetric CFRP composite beam specimen under four-point bending displayed the occurrence of multiple failure events. These include matrix cracking at lamina No. 9 (90^o), and delamination at interfaces No. 8 ($-45^o/90^o$) and No. 9 ($90^o/45^o$). In addition, intralaminar multi-failure events are predicted in lamina No. 1 (-45^o) due to matrix shear and fiber buckling failures. FE simulation of the test predicted an accurate flexural response with less than 4% average error when compared with measured data, along with similar multiple failure zones in the specimen. Damage dissipation energy is used to illustrate the quantity of the overall progressive damage in FRP laminas, interfaces and the laminated composite. The simultaneous use of lamina and interface damage models in the FE simulation of the FRP composite laminate is recommended in view of the occurrence of multiple intralaminar-interlaminar failure modes and fractures under general loading conditions.

ABSTRAK

Penggunaan laminat komposit polimer bertetulang gentian (FRP) dalam industri termaju didapati telah meningkat. Walau bagaimanapun, pengetahuan yang terhad dan model bahan tervalidasi untuk proses kegagalan laminat komposit tersebut terus memberi cabaran dalam memastikan kebolehharapan dan integriti sesuatu struktur. Kajian ini bertujuan untuk menghasilkan suatu metodologi simulasi tervalidasi bagi penilaian patah laminat komposit FRP. Pendekatan ini mengambil kira proses kegagalan dan mekanisme kerosakan yang berkaitan melalui simulasi unsur terhingga (FE). Pembangunan model FE mengambil kira kewujudan lapisan fizikal di antara lamina-lamina yang terhasil dari proses pembuatan. Suatu pendekatan eksperimen-komputeraan hibrid dibangunkan untuk pelaksanaan metodologi simulasi yang sistematik. Gabungan mod kegagalan yang berbeza telah diperhatikan termasuk retak-hancur matrik, lekangan gentian/matrik, berbilang lekangan antara-muka dan ledingann-patah gentian. Kegagalan setempat bahan dimodel oleh kejadian kerosakan permulaan dan diikuti oleh evolusi kerosakan sehingga patah. Dua jenis model berasaskan kerosakan telah disiasat; model kerosakan kontinum yang merangkumi kriteria pelbagai kerosakan untuk lamina komposit FRP dan model zon kohesif untuk lekangan antara-muka. Suatu terbitan penuh model kerosakan kontinum untuk bahan anisotropik telah disediakan dan diguna pakai untuk ramalan evolusi kerosakan dalam lamina. Suatu siri eksperimen ke atas spesimen laminat komposit CFRP dan GFRP telah dijalankan untuk mewujudkan gaya laku lenturan dan patah bahan. Model pelengkap FE 3D untuk spesimen dan tentuatur ujian telah dibangunkan. Dua model FE yang berbeza; iaitu model *conventional* dan *prepreg* telah dibangunkan dan diteliti untuk komposit GFRP dan CFRP. Keputusannya menunjukkan bahawa ramalan tepat kelakuan anjal-rosak dan proses kerosakan yang progresif dalam komposit FRP bergantung kepada model FE yang dipilih untuk laminat komposit FRP tersebut dan model berasaskan kerosakan yang diguna pakai. Ujian lenturan ke atas specimen rasuk komposit CFRP 12-lapis yang antisimetri di bawah beban titik-empat lenturan menunjukkan berlakunya kejadian pelbagai kegagalan. Ini termasuk keretakan matrik pada lamina No. 9 (90^o), dan lekangan pada antara-muka No. 8 ($-45^o/90^o$) dan No. 9 ($90^o/45^o$). Tambahan lagi, kejadian pelbagai kegagalan dalam-lamina diramal berlaku dalam lamina No.1 (-45^o) disebabkan oleh ricih matrik dan kegagalan ledingan gentian. Simulasi FE ujian tersebut meramalkan respon lenturan yang tepat dengan ralat purata kurang daripada 4% berbanding dengan data yang diukur, berserta zon kegagalan yang serupa di dalam specimen. Tenaga pelesapan rosak boleh digunakan untuk menggambarkan kuantiti keseluruhan proses kerosakan yang progresif dalam lamina-lamina FRP, antara-muka dan laminat komposit. Penggunaan serentak model kerosakan lamina dan antara-muka dalam simulasi FE bagi laminat komposit FRP adalah disyorkan memandangkan boleh berlakunya pelbagai mod kegagalan dalam-lamina/antara-lamina dan keretakan di bawah keadaan pembebanan umum.

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LIST OF ABBREVIATIONS

AFR	-	Automated fiber replacement
ASTM	-	American society of testing method
ATL	-	Automated tape laying
CDM	-	Continuum damage model
CFRP	-	Carbon fiber reinforced polymer
CNC	-	Carbon nanocoil
CNF	-	Carbon nanofiber
CNT	-	Carbon nanotubes
CVD	-	Chemical vapor decomposition
CZM	-	Cohesive zone model
DCB	-	Double cantilever beam
DI	-	Damage initiation
DP	-	Damage propagation
DPL	-	Deviation point from linearity
ELS	-	End loaded split
ENF	-	End-notched flexure
FE	-	Finite element
FEM	-	Finite element method
FLF	-	First lamina failure
FRP	-	Fiber-reinforced polymer
GFRP	-	Glass fiber reinforced polymer
GLARE	-	Glass laminate aluminum reinforced epoxy
HME	-	Hypothesis of mechanical equivalence
HSE	-	Hypothesis of strain equivalence
LEFM	-	Linear elastic fracture mechanics
LSL	-	Linear softening law

MBT	-	Modifed beam theory
ML	-	Maximum load
PR	-	Poisson's ratio effect
RFI	-	Resin film infusion
RTM	-	Resin transfer molding
SLSSZ	-	Stable limit of shear stretch zone
SEM	-	Scanning electron microscope
microCT	-	micro computer tomography
VAP	-	Vacuum-assisted Resin process
VIP	-	Vacuum infusion process
WWFE	-	worldwide failure exercises
3D	-	Three-dimensional

LIST OF SYMBOLS

E	-	Young's modulus
ν	-	Poisson's ratio
$\overline{Q}_{ij}$	-	Element of the transformed reduced stiffness matrix
Z	-	Distance from the central line
ε^{o}	-	Strain at $Z = 0$ (center-line of the composite beam)
E_{o}	-	Original material stiffness
$E_{(D)}$	-	Elastic modulus of the material at damaged state
D	-	Scalar damage variable
σ	-	Nominal, true or Cauchy stress tensor
$\hat{\sigma}_{ij}$	-	Effective stress component
$E_{(D)}$	-	Elastic modulus of the structure at damaged state
Y_{C}	-	Normal strength perpendicular to fiber direction under compression loading condition
S_{12}	-	Shear strength
α	-	Shear direction
Y_{T}	-	Normal strength perpendicular to fiber direction under tension loading condition
σ_{22}^{m}	-	Normal stress in 2D kinking frame
τ_{12}^{m}	-	Shear stress in 2D kinking frame
$\overline{\sigma}$	-	Effective normal stress
$\overline{\tau}$	-	Effective shear stress
φ	-	Matrix crack density
ζ	-	Curve fitting parameter
Z_{T}	-	Traction strength along through-thickness of interface
K	-	Curve fitting parameter

k	-	Number of nodes in a lamina
f	-	Number of nodes in one surface of a lamina
h	-	Number of elements through a lamina thickness
n	-	Number of the laminas
K_{Conv}	-	Number of nodes in lcomposite aminate with conventional model
K_{Prepr}	-	Number of nodes in composite laminate with prepreg model
ε_{ij}	-	Normal strain compoinent of strain tensor
γ_{ij}	-	Shear strain compoinent of strain tensor
σ_{ij}	-	Normal stress compoinent of stress tensor
τ_{ij}	-	Shear stress compoinent of stress tensor
ε_i^0	-	Midplane normal strain of composite laminate
γ_{ij}^0	-	Midplane shear strain of composite laminate
K_i	-	Midplane curvature of composite laminate
$f_{(\sigma_{ij})}$	-	Function of stress tensor component
Υ	-	Yield stress of a bar under uniaxial tension load
d_{11}^t	-	Internal damage variable of lamina in fiber direction under tension load
d_{11}^c	-	Internal damage variable of lamina in fiber direction undercompression load
d_{22}^t	-	Internal damage variable of lamina perpendicular to fiber direction under tension load
d_{22}^c	-	Internal damage variable of lamina perpendicular to fiber direction under compression load
X^T	-	Lamina normal strength in fiber direction under tension load
Y^T	-	Lamina normal strength perpendicular to fiber direction under tension load
X^C	-	Lamina normal strength in fiber direction under compression load
Y^C	-	Lamina normal strength perpendicular to fiber direction under compression load
S^L	-	Lamina longitudinal shear strength

S^T	-	Lamina transverse shear strength
G_{XT}	-	Longitudinal tensile fracture energy
G_{XC}	-	Longitudinal compressive fracture energy
G_{YT}	-	Transverse tensile fracture energy
G_{YC}	-	Transverse compressive fracture energy
M	-	Damage effect tensor
$k_{eq.}^{0}$	-	Orginal equivalent stiffness prior to damage initiation
$\delta_{eq.}^{o}$	-	Equivalent displacement at damage initiation
δ_{eq}^{f}	-	Equivalent displacement at failure
σ_{eq}	-	Equivalent stress of failure modes
σ_{eq}^{f}	-	Equivalent stress at failure
C_o	-	Elastic compliance tensor
D_P	-	Damage propagation parameter
G	-	Strain energy release rate
L^c	-	Characteristic length in the reference surface of shell elements
G_C	-	Critical energy release rate
G_T	-	Total energy release rate
G_{DDE}	-	Damage dissipation energy
F_i	-	Force in i^{th} node
u_j	-	Motion of the node j^{th}
T_i	-	Composnent of traction
δ_{Shear}	-	Equivalent relative shear displacement
β	-	Mode mixity in interface material point
G_{Shear}	-	Energy release rate of mixed shear loading in modes II and III
G_I	-	Energy release rate in mode I
G_{II}	-	Energy release rate in mode II
G_{III}	-	Energy release rate in mode III
G_{IC}	-	Critical energy release rate in mode I
G_{IIC}	-	Critical Energy release rate in mode II
G_{IIIC}	-	Critical Energy release rate in mode III
G_{TC}	-	Total critical strain energy release rate in mixed-mode loading condition

$\delta_{i_m}^{f}$	-	Relative displacement at failure under mixed-mode loading for each mode of interface damage
D_{sr}	-	Operator of the interface constitutive model
$\bar{\delta}_{sr}$	-	Kronecker delta
P	-	Current mass density
υ	-	Velocity field vector
U	-	Internal energy per unit mass
t	-	Surface traction vector
f	-	Body force vector
E_U	-	Dissipated portions of the internal energy
E_K	-	Kinetic energy
E_F	-	Energy dissipated by contact friction forces between the contact surfaces
E_W	-	Work of a body by external forces
E_{QB}	-	Energy dissipated by the damping effect of solid medium infinite elements
σ^{υ}	-	Viscous stress
σ^{c}	-	Stress derived of a constitutive equation
$\dot{\varepsilon}^{el}$	-	Elastic strain rate
$\dot{\varepsilon}^{pl}$	-	Plastic strain rate
$\dot{\varepsilon}^{cr}$	-	Creep strain rate
E_S	-	Applied elastic strain energy
G_U	-	Internal energy
G_E	-	Strain energy
G_D	-	Dissipated energy

LIST OF TERMINOLOGIES

Multi-damage or -failure	-	Various types of damage or failure events that occur in a FRP lamina as a solid continuum part.
Multi-delamination	-	Occurrence of several delamination events in FRP composite laminates.
Multiple damage, failure, fracture or crack	-	Simultanious occurrence of several damage, Failure, fracture or cracking events in intralaminar and interlaminar constituents of FRP composite laminates.
Crack-jump phenomenon	-	An initial interlaminar crack in FRP composite laminate under mode I or II loading condition, which propagated suddenly with large size.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Fiber-reinforced polymer (FRP) composite laminate materials are increasingly replaced by metal materials in advanced structural application in defense, transport and etc. industries. Therefore, a correct comprehension about failure phenomena in FRP composite is necessary for the design and analysis of such structures. The knowledge of failure in composites normally obtained using numerical and experimental approaches. The experimental procedures normally are expensive and time consuming for complex loading condition which rarely can be used for design stages of composite structures. The numerical methods involve the mathematical derivation of structural behavior, failure phenomena and energy absorption of composites, which normally provide a deeper insight on structural failure for the design phase, however it is incomplete to define a response map of the three-dimensional (3D) structures. In the past three decades, development of *Simulation Methodologies* has been considered as one of the most effective method in bridging the mathematical models and experiments for realistic design and analysis of advanced industrial structures. Simulation procedures are benefit scientists to characterize the mechanical properties, to define the response map, and to enhance the final design of the composite structures using the lowest number of expensive samples and tests.

At the current state of development, an extensive analytical models have been introduced for numerical investigation of failure in composites, however the simulation methodology in prediction of complex multiple failure is still considered as an open topic for investigation. The present study uses the finite element method (FEM) as the most used approach, to develop a simulation methodology for prediction of multiple failure in multidirectional FRP composite laminates. The theory of continuum damage mechanics is used to develop the constitutive models for prediction of elastic-damage and fracture behaviors. Simulation of several tests on unidirectional/multidirectional FRP composites with and without pre-cracks are performed to examine the considered models and the methodology procedure.

1.2 Problem Background and Rationale

In the past few decades, advanced industries demand for materials with both light and strong features has been the main force to develop composite materials (Dempster D., 2003; Taylor, 2008). Advanced composite materials are constructed of two or more separate phases, mainly consisted of matrix phase, reinforcement phases and matrix/reinforcement interface that is known as interphase region. Fiber Reinforced Polymer (FRP) composites as one of the important advanced composites are created using polymeric matrix phase (thermoplastic, thermoset and etc.) which typically reinforced with fibrous (glass, carbon, aramid and etc.) materials. The design flexibility of FRP laminate composites through variation of matrix/reinforcement phase types, adjustment of reinforcement volume fraction in micro-scale and modification of laminas orientation in meso-scale, highlighted the capability of these materials for creation of superstructures with preferable solidity in various directions. The great advantages of FRP composites including high stiffness-strength combined with low weight bring a steady increase of investment in transport, aerospace and green industries on continuous replacement of metallic structures to composites. For this reason, the development of reliable and well-validated mathematical-physical models to describe the linear and nonlinear behavior of composites, become essential. Therefore, development of continuum damage model (CDM) for anisotropic material is important (Baker et al., 2004; Kaw, 1997; S. Murakami, 2012).

Mechanics of FRP composite materials is classified based on the level of the analysis in micro-, meso- or macro-scales. Therefore, damage and failure analyses of composite structures are practiced in different scales too. In this respect, the influences of mechanical features and properties in the microstructure of lamina have to be considered in the constitutive elastic-damage model parameters when it viewed in meso-macro scales too. Therefore, bridging between micro-to-macro mechanics is always one of the factors that is used prediction of mechanical behavior in composite materials (Baker, et al., 2004; R. Talreja and Singh, 2012).

In constructional view, FRP composites are created with a soft polymeric phase that is reinforced with stiff fibrous phase with almost 30-95% (e.g. Typical glass fiber reinforced polymer (GFRP), carbon fiber reinforced polymer (CFRP)) elastic-stiffness properties differences. Likewise, the anisotropic strength of the FRP composites normally shows up to 90% difference in the fiber direction compared with transverse to the fiber direction. Such big differences in elastic-strength properties accelerate early failure in weaker phases while structural performance is considered to be in the safe zone. In a FRP composite structure, fibers are assumed to be responsible for load bearing due to high stiffness, but in the other hand consideration of Poisson's ratio influences as a part of anisotropic continuum behavior is undeniable. Therefore, occurrence of matrix failure in high strength FRP composites such as CFRP is likely, which has to be considered as one the factors in design FRP composite structures. Therefore, understanding of yielding phenomena in composite lamina in meso-scale and laminate in macro-scale and also the related criteria with respect to yield surface is important. The present study, is attempting to introduce an overall yielding point in FRP *lamina* and *laminate*, using damage mechanics concept by considering a certain value of accumulated irrecoverable energy in the structure over total damage dissipation energy (Dempster D., 2003; R. Talreja and Singh, 2012; Taylor, 2008).

Most of the existing knowledge of damage and failure in FRP composites obtained through experimental and numerical methods. Normally, experimental data are limited due to the high value of cost for tests implementation and less diversity of data which rarely can be utilized in earlier design methods. In the other hand, internal analysis of structures in terms of deformation and damage zone is hardly possible, which most of the time considered as important knowledge that have to be obtained for design and analysis of composite superstructures. Numerical methods are normally cost saving in comparison with the experimental method, which is enabling a huge amount of data on mechanical parameters that lead to a deep insight into the design and failure analysis of composite structure. In the other hand, once a model is established, it could be used for various analyses, including different types of loads and boundary conditions. These results can be used in defining the responses map of the material as a support for enhancing the final design of the structure at low cost (Baker, et al., 2004; R. Talreja and Singh, 2012). However, at the current state, numerical models are not developed fully to cover the failure behavior of composite materials under complex loading condition. Several constitutive elastic-damage models based on continuum mechanics approach are derived to overcome this challenge, including a series of studies called the worldwide failure exercises (WWFE) that is made to describe the foremost theories for FRP composites (Chamis et al., 2013; Hinton, Kaddour and Soden, 2004; Kaddour et al., 2013; Labeas et al., 2011; Varna, 2013). In this exercise, a huge number of comparisons have been made on the capability of different mathematical models in order to predict the evolution of damage and failure events under various types of loading consist of biaxial, bending, thermal loadings and loading-unloading condition (Hinton, et al., 2004; Kaddour, et al., 2013). Several approaches including multi-scale hybrid damage and failure (Laurin et al., 2013), micromechanics based model (Chamis, et al., 2013), shear lag and equivalent constraint model (Kashtalyan and Soutis, 2013), enhanced damage meso-model (Daghia and Ladeveze, 2013), energy methodology (McCartney, 2013a, 2013b), constitutive damage model (Schuecker and Pettermann, 2013), plasticity-based theory (S. Pinho, Vyas and Robinson, 2013), classical damage model (Sapozhnikov and Cheremnykh, 2013), synergistic damage mechanics (Singh and Talreja, 2013), global-local cracking approach (Varna, 2013), structural damage modeling framework (Forghani et al., 2013) and its, are used to make comparison between the models and the experimental data. The conclusion of this research was that, out of 12 leading theories and 13 challenging tests for prediction of failure evolution, "*Only three groups solved all the 13 challenging problems and approximately 30% of the test cases were not solved*" (Kaddour, et al., 2013). It is noted that in general, the lack of consensus appears regarding the effects of ply thickness and lay-up sequences, influences of unloading-reloading behavior, and interaction in multiple crack locations and matrix crack-delamination (Kaddour, et al., 2013). Miscomprehension of the complex physics of FRP composite failure also commented as one of the reasons for low accuracy in prediction of failure (Silvestre Taveira Pinho, 2005). Most of the mathematical models are stress-based models computed at local material point through damage criteria to address the local failure process. Variation of effective stresses in FRP composites depend on assumed construction based on FEM and also the theoretical basis. One of the aspects, which have not been paid enough attention, is the influences of manufacturing processes in micro-meso construction of FRP composites through computational method. The present work investigated on the finite element (FE)-based model construction that could represent the actual construction of the composite created through different fabrication processes. This point is recommended for further investigation in previous works as multi-layer modeling methodology for failure analysis of FRP laminate composites (Kaddour, et al., 2013; Siromani, 2013). In other study, investigation on the physical properties reduction of composite structure due to damage and multiple failure is recommended for future work (Lasn, 2015). Full set of CDMs is reviewed and applied to address the progressive damage processes of FRP composites. FEM as an affective approximate method is used for predicting the complex response of composite structures. Implementation procedure of FEM is described extensively through a hybrid experimental-computational approach in order to combine the FE and test data for a comprehensive understanding of the failure process. Emphasis is placed on engineering aspects, such as the analytical descriptions, effective analysis tools, modeling of physical features and evaluation of approaches used to formulate and predict the actual response of composite structures (Ochoa and Reddy, 1992).

1.3 Statement of the Research Problem

How to identify and characterize the fracture processes of FRP laminate composites using damage-based models and finite element method under quasi-static monotonic loads?

1.4 Research Questions

The relevant research questions to the problem statement of the present study can be sorted out as follow:

1. What are the dominant damage mechanisms of FRP composites?
2. What models are suitable for simulating the observed linear-nonlinear deformation and fracture of FRP composites?
3. How does damage, initiate and propagate in matrix, interface and fiber of FRP composites?
4. How to evaluate the mechanics and mechanism of multiple damage processes (matrix cracking/crushing, multi-delamination and fiber breakage/buckling) in FRP composite materials under quasi-static monotonic loading condition?
5. How would the damage models and failure process be validated?

1.5 Objectives of Study

The aims of the present study are to develop a validated simulation methodology for failure processes of the FRP laminate composite under quasi-static monotonic loads. In this respect, the objectives of the study are defined in the main fields of mathematical-physical modeling, FE simulation and experimental works to solve the problem, which are develop and completed in the next chapters. The objectives are linked and highlighted throughout the research in the result and discussion chapters, which a short summery of them is listed in the conclusion remarks (Chapter 8).

The specific objectives of this study are:

1. To develop and derive bilinear physically-based damage model for FRP lamina.
2. To establish FE-based model constructions of FRP composite based on different manufacturing processes.
3. To identify the mechanics and mechanism of failure of FRP laminate composites under quasi-static loading.
4. To investigate on the effect of different constructions on the progressive damage processes of FRP laminate composites
5. To predict the elastic-plastic behavior and mechanism of multiple failure in FRP composite beams under flexural loading.
6. To represent the FE implementation of damage and failure in FRP composite using a hybrid experimental-computational approach.
7. To validate the damage-based FE model using experimental results.

1.6 Scope of Study

The present study is concentrating on the simulation methodology to identify and characterize the mechanics and mechanisms of failure in FRP laminate composites under monotonic loading condition. The scope of this research is restricted to unidirectional FRP laminate composites as:

1. Only, the two manufacturing processes of Prepreg/Autoclave method and vacuum infusion process (VIP) are considered, to fabricate multidirectional FRP composite laminates.
2. To prepare CFRP composite manufactured using Prepreg/Autoclave method, with uni/multi-directional ply sequences, and with/without pre-crack.
3. To manufacture anti-symmetric GFRP composites using VIP method, and machining into beam samples for mechanical test.
4. To perform mechanical tests on the FRP composite beams, to obtain the structural response and mechanical properties as follow:
   a. Three and four-point bending tests on anti-symmetric CFRP and GFRP composite laminates.
   b. Double cantilever beam (DCB) and end-notched flexure (ENF) tests on CFRP composite to obtain the critical fracture energy of interface in modes I & II loading condition.
   c. To perform critical ENF test on a specially designed specimen to capture unstable crack-jump.
5. To identify the various types of intralaminar and interlaminar fracture events in FRP composite laminates, using fractographic investigation on the tests performed in the above cases (No. 3).
6. To develop and describe the theories as bilinear CDMs for FRP lamina and interface.
7. To create FE models using ABAQUS 6.9EF software, in order to simulate the following cases:
   a. To develop FE model-based constructions that represent the construction of FRP composite laminates, which are manufactured using VIP and Prepreg/Autoclave methods.
   b. To develop individual FE models of FRP composite laminate, to simulate laminas failure using CDM, and also interface delamination using cohesive zone model (CZM).
   c. To develop a FE model that comprises both CDM and CZM models to simulate multiple fracture in CFRP composite laminates manufactures using Prepreg/Autoclave methods.

8. To validate the damage theories and FE models (above cases, No. 6) using experimental data, in both aspects of mechanics and mechanism of damage.
9. To establish the simulation methodology for fracture processes of FRP composites using hybrid experimental-computational approach throughout of the present study.

1.7 Layout of the Thesis

In this thesis, chapters are arranged to address the FE simulation methodology for prediction of the mechanics and mechanism failure in FRP laminate composites. Assessment of progressive multiple damage processes through laminas and the interface of the composite are the main interest. In this respect, the content of the chapters is classified to explain the objectives and scope of the research as follow.

Chapter 1 gives an overview on the background of laminate composites and the challenges in simulation and analysis for real applications. Then the problem statement, objectives and the scope of the research are described. The limits of what this study is restricted to, are notified.

Chapter 2 provides a summary of the literature and previous researches about FRP composite specification, properties and manufacturing methods. The applications of FRP composites in advanced industries are investigated. The use of FEM in simulation of mechanical cases is studied. A brief description of the mechanics deformation and mechanism of failure in FRP composite laminates is provided. Continuum damage mechanics of composite materials are explained to represent a physical view of the damage phenomena. The various modes of failure in FRP composite are studied, and the related damage models, available numerical tools and FE procedures to estimate and predict damage modes are described. Multiple failure phenomena in FRP composite are demonstrated using fractographic image of a CFRP beam sample under tension loading condition. The missing points and the gaps to previous researches are highlighted.

Chapter 3 discusses about research methodology of the present work. The research framework of the study is provided based on the three activities of modeling, computation and experiment. Types of the specimen, test procedure and the related material properties are provided. The steps for FE simulation of a composite system are described. The manufacturing issues of FRP composite laminates and the related FE model-based constructions are discussed. A hybrid experimental-computational approach is introduced, which is used entirely through the research investigation. The basis of FE implementation of the damage and fracture analyses on different FE constructions of FRP composite is described.

In *chapter 4*, the physically-based continuum models for prediction of multiple failures of FRP laminate composites are described. The phenomena of CDM of lamina and its physical interpretation is discussed. The physical influences of interlaminar region are described for the modeling of FRP composites in the conditions, where perfect laminas bonding or interface debonding are targeted. FE implementation of the model is illustrated through FE simulation by describing the evolution of effective stresses and variation of damage parameters.

Chapter 5 illustrates the FE simulation methodology of FRP composite lamina by introducing specific FE based-model construction for different manufacturing processes. The influences of different constructions in the computation of progressive intralaminar damage process are described. The validated FE models are used to describe the mechanics of system response and mechanisms of multi-damage processes in FRP composite laminates.

Chapter 6 works on the mechanics of interface delamination in CFRP composite in the presence of initial crack. Experimental investigation on CFRP composite under mode-I test is provided (DCB Test) to discuss about delamination phenomenon. FE simulation and experiment of CFRP composite under mode-II loading is provided (ENF test) to study on the mechanism of interface delamination using CZM theory. The capability of the governing law in prediction of the crack growth and crack-jump phenomena are examined. The concept of stable and unstable crack-jump is developed.

Chapter 7 demonstrates the FE simulation methodology for prediction of multiple failure events in FRP composites by applying CDM and CZM theories in intralaminar/interlaminar parts. The predictive capability of these models in the simultaneous prediction of various failure modes in the lamina and interface of anti-symmetric multidirectional CFRP specimen is examined under four-point bending load condition. Validation of the damage mechanics and mechanism of failure is the main concern.

Chapter 8 explains the conclusion related to the FE simulation methodology and failure mechanism of FRP composites in the present study. The future work on the development of the failure models for fatigue mechanics and etc. of FRP composites are recommended.

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