Bi-axial testing of composite laminates and adhesive bonded joints

Nguyen, Hai Dang

2018

Nguyen, H. D. (2018). Bi-axial testing of composite laminates and adhesive bonded joints.
Doctoral thesis, Nanyang Technological University, Singapore.

<http://hdl.handle.net/10356/74090>

<https://doi.org/10.32657/10356/74090>

NANYANG
TECHNOLOGICAL
UNIVERSITY

**BI-AXIAL TESTING OF COMPOSITE LAMINATES
AND ADHESIVE BONDED JOINTS**

NGUYEN HAI DANG

**INTERDISCIPLINARY GRADUATE SCHOOL
ENERGY RESEARCH INSTITUTE @ NTU (ERI@N)**

2017

**BI-AXIAL TESTING OF COMPOSITE LAMINATES
AND ADHESIVE BONDED JOINTS**

NGUYEN HAI DANG

Interdisciplinary Graduate School
Energy Research Institute @ NTU (ERI@N)

A thesis submitted to the Nanyang Technological
University in partial fulfilment of the requirement for
the degree of
Doctor of Philosophy

2017

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

... 21-August-2017 ...
Date

.....
Nguyen Hai Dang

Abstract

Glass/carbon fiber-reinforced polymer (FRP) matrix composite materials are commonly used in many industrial fields, especially in aerospace and wind energy. With a rapid expansion of horizontal-axis wind turbine size, a safe and reliable design procedure for turbine blades, which are usually subjected to multi-axial loads, is highly necessary. By using data from a conventional uniaxial test of the composite laminate in the design processes, safety factors might be overestimated which lead to unnecessary increase in size, cost and weight of the blade structure. Therefore, various bi-axial tests have been conducted in order to achieve the more realistic design. However, there is still a lack of reliable biaxial testing data to verify failure initiation and propagation of composite materials, due to the difficulties and expense of conducting these tests. The aim of this study is to investigate the failure behavior of FRP matrix composite laminates and adhesively bonded joints under in-plane bi-axial loading conditions, as detailed below.

Initially, a novel bi-axial testing fixture which can produce the tension – tension, tension – compression, compression – compression bi-axial loading conditions with different displacement ratios was developed with one loading actuator. This device is a cost-effective alternative for bi-directional material characterization tests which is utilized to validate of theoretical failure models.

Secondly, fracture characteristics of unidirectional and cross-ply glass FRP composite laminates were investigated under bi-axial tension – shear loading conditions using a modified Arcan fixture. The fracture toughness values were determined and plotted in a fracture toughness space, which showed three regions including mode I dominant, mode II dominant, and mixed-mode dominant.

Thirdly, the failure behavior of cross-ply laminate cruciform specimens was studied under the in-plane bi-axial tension – tension and tension – compression static loading conditions using cruciform specimens. The failure envelopes were generated in axial – transverse stress space and fracture toughness domain. The results showed that the laminate with cracks fails in crack opening mode under

bi-axial tension - tension loading conditions. These realistic behavior are significant to enhance material efficiency in composite designs.

Finally, the influences of adherend interface geometry of adhesively bonded butt joints on the failure response were experimentally and numerically studied under bi-axial tensile – shear loads. Three different types of specimens with the straight, rectangle and triangle shape contours were used in the experiment using a modified Arcan fixture. The obtained experimental results showed that the straight contour specimens gave the highest strength for all combination of tension and shear loads. Furthermore, three-dimensional finite element models were developed to predict the strength of the adhesively bonded joints based on the cohesive zone modeling approach. The current numerical model predicted the strength of traditional butt joints in good agreement with the experimental measurements.

Acknowledgements

I would like to express my great gratitude towards my thesis advisors, Associate Professor Sridhar Idapalapati from School of Mechanical and Aerospace Engineering, Nanyang Technological University (NTU) and Dr. Srikanth Narasimalu from Energy Research Institute @ NTU (ERI@N). They not only help me to touch deeper knowledge in my research but also give me a comfortable working environment with their kindness and patience. Without their supports, I would never have been able to finish this report.

I am deeply grateful to Associate Professor Chai Gin Boay and Associate Professor Sunil Chandrakant Joshi for their willingness to be involved in my Thesis Advisory Committee.

I wish to express my thanks to Energy Research Institute @ NTU, Interdisciplinary Graduate School and Nanyang Technological University for giving me a change to live and study in this peaceful country.

I would like to thank Material laboratory's technicians, Mr. Leong Kwok Phui and Mr. Lew Sui Leung for their great help when I was doing my experiments there. I would also like to extend my thanks to Mr. Rajaneesh Anantharaju, Mr. Tang Jiann Haur, Mr. Maburur Ahmad Rashedi for sharing their research experiences through many useful discussions.

Finally, I would like to send my deepest gratitude to my parent, my wife and my little daughter and son who always encourage me even in my worst time. Their love is the biggest gift in my life.

Table of Contents

Abstract.....	iii
Acknowledgements	v
Table of Contents	vii
Table Captions.....	xiii
Figure Captions	xv
Abbreviations	xxi
Publications.....	xxiii
Chapter 1	1
Introduction	1
1.1 Background	2
1.2 Motivation and research objectives.....	4
1.3 Dissertation Report Layout.....	9
1.4 Findings and Contributions.....	10
References	11
Chapter 2.....	17
Litterature Review	17
2.1. Introduction.....	18
2.2. Bi-axial testing methods	18
2.3. In-plane bi-axial testing of composite laminates	21
2.4. Adhesively bonded joint under tension/compression – shear.....	24
2.5. Stress calculation for cruciform specimens.....	25
2.6. Fracture toughness test of composite materials	26
2.7. Analysis of composite materials	29
2.8. Failure criteria for composite materials	32
2.9. Summary	39
References	39
Chapter 3	51
Experimental Methodology	52

3.1	Material information.....	52
3.2	Mechanical testing method	53
3.2.1	Tension – shear Mixed mode test	53
3.2.2	Tension – tension and tension – compression bi-axial test	54
3.3	Specimen preparation	56
3.3.1	GFRP laminate preparation	56
3.3.2	Adhesive bonding composite joint preparation	57
3.4	Material characterization	58
3.4.1	Bi-axial failure envelope	58
3.4.2	Digital image correlation for surface strain.....	59
3.5	Analysis of composite laminate	60
3.5.1	Finite element models of composite laminates.....	60
3.5.1	Finite element models of adhesive bonding composite joint	61
3.6	Summary	62
	References	63
	Chapter 4.....	65
	Bi-axial Fixture Design and Development	65
4.1	Introduction.....	66
4.2	Design and development of bi-axial tensile fixture	71
4.2.1	Design criteria.....	71
4.2.2	Assembly of the fixture	72
4.2.3	Kinematic relation.....	74
4.3	Experimental validation.....	76
4.3.1	Test sample	76
4.3.2	Experimental validation	78
4.4	Conclusion	81
	References	82
	Chapter 5.....	85
	Fracture of Composite Laminate under Tension and Shear Loading	85
5.1	Introduction.....	86
5.2	Experimental methods	87

5.2.1	Modified Arcan testing.....	87
5.2.2	Fracture toughness calculation	90
5.3	Result and discussion	92
5.3.1	Load vs displacement curve	92
5.3.2	Critical load	94
5.3.3	Fracture toughness	102
5.4	Conclusion	105
	References	106
Chapter 6.....		109
Fracture Capacity of Composite Laminate under Bi-axial Loadin		109
6.1	Introduction.....	110
6.2	Experimental methods	111
6.2.1	Material system.....	111
6.2.2	Tension – tension test method	111
6.2.3	Tension – Compression test method	114
6.2.4	DIC method	116
6.3	Data reduction	117
6.3.1	Equivalent loaded area	117
6.3.2	Failure surface in stress space.....	118
6.3.3	Fracture toughness surface	119
6.4	Results and discussion	122
6.4.1	Tension – tension bi-axial test	122
6.4.1.1	Load versus displacement plots and crack paths	122
6.4.1.2	Failure response of axial and transverse stress.....	128
6.4.1.3	Failure graph of transformation stress components	132
6.4.1.4	DIC and FEM analysis	133
6.4.1.5	Fracture toughness	135
6.4.2	Tension – compression bi-axial test.....	138
6.4.2.1	Load versus displacement plots and crack paths	138
6.4.2.2	Failure graph of axial and transverse stress.....	142

6.4.2.3 Fracture toughness	144
6.4 Conclusion	146
References	148
Chapter 7.....	149
Fracture of Adhesively Bonded Joints under Tension and Shear Loading	149
7.1 Introduction.....	150
7.2 Experimental methods	150
7.2.1 Material and specimen	150
7.2.2 Experimental procedure	153
7.2.3 Finite element model.....	154
7.3 Result and discussion	157
7.3.1 Force -displacement curve and crack pattern	157
7.3.2 Strength of adhesively bonded joint.....	160
7.3.3 Finite element analysis result.....	162
7.3 Conclusion	167
References	168
Chapter 8.....	171
Conclusions and Recommendations	171
8.1 Conclusions.....	172
8.1.1 Development of a novel bi-axial fixture	172
8.1.2 Fracture of composite laminate under tension and shear loads	172
8.1.3 Fracture capacity of composite laminates under bi-axial loads.....	173
8.1.4 Fracture of adhesively bonded joints under tension and shear loads.....	174
8.2 Recommendation.....	175
8.2.1 Bi-axial tests of composite materials under static and fatigue loading conditions	175
8.2.2 Numerical model of composite laminates under bi-axial loading condition	176
8.2.3 Bi-axial testing of the adhesively bonded joint using thick specimens or tubular specimen.....	176
APPENDIX	177

Table Captions

Table 2.1 Common failure criteria for composites materials [80-83].	34
Table 3.1 Material elastic properties of G17500 unidirectional lamina [2].	52
Table 4.1 General information of in-plane bi-axial testing systems.	70
Table 5.1 Ratio between tension and shear loads.	90
Table 5.2 Fracture toughness of GFRP laminates.	102
Table 6.1 Material elastic properties of G1750 unidirectional lamina	111
Table 7.1 Material properties of the DP460 epoxy adhesive used in the study.	151
Table 7.2 Interfacial properties of cohesive layer	156

Figure Captions

Figure 1.1 Renewable power energy capacity for 2015 and 2016 [4].	3
Figure 1.2 Wind turbine blade cross-section structural elements [6].	4
Figure 1.3 Simplify loading conditions of wind turbine blade components [11].	5
Figure 1.4 Damage types of (a) wind turbine blade shell and (b) spar [20].	6
Figure 1.5 Stress conditions in the adhesive layer of various joint types.	8
Figure 2.1 Common bi-axial testing methods: (a) A bulge test; (b) A tubular specimen under axial loading and internal pressure; (c) A tubular specimen under axial loading and torsion; (d) A rectangle specimen under tension and shear; (e) An Arcan test; and (f) A flat cruciform specimen under in-plane bi-axial loading.	19
Figure 2.2 Method to calculate the equivalent areas [29].	26
Figure 2.3 Three fracture modes: (a) opening, (b) in-plane shear, (c) out of plane shear.	27
Figure 2.4 Fracture toughness testing methods: (a) DCB method, (b) MMB method and (c) CCT method [67-69].	27
Figure 2.5 Modification Arcan fixture [46].	29
Figure 2.6 Numerical methods of failure analysis: (a) Finite element method, (b) Extended finite element method [70].	32
Figure 2.7 Illustration of failure mechanisms of composite laminates.	33
Figure 2.8 Inter-fiber fracture mode C, mode B, and mode A respectively [83].	36
Figure 3.1 A modified Arcan fixture.	54
Figure 3.2 Cruciform specimen on the static bi-axial testing fixture.	55
Figure 3.3 Schematic diagram of the bi-axial testing system with a photograph of test set-up.	56
Figure 3.4 Schematic illustration of (a) Arcan specimen, and (b) Cruciform specimen.	57
Figure 3.5 Schematic illustration of adhesive bonding composite joints with different adherend geometries.	58
Figure 3.6 Illustration of bi-axial failure envelope for the IM7/997-2 carbon/epoxy quasi-isotropic laminate [5].	59
Figure 3.7 A digital image correlation system using the single-lens reflex camera.	60
Figure 3.8 Finite element model of the cruciform specimen.	61
Figure 3.9 Finite element model of the adhesively bonded joint with the Arcan fixture.	62

Figure 4.1 Common bi-axial testing specimens (a)(b) thin-wall tube specimen, (b) cruciform specimen and (d) punching plate.	66
Figure 4.2 (a) Frame fixture (b)(c) Tensile/Compressive - shear loading Arcan fixture (d) Four independent hydraulic actuator system (e) Add-on actuator fixture (f)(g) Linkage fixture and (h)(i) Tan relation fixtures.....	68
Figure 4.3 Schematic illustration of a bi-axial fixture at (a) front view and (b) back view.	73
Figure 4.4 (a) Loadcell set-up and (b) Displacement magnetic location sensor.	74
Figure 4.5 Schematic illustration of the bi-axial loading fixture.	75
Figure 4.6 Bi-axial cruciform specimen geometry.....	76
Figure 4.7 (a) Mesh and (b) Boundary condition of the cruciform specimen. ..	77
Figure 4.8 (a) E11 strain field, (b) E22 strain field, (c) S11 stress field and (d) S22 stress field of a half of the 3D model under equi-biaxial displacement of 1mm for axial and transverse direction.	78
Figure 4.9 Axial displacement versus transverse displacement for unloading conditions.....	79
Figure 4.10 Axial displacement versus transverse displacement for loading conditions.....	80
Figure 4.11 Axial force versus transverse force for loading conditions.....	81
Figure 5.1 (a) A modified Arcan fixture; (b) Geometry of Arcan testing specimen.	87
Figure 5.2 Curing cycle of glass FRP G17500 for Arcan specimen.	89
Figure 5.3 Arcan testing fixture at different loading angles: (a) 0°; (b) 15°; (c) 30°; (d) 45°; (e) 60° and (e) 90°.	90
Figure 5.4 Finite element model of mode I Arcan testing.	92
Figure 5.5 Load-displacement plot for (a) UD specimens at 0° and 90° loading angles and (b) cross-ply [0/90] _{5s} specimens from 0° to 90° loading angles.....	93
Figure 5.6 The crack patterns for [0/90] _{5s} laminate during the pure mode II test.	94
Figure 5.7 Average critical load vs. loading angle of [90] ₄ and [0/90] _s laminates.	95
Figure 5.8 Average critical load vs. loading angle of [0] ₂₀ , [90] ₂₀ and [0/90] _{5s} laminates.	96
Figure 5.9 GFRP Arcan specimens in the testing conditions of [90] ₄ and [0/90] _s laminates in (a) 0°, (b) 90° loading angles and cross-ply laminates in (c) 0°, (d) 15°, (e) 30°, (f) 45°, (g) 60°, (h) 75° and (i) 90° loading angles.....	97

Figure 5.10 Arcan specimens in the testing conditions of $[0]_{20}$, $[90]_{20}$ and (a, c) 0° , (b, d) 90° loading angles and cross-ply laminates $[0/90]_{5s}$ in (e) 0° , (f) 15° , (g) 30° , (h) 45° , (i) 60° , (j) 75° and (k) 90° loading angles.....	98
Figure 5.11 (a) Photograph and (b) schematic of mode I dominant failure under bi-axial tension – shear loading condition of the cross-ply laminate.	99
Figure 5.12 (a) Photograph and (b) schematic of mode II dominant failure under bi-axial tension – shear loading condition of the cross-ply laminate.	100
Figure 5.13 The mixed mode effect to the crack pattern for 45° and 60° loading angle tests.....	101
Figure 5.14 Geometrical factor vs. loading angle for GFRP UD and cross-ply laminates for the crack length 24 mm for different loading angles.....	103
Figure 5.15 Critical stress intensity factor vs. loading angle for GFRP UD and cross-ply laminates for the crack length 24 mm for different loading angles.	104
Figure 5.16 The mixed-mode fracture condition for $[0/90]_{5s}$ and $[0/90]_s$ laminates.	105
Figure 6.1 Flowchart of bi-axial testing experiment and simulation.....	111
Figure 6.2 Cruciform specimen dimensions and orientation. All dimensions are in mm.	112
Figure 6.3 Fabrication process steps of GFRP specimens.....	113
Figure 6.4 Photograph of the bi-axial testing set-up.	114
Figure 6.5 Cruciform specimen dimensions and orientation. All dimensions are in mm.	115
Figure 6.6 The bi-axial testing fixture set-up.....	116
Figure 6.7 Photograph of digital image correlation setup using the single-lens reflex camera.....	117
Figure 6.8 Illustration of stress transformation in a bi-axial sample.....	119
Figure 6.9 FEM model of a bi-axial cruciform specimen under bi-axial loading.	120
Figure 6.10 Load -displacement plot for 0° , (a) 40 mm cracks and (b) 45 mm cracks for bi-axial tension-tension loading.	123
Figure 6.11 Load-displacement plot for 30° , 40 mm cracks under (a) ratios from 1:0 to 1:1 and (b) ratios from 0.4:1 to 0:1 bi-axial tension-tension loading. ...	124
Figure 6.12 Load-displacement plot for 30° , 45 mm cracks under (a) ratios from 1:0 to 1:1 and (b) ratios from 0.4:1 to 0:1 bi-axial tension-tension loading. ...	125
Figure 6.13 Crack propagation direction (a) for load ratio of 0:1 and 0.4:1; (b) for load ratio of 0.8:1.....	126
Figure 6.14 Crack propagation direction (a) for load ratios from 1:0 to 18:1; (b) for load ratio from 0.8:1 to 1:1.....	127

Figure 6.15 Crack patterns of (a) 30° crack 1:0.4 load ratio; (b) 30° crack 0.4:1 load ratio; and (c) 45° crack 0.8:1 load ratio.	128
Figure 6.16 Failure graph of axial and transverse stress of (a) 40 mm cracks and (b) 45 mm cracks under bi-axial tension – tension loading conditions.	129
Figure 6.17 Critical stress against increasing stress ratio (a) for stress ratio from 1:0 to 1:0.83 of 40 mm crack; (b) for stress ratio from 1:0 to 1:0.83 of 45 mm crack; (c) for stress ratio from 1:0.67 to 0:1 of 40 mm crack; and (d) for stress ratio from 1:0.67 to 0:1 of 45 mm crack (the stress ratios for a and b are drawn in transverse stress to axial stress ratios; the stress ratios for c and d are drawn in axial stress to transverse stress ratios).	130
Figure 6.18 Crack closure and crack opening effects of cracks under tension or compression loading.	131
Figure 6.19 Plot of transformation stress components against stress ratio.	133
Figure 6.20 Comparison between FEM analysis (left) and DIC results (right) for (a) ϵ_x ; (b) ϵ_y ; and (c) ϵ_{xy} of 40 mm 30° crack under stress ratio 1:0.33.	134
Figure 6.21 Non-dimensional geometric correction factors Y1 and Y2 of bi-axial testing specimens.	135
Figure 6.22 Mode I fracture toughness versus stress ratio for 0° cracks.	136
Figure 6.23 Mode I and mode II fracture toughness versus stress ratio for 30° cracks and 45° cracks.	137
Figure 6.24 Plot of K_{II}/K_{IC} against K_{II}/K_{IC} for cruciform specimens and Arcan specimens under bi-axial tests.	138
Figure 6.25 Load – displacement plot for 20 mm cracks for (a) 0° cracks; and (b) 45° cracks under bi-axial tension-compression loading.	139
Figure 6.26 Crack propagation direction (a) for 0° cracks at all ratios; (b) for 45° crack at load ratios of 0:1 and 0.14:1.	140
Figure 6.27 Crack propagation direction for 45° crack at load ratios of 0.48:1 and 0.65:1.	141
Figure 6.28 Crack patterns of (a) 0° crack; (b) 45° crack 0:1 load ratio; and (c) 45° crack 0.65:1 load ratio.	142
Figure 6.29 Failure graph of axial and transverse stress of 20mm; (a) 0° cracks and (b) 45° cracks under bi-axial tension – compression loading conditions. .	143
Figure 6.30 Critical stress against increasing stress ratios for 0° and 45° crack under tension – compression bi-axial loading.	144
Figure 6.31 Mode I and mode II (a) non-dimensional geometric correction factors and (b) fracture toughness versus stress ratios for 0° cracks and 45° cracks under tension – compression bi-axial loadings.	145

Figure 7.1 Geometric parameters of adhesively bonded joints; (a) straight contour (Type I), (b) rectangle shape contour (Type II), and (c) triangle shape contour (Type III).	152
Figure 7.2 Photographs of (a) adherend in the Acrylic mold with secure tape, (b) testing sample geometry.	152
Figure 7.3 The modified Arcan setup on INSTRON® UTM 5569.	154
Figure 7.4 Finite element analyses models of adhesively bonded joints; (a) model with Arcan fixture, (b) mesh geometry of Type I specimen, (c) mesh geometry of Type II specimen, and (c) mesh geometry of Type III specimen.	156
Figure 7.5 Crack formation and propagation in Type I specimen for (a) 0° and (b) 90° loading angles.	157
Figure 7.6 Force – displacement curve for (a) Type I specimen, (b) Type II specimen, and (c) Type III specimen.....	158
Figure 7.7 Crack formation and propagation in Type II specimen for (a) 0° and (b) 90° loading angles.	159
Figure 7.8 Crack formation and propagation in Type III specimen for (a) 0° and (b) 90° loading angles.	160
Figure 7.9 Strength of the adhesively bonded joints for the loading angles from 0° to 90°.....	161
Figure 7.10 Critical shear load vs critical tension load for three types of specimens.....	162
Figure 7.11 The predicted strength of three types of specimens using finite element models with their relative experimental results.	163
Figure 7.12 The stress concentration zones of (a) Type I specimen, (b) Type II specimen, and (c) Type III specimen for 0° loading angle and (d) Type I specimen, (e) Type II specimen, and (f) Type III specimen for 90° loading angle.....	164
Figure 7.13 Deleted element zones in the cohesive element layers of (a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60°, (f) 75°, and (g) 90° loading angles.....	166
Figure A.1 Bi-axial fixture dimensions (all dimensions in mm).	177
Figure B.2 Adherend dimensions of (a) Type II and (b) Type III specimens (all dimensions in mm).	178

Abbreviations

P_c	Critical load at fracture
w	Specimen length
t	Specimen thickness
α	Loading angle
a	Crack length
$f_1(a/w)$	Geometrical factors of mode I
$f_2(a/w)$	Geometrical factors of mode II
K_{IC}	Critical stress intensity factors in mode I
K_{IIC}	Critical stress intensity factors in mode II
K_I	Stress intensity factor in mode I
K_{II}	Stress intensity factor in mode II
P	Reaction force in finite element analysis
HAWT	Horizontal-axis wind turbines
VAWT	Vertical-axis wind turbines
GFRP	Glass fiber reinforced polymer
CFRP	Carbon fiber reinforced polymer
WWFE	World-wide failure exercise

FEM	Finite element method
DCB	Double cantilever beam
ENF	End-notched flexure
CTT	Compact tension test
FEA	Finite element analysis
UTM	Universal testing machine
UD	Unidirectional
S8R5	Quadric 8-node reduced integration element in ABAQUS
2D	Two-dimensional
3D	Three-dimensional
XFEM	Extended finite element method
DIC	Digital image correlation
ESPI	Electronic speckle pattern interferometry
WTG	Wind turbine generators
TAST	Thick Adherend Shear Test
ESPI	Electronic Speckle Pattern Interferometry
AE	Acoustic Emission
HI	Holographic Interferometry
LRS	Laser Raman spectroscopy

Publications

Ng. H. Dang, I. Sridhar, N. Srikanth,” Fracture behavior of cross-ply fibre reinforced composite laminates with cracks under biaxial loading conditions”, Conference Proceedings ICCM20, Copenhagen, Denmark (2015)

Chapter 1

Introduction

This chapter introduces the background, motivation, and objectives of this research. Renewable energy has been an alternate of the energy from the fossil fuels as these are clean, affordable, local and effectively infinite. Among renewable energy resources, wind power shows a potential to provide enormous amounts of clean energy. Wind turbines generators (WTG) are commonly used to harvest the wind power then convert it to electric power. The wind turbine blades in its rotor are important components which are subjected to complex forces. Hence, the multi-axial stress states are generated on the blade composite laminate components or adhesive joints comprising in them. This research focuses on investigating experimentally and numerically the behavior of composite laminates and adhesive joints under bi-axial loading conditions.

1.1 Background

For centuries, the world is relying heavily on the fossil fuels such as coal, oil and natural gas for energy needs. More than 80% of worldwide energy demand is depended on these energy resources. However, these fuels having been exhausted and are indicated as a primary source of CO₂ emissions which arises the climate change and global warming. The renewable energy, an enormous energy resource, has been applied from thousand years using biomass, wind, solar, hydropower, and geothermal. The renewable energy sector is reported to have 9.8 million employers in 2016, and an increase of 1.1% over 2015 [1, 2]. The renewable power capacities of renewable sources in 2015 and 2016 are shown in Figure 1.1. It is clear that there is a significant growth of capacity in solar energy and wind energy as these are clean, affordable, domestic and effectively infinite. The wind power generator needs water for its heat-exchanger through not much as well as producing low greenhouse gas. Nowadays, wind power has been one of the most cost-effective energy sources which have been expanding in Europe and North America with great potential to replace the use of the fossil resources. In 2010, the wind energy supplied about 2% of total US electric demand, equal to the need of 8.7 million homes. Also, 42.1% of the Denmark power demand comes from wind resources in 2015, and the plan is 50% of their power supply by 2020 [3]. Therefore, wind power is growing as an important source of the world energy which provides a green environmental friendly power. Moreover, the offshore wind farms have been constructed to generate more power due to the much stronger wind off the coasts. However, the offshore wind industry has faced the difficulty of design and build robust and secure wind farms in the deep water with effects of ocean waves, hurricanes, salty environment. Therefore, it is vital to conduct the investigation on the operation of wind turbine components under the offshore conditions.

Figure 1.1 Renewable power energy capacity for 2015 and 2016 [4].

Wind turbines which convert the kinetic energy of wind into power can be classified into two types, i.e. horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs). As HAWTs can produce electricity more efficiently than VAWTs, they have played a dominant role in the wind power industry[5]. Turbine blades, which drive the turbine shaft to spin and thus generate electricity, are among the most important components of a HAWT. To obtain a long service life, it is required that turbine blades have high specific strength and stiffness, low weight, excellent fatigue resistance and good corrosion resistance. As such, glass or carbon fiber-reinforced polymer (FRP) matrix composites have been selected as the blade materials of HAWTs during the last decades for their superior mechanical properties and being light. Figure 1.2 shows the cross-section of a wind turbine blades with relative parts. The shells and spar caps were made of the FRP laminates while the shear web has the sandwich design with FRP skins and a foam core. Construction adhesives are typically used to connect the lower and upper shells at the leading and trailing edges, and the spar caps to the shells. Although carbon fiber laminates show superior specific strength and specific stiffness, which has been applied in the

high stiffness parts. Glass fibers remain the most widely used fibers for HAWT blades due to their cost-effectiveness for high volume or mass construction.

Figure 1.2 Wind turbine blade cross-section structural elements [6].

1.2 Motivation and research objectives

With a rapid increase in quantity and size of HAWTs, a safe and reliable design procedure for turbine blades is highly required. HAWT blades are subjected to complex loads during their service life i.e. unsteady aerodynamic, gravitational and centrifugal forces which induce multi-axial conditions of two or three principal stresses in the blade materials. Figure 1.3 illustrates the simplify loading conditions of wind turbine blade components under operation. The standardized uniaxial tests are commonly used to investigate the behavior of FRP laminates under tension, compression, or shear loading condition. However, it may not provide accurate data for predicting the orthotropic composite materials under multi-axial stress conditions [7-10], which tend to the conservative design of the blades with high weights. Thus, an alternative approach is to conduct bi-axial testing methods to measure the complex behavior of materials under bi-axial stress/strain conditions. This relaxes the conservativeness in the design and further reduces their weight and hence cost.

Figure 1.3 Simplify loading conditions of wind turbine blade components [11].

Some typical damages in the blade that occur during the operation of a wind turbine generator are illustrated in Figure 1.4. The damage modes are numerous which occur in the shell, gelcoat, laminate, sandwich core, and adhesive joints. To predict the failure of these components, different failure theories are introduced which capture the interlaminar, intralaminar fracture behavior of composite laminates as well as adhesive bonding layers. However, these failure theories are limitedly verified by multi-axial data due to the complexity of multi-axial testing equipment and specimen preparation. Recently, a comprehensive effort to validate failure theories was conducted under worldwide failure exercise (WWFE); bi-axial testing data of tubular specimens from 14 testing cases were used to verify 19 different failure theories of FRP composite materials [12-15]. This study indicated a need for reliable bi-axial experiment data for FRP composite materials to verify the failure criteria. Besides, the request for bi-axial data is frequently established in the composite community [2, 16-19]. Therefore, this study is to fulfill the lack of reliable experimental data for the failure behavior of FRP composite laminates and adhesive bonding layer under multi-axial stress.

Figure 1.4 Damage types of (a) wind turbine blade shell and (b) spar [20].

The multi-axial test can be conducted under triaxial or bi-axial loading conditions in which the specimens are subjected to a combination of three or two distinct components of normal load, bending, torsion, and shear. The triaxial test data are insufficient due to the difficulty associated with the very complex testing machine, data collection methods, and specimen geometry [21]. Therefore, the bi-axial tests have been demonstrated more appropriate to investigate the behavior of composite materials. Different experimental techniques and samples have been used to produce the bi-axial loading conditions [9]. A suitable bi-axial method is chosen due to the characteristics of structure geometry and loading conditions. Because most composite laminate surfaces of wind turbine blades are flat or gently curved, the in-plane bi-axial tests show potential to describe the

actual conditions of these laminates. Moreover, all tests in this study are conducted using the in-plane bi-axial methods.

FRP laminates are commonly employed in the many components of wind turbine blades as an outer shell or side layers of a sandwich structure (see Figure 1.3). As seen in Figure 1.4, shell crack split is a typical damage of wind turbine blades during operation which occurs in the laminate layers at the outer surface, shear webs. The through-thickness cracks are appeared and then propagated along the component surfaces. Nowadays, the modern WTG blades are giant of the order of more than 100 m in diameter and prone to manufacturing defects such as delamination, cracks, voids, resin rich zones, etc. Many investigations had been conducted for the bi-axial laminates under bi-axial loading condition, which presented a reliable data for composite laminate failures. However, most studies focus on the behavior of undamaged or contained a circle hole laminates. It shows a lack of experimental data for the composite laminate contained pre-cracks with its damage progress and failure modes [22]. This motivates a research on the fracture of damaged composite laminates under tension – tension, tension – compression loads.

Besides, the damages which occur in the adhesive bonded composite joints at the leading and trailing edges, and the spar caps to the shells also need to be considered. The loading conditions of the conventional adhesive joint structure with their relative stress conditions are illustrated in Figure 1.5. It is evident that the adhesive joints are subjected to the bi-axial stress conditions in performance. The failure behaviors of the adhesive joints are well captured in many kinds of literature [23-31]. Most of the adhesively bonded joints consider planar straight adherend surfaces. One way of increasing the load-bearing capability of these joints is by contouring the adherends at the adhesive interface. However, the influence of adherend profiles to the strength of adhesively bonded joints is still unclear. This induces a motivation to study the behavior of different geometry of adhesive joints under bi-axial loads. Thus, another motivation of this study is to investigate experimentally and numerically the failure behavior of adhesive

bonded composite joints with different geometries under in-plane bi-axial stress conditions.

Figure 1.5 Stress conditions in the adhesive layer of various joint types.

Therefore, the research focuses on investigating experimentally and numerically the fracture behavior of pre-cracked FRP composite materials and adhesive bonded composite joints under static in-plane bi-axial loading conditions. For the overall dissertation, the scopes of this dissertation are as follows:

- To design and fabricate the bi-axial fixtures for tension – shear, tension – tension, and tension - compression load conditions.
- To characterize damage of cross-ply laminates under normal stress – shear bi-axial condition and to generate a failure envelope in fracture toughness space.

- To investigate failure initiation and propagation of cross-ply laminates under tension – tension and tension - compression bi-axial condition and to generate a failure envelope in both stress and fracture toughness space.
- To explore the direction and pattern of crack propagation on the failure envelopes along with the laminate configuration.
- To investigate the effect of adherend geometry on the failure of adhesive bonding composite joints.
- To implement a numerical approach for prediction of adhesive bonded composite joints by employing commercial finite element modelling package ABAQUS software.

1.3 Dissertation Report Layout

The structure of this dissertation will be presented as follows:

Chapter 1 introduces the background, motivation, and objectives of this study.

Chapter 2 reviews the fundamental theories and contemporary literature related to this study. Firstly, the current works on bi-axial tests for composite laminates under tension – shear, tension – tension and tension – compression loads are addressed. Secondly, investigation efforts on the adhesive bonding composite joints are provided. Lastly, the background knowledge regards to the research practices is summarized.

Chapter 3 present the briefs of experimental methods with the material system and specimen preparation.

Chapter 4 describes the design of a novel fixture which can generate all quarters of principal stress envelope using cruciform specimens.

Chapters 5 to 7 delineate the main results and discussion of this research.

Chapter 5 quantifies the damage of the cross-ply GFRP composite laminates under tension – shear loads using a modified Arcan fixture. Crack patterns were discussed with the relative failure modes. Moreover, the fracture toughness surface was plotted to characterize the mixed-mode behavior of the laminates.

Chapter 6 examines the effects of crack size, crack direction, and loading ratios on the bi-axial strength and progressive damage of damaged FRP laminate. Experimental methods and results are detailed in various test cases, with the following parameter of crack length, namely 40mm and 45mm, 0°, 30°, and 45° crack angles, corresponding 0:1 to 1:0 stress ratios.

Chapter 7 investigates the failure of adhesive bonding composite joints with three shapes under various loading ratios. A numerical approach is proposed to predict the behavior of these joints in all test cases studied experimentally in this chapters.

Chapter 8 summarizes conclusions from the experimental and numerical studies and briefly propose recommendations for further research.

1.4 Findings and Contributions

The major findings and contributions of this research are summarized as follows:

- A novel design of bi-axial testing fixture which can produce the tension – tension, tension – compression, compression – compression bi-axial loading conditions with different displacement ratios was proposed. Cruciform specimens were used for the in-plane bi-axial tests. Therefore, this can be a low-cost alternative to characterize the behavior of composite laminates under in-plane bi-axial stress states.
- Fracture characteristics of unidirectional and cross-ply glass FRP composite laminates were investigated under bi-axial tension – shear loading conditions using a modified Arcan fixture. Different crack propagation patterns were observed in these tests. Moreover, the fracture toughness values were determined and plotted in a fracture toughness space. The failure envelope in the fracture toughness space shows three regions including mode I dominant, mode II dominant, and mixed-mode dominant. The mode I fracture pattern were likely to occur more frequently than the mode II fracture pattern. These findings offer a better understanding of crack initiation and propagation mechanisms of FRP composite laminates under biaxial tension – shear loading conditions.

– Failure behavior of cross-ply laminate cruciform specimens was studied under the in-plane bi-axial tension – tension and tension – compression static loading condition using cruciform specimens. The failure envelopes were generated under axial – transverse stress space and fracture toughness domain. The results showed that the failure of the laminate with cracks occurred in crack opening mode under bi-axial tension – tension loading conditions. This realistic behavior is significant to the composite community to enhance material efficiency in composite designs.

– The influences of adherend interface geometry in adhesively bonded butt joints on the failure response were experimentally and numerically studied under bi-axial tensile – shear loads. Three different types of specimens with the straight, rectangle and triangle shape contours were used in the experiment using a modified Arcan fixture. The obtained experimental results showed that the straight contour specimens gave the highest strength for all combination of tension and shear loads. The finite element model using fracture mechanics approach i.e. stress singularity based calculations should be implemented for further study. However, the current models predicted the strength of traditional butt joints in good agreement with the experimental measurements.

References

- [1] IRENA, "Renewable Energy and Jobs - Annual Review 2017," in *International Renewable Energy Agency*, ISBN: 978-92-9260-027-3 ed. Abu Dhabi, 2017.
- [2] Y. Huang, S. K. Ha, J. Koyanagi, J. D. D. Melo, H. Kumazawa, and I. Susuki, "Effects of an open hole on the biaxial strengths of composite laminates," *Journal of Composite Materials*, vol. 44, pp. 2429-2445, 2010.
- [3] "Retrieved August 11, 2017, from <https://www.euractiv.com/section/climate-environment/news/denmark-breaks-its-own-world-record-in-wind-energy/>."

- [4] REN21., "Renewables 2017 Global Status Report," ISBN 978-3-9818107-6-9 ed. Paris: REN21 Secretariat, 2017.
- [5] M. M. M. Saad and N. Asmuin, "Comparison of horizontal axis wind turbines and vertical axis wind turbines," *IOSR Journal of Engineering (IOSRJEN)*, vol. 4, pp. 27-30, 2014.
- [6] R. H. Barnes and E. V. Morozov, "Structural optimisation of composite wind turbine blade structures with variations of internal geometry configuration," *Composite Structures*, vol. 152, pp. 158-167, 2016/09/15/ 2016.
- [7] A. S. Chen and F. L. Matthews, "A review of multiaxial/biaxial loading tests for composite materials," *Composites*, vol. 24, pp. 395-406, 7// 1993.
- [8] H. Thom, "A review of the biaxial strength of fibre-reinforced plastics," *Composites Part A: Applied Science and Manufacturing*, vol. 29, pp. 869-886, 8// 1998.
- [9] A. Smits, C. Ramault, A. Makris, D. Hemelrijck, A. Clarke, C. Williamson, *et al.*, "A Review of Biaxial Test Methods for Composites," in *Experimental Analysis of Nano and Engineering Materials and Structures*, E. E. Gdoutos, Ed., ed: Springer Netherlands, 2007, pp. 933-934.
- [10] R. Olsson, "A survey of test methods for multiaxial and out-of-plane strength of composite laminates," *Composites Science and Technology*, vol. 71, pp. 773-783, 4/12/ 2011.
- [11] B. Hayman, J. Wedel-Heinen, and P. Brøndsted, "Materials challenges in present and future wind energy," *Mrs Bulletin*, vol. 33, pp. 343-353, 2008.
- [12] M. Hinton, A. Kaddour, and P. Soden, "The world-wide failure exercise: Its origin, concept and content," *Failure criteria in fiber reinforced polymer composites: the world wide failure exercise*. Elsevier, Amsterdam, pp. 2-28, 2004.

- [13] M. J. Hinton, A. S. Kaddour, and P. D. Soden, *Failure criteria in fibre reinforced polymer composites: the world-wide failure exercise*: Elsevier, 2004.
- [14] A. Kaddour and M. Hinton, "The background to the second world-wide failure exercise (WWFE-II)," *J Compos Mater*, vol. 46, pp. 2283-2294, 2012.
- [15] A. Kaddour, M. Hinton, P. Smith, and S. Li, "The background to the third world-wide failure exercise," *Journal of Composite Materials*, vol. 47, pp. 2417-2426, 2013.
- [16] C. Dalle Donne, K.-H. Trautmann, and H. Amstutz, "Cruciform specimens for in-plane biaxial fracture, deformation, and fatigue testing," in *Multiaxial Fatigue and Deformation: Testing and Prediction*, ed: ASTM International, 2000.
- [17] A. Smits, D. Van Hemelrijck, T. Philippidis, and A. Cardon, "Design of a cruciform specimen for biaxial testing of fibre reinforced composite laminates," *Composites science and technology*, vol. 66, pp. 964-975, 2006.
- [18] J. S. Welsh, J. S. Mayes, and A. C. Biskner, "2-D biaxial testing and failure predictions of IM7/977-2 carbon/epoxy quasi-isotropic laminates," *Composite Structures*, vol. 75, pp. 60-66, 2006.
- [19] A. Makris, C. Ramault, D. Van Hemelrijck, D. Zarouchas, E. Lamkanfi, and W. Van Paepegem, "An investigation of the mechanical behavior of carbon epoxy cross ply cruciform specimens under biaxial loading," *Polymer Composites*, vol. 31, pp. 1554-1561, 2010.
- [20] B. F. Sørensen, E. Jørgensen, C. P. Debel, F. M. Jensen, H. Jensen, T. Jacobsen, *et al.*, "Improved design of large wind turbine blade of fibre composites based on studies of scale effects (Phase 1). Summary report," 8755031765, 2004.

- [21] J. S. Welsh and D. F. Adams, "Development of an electromechanical triaxial test facility for composite materials," *Experimental Mechanics*, vol. 40, pp. 312-320, 2000/09/01 2000.
- [22] A. Rashedi, I. Sridhar, and K. J. Tseng, "Fracture characterization of glass fiber composite laminate under experimental biaxial loading," *Composite Structures*, vol. 138, pp. 17-29, 2016/03/15/ 2016.
- [23] H. L. J. Pang and C. W. Seetoh, "A Compact Mixed Mode (CMM) fracture specimen for adhesive bonded joints," *Engineering Fracture Mechanics*, vol. 57, pp. 57-65, 1997/05/01/ 1997.
- [24] J. Y. Cognard, P. Davies, B. Gineste, and L. Sohier, "Development of an improved adhesive test method for composite assembly design," *Composites Science and Technology*, vol. 65, pp. 359-368, 2005/03/01/ 2005.
- [25] J. Y. Cognard, L. Sohier, and P. Davies, "A modified Arcan test to analyze the behavior of composites and their assemblies under out-of-plane loadings," *Composites Part A: Applied Science and Manufacturing*, vol. 42, pp. 111-121, 2011/01/01/ 2011.
- [26] J. Y. Cognard, P. Davies, L. Sohier, and R. Créac'hacdec, "A study of the non-linear behaviour of adhesively-bonded composite assemblies," *Composite Structures*, vol. 76, pp. 34-46, 2006/10/01/ 2006.
- [27] P. Davies, L. Sohier, J. Y. Cognard, A. Bourmaud, D. Choqueuse, E. Rinnert, *et al.*, "Influence of adhesive bond line thickness on joint strength," *International Journal of Adhesion and Adhesives*, vol. 29, pp. 724-736, 2009/10/01/ 2009.
- [28] J. Y. Cognard, "Numerical analysis of edge effects in adhesively-bonded assemblies application to the determination of the adhesive behaviour," *Computers & Structures*, vol. 86, pp. 1704-1717, 2008/09/01/ 2008.
- [29] J. Legendre, R. Créac'hacdec, F. Gilbert, and D. Jacquet, "A new method to measure the adhesion capability of the metallic surface under shear

- loading using a modified Arcan test," *The Journal of Adhesion*, pp. 1-19, 2017.
- [30] B. Valès, S. Marguet, R. Créac'hacdec, L. Sohier, J. F. Ferrero, and P. Navarro, "Experimental & numerical study of the Tensile/Compression-Shear Arcan test under dynamic loading," *International Journal of Adhesion and Adhesives*, vol. 78, pp. 135-147, 2017/10/01/ 2017.
- [31] M. Costa, R. Carbas, E. Marques, G. Viana, and L. F. M. da Silva, "An apparatus for mixed-mode fracture characterization of adhesive joints," *Theoretical and Applied Fracture Mechanics*, 2017/04/25/ 2017.

Chapter 2

Literature Review

This chapter reviews the fundamental theories and previous work related to this study. Firstly, the important aspects of bi-axial testing methods are presented. Afterwards, the literature on bi-axial tests using cruciform specimens and Arcan tests are introduced. Subsequently, the background knowledge of bi-axial testing and analysis of composite laminates are described. Finally, this chapter briefly summarizes all aspects related to this research topic and indicates the research gaps.

2.1. Introduction

Glass/carbon fiber-reinforced polymer (FRP) matrix composite shell/laminates have been increasingly employed in wind power industry to fabricate lightweight and stiff blades. These anisotropic materials has been used in the wind turbine blades which are subjected complex stress states. By using data from a conventional uniaxial test of the composite laminate in the design processes, safety factors might be overestimated which might lead to unnecessary enlargement of structure sizes [1]. Compared to the uniaxial testing method, the bi-axial testing approach provides more realistic data on the behavior of the composite structure under complex loading situations [2]. Due to the lack of bi-axial experimental data results of FRP composite shell/laminates and adhesive bonded composite joints [3-6], the effects of bi-axial stress states on failure behavior of these composite components under static bi-axial conditions are investigated in this study. Although the literature covers a variety of contexts in this topic, this chapter will focus on four themes for FRP composite materials i.e. bi-axial test methods, in-plane bi-axial testing of composite laminates, adhesively bonded joint under tension/compression – shear, and background.

2.2. Bi-axial testing methods

As discussed in Chapter 1, important wind turbine parts such as shells, laminates, and adhesively bonded joints are operating under bi-axial stress states such as tension – tension, tension – compression, tension – compression for composite laminates, and tension/compression – shear for adhesively bonded joints. Over the past decades, different methods to produce bi-axial stress/strain states for FRP composite materials have been proposed such as bulge test (Figure 2.1a), tubular specimens under axial loading and torsion or internal pressure (Figures 2.1b and 2.1c), plates under tension and shear (Figure 2.1d), Arcan test (Figure 2.1e), cruciform specimen test (Figure 2.1f), etc.[7-10]. Bulge test is limited in the testing of composite laminates because delamination damage occurs in laminates under bending forces which affect the testing results. The

methods using tubular specimens are commonly applied due to their ability to perform any bi-axial stress ratio. However, these methods have some drawbacks such as the difference between tubular structure, and flat or gently curved structure of real components, the effect of radial stress gradients may be significant in some cases, the difficulty of fabricating thin walled tubes [11]. Therefore, specimens such as Arcan test specimens and cruciform specimens under in-plane bi-axial forces have been used as an alternate for tubular specimens to produce more realistic uniform stress/strain distribution in the test sample gauge area.

Figure 2.1 Common bi-axial testing methods: (a) A bulge test; (b) A tubular specimen under axial loading and internal pressure; (c) A tubular specimen under axial loading and torsion; (d) A rectangle specimen under tension and shear; (e) An Arcan test; and (f) A flat cruciform specimen under in-plane bi-axial loading.

The specimen under Arcan test has an in-plane uniform bi-axial tension/compression - shear stress zone along the middle. This test has been used to investigate the many in-plane behavior of composite laminates under tension – shear loadings [6, 12-15]. Recently, Taher et al. introduced a novel design of a modified Arcan fixture to determinate the properties of PVC foam [16, 17] which can also be used for composite sandwich structures.

Development of two normal bi-axial stress components using cruciform specimens for composite materials has attracted considerable attention recently. The test machines can be the specified design attachments such as frame fixture or linkage fixtures; and stand-alone bi-axial testing machines. In the former group, many designs had been proposed as compact linkage mechanism or fixture frames which were mounted on uniaxial universal testing machines and connected to cruciform specimens through four arms [18-22]. Although these fixtures could reduce the machine cost, the length of linkage bars needs to be changed for each bi-axial loading ratio. An alternative is to use stand-alone systems which have four hydraulic actuators with their individual four load cells. This apparatus has been increasingly sought after to investigate the behavior of composite materials due to their capability of creating a wide range of bi-axial loading ratios [23, 24]. However, the drawback of this device includes the complication in the design, control and operation, large overall dimensions and costly specimen fabrication. Thus, it is necessary to develop bi-axial testing systems which can flexibly generate various bi-axial loading ratios at reasonable expenditures.

The shape of cruciform testing specimens is also critical to create a relevant bi-axial stress distribution in the gauge section of the test specimen. Numerous investigations have been carried out to optimize the geometry of composite cruciform specimens [25-31]. The requirements of specimens for a successful bi-axial test include (i) uniform stress distribution in the gage area, (ii) failure in gage area and (iii) repeatable results [32]. To fulfill the first requirement, finite element analysis (FEA) models are used to evaluate the effect of geometric

parameters (the rounding radius at the corner of two arms, the thickness of gage zone and the arms, the shape of gage zone) on the stress and strain distribution in the specimens. To satisfy the second requirement, the cruciform specimens are designed with a reduction in the thickness of central test zone or having a stress riser function such as a hole, a notch or a crack in the center of the specimens. Subsequently, experiments are carried out to validate the uniform of strain field on the gage zone by using strain monitoring techniques. Although the specimen geometry is carefully designed, it is possible that testing specimens fail outside the gage area due to defects during fabrication.

Besides, the full stress/strain field monitoring techniques are an important aspect of a comprehensive test of composite materials under bi-axial loading. Recently, various methods have been introduced such as digital image correlation (DIC), holographic interferometry (HI), electronic speckle pattern interferometry (ESPI), acoustic emission (AE), Laser Raman spectroscopy (LRS), and Photoelastic and Thermoelastic testing [8]. Besides, the X-ray photography, ultrasonic inspection, optical and scanning electron microscopy are employed to inspect the post failure data of bi-axial tests [33].

In summary, bi-axial testing methods using cruciform specimen on composite materials have improved due to the development of bi-axial testing facilitates, process monitoring methods and numerical tools. However, the bi-axial data from these methods are limited because of the expensive costs of the testing equipment, sample preparation, and experiment operation. Consequently, an innovative testing fixture which is compatible with the conventional uniaxial testing machine is required to investigate the failure behavior of composite laminates under bi-axial stress states.

2.3. In-plane bi-axial testing of composite laminates

Though many testing methods for composite materials had been introduced, the bi-axial tests using cruciform specimens and Arcan butterfly specimens show potential to generate the reliable in-plane bi-axial stress states in the composite laminates. Various applications of bi-axial testing using composite cruciform are

presented in many aspects of engineering such as generating failure bi-axial data, identifying the material characterization etc. Welsh et al. [26, 34] studied the ultimate bi-axial strength of carbon/epoxy cross-ply and quasi-isotropic laminates to generate the bi-axial failure envelopes experimentally and analytically. Lecompte et al. [35, 36] proposed an inverse method to identify the composite material engineering constantly by using DIC method to record the full field strain distribution on cruciform specimens under bi-axial tension. Then this data was analyzed to calculate the material mechanical properties which would be directly applied in the prediction of laminate behavior using FEA in the subsequent studies.

The effect of bi-axial stress condition on the behavior of glass/carbon FRP composite materials using cruciform specimens is studied by numerous early researchers. Bert et al. [37] found that limit strengths of glass fiber woven cloth reinforced epoxy laminates under bi-axial tension tests were significantly greater than that under uniaxial tension tests. A later investigation by Daniel [38] measured the nonlinearities of strain distribution on the boundary of a circular hole, which was in quasi-isotropic graphite/epoxy composite plates, under equal bi-axial tensile loadings. This study indicated a decrease in notch sensitivity of the laminates under bi-axial stress condition. Jone et al. [39] performed a similar study to Daniel but with various bi-axial loading ratios on $[0/\pm 45/90]_{ns}$ and $[0_2/\pm 45]_{ns}$. It was concluded that an increase in loading bi-axiality could lead to an increase in failure strength of $[0/\pm 45/90]_{ns}$ laminates and a change in the fracture path from 90° to approximately 45° . For cyclic loading, they also conducted in-plane fatigue tests on graphite/epoxy composites cruciform specimens with a central hole under bi-axial cycle loads. The results showed that the fatigue life was longer for the cases of bi-axial stress ratio of 0.5 on $[0/\pm 45/90]_{ns}$ lay-up and the ratio 0 to 0.5 on $[0_2/\pm 45]_{ns}$ lay-up. In a study on damage mechanisms in GFRP with $[0,90]_n$, $[22.5/112.5]_n$ and $[\pm 45]_n$ laminates under many bi-axial fatigue ratios, Smith and Pascoe [40] reported that extent of bi-axial load ratio and mode of damage could affect fatigue strength. These

efforts had highlighted the bi-axial strengthening effects or bi-axial load benefits under bi-axial test on composite cruciform specimens, especially in quasi-isotropic laminates and therefore showed a need for further investigations.

Besides, bi-axial data from cruciform tests have been commonly used to verify the failure model of the composite laminate. The requirement of these data was represented in the world wide failure exercise (WWFE) [3, 5, 41]. Sun et al. [42] introduced a new multi-axial fatigue model for composite laminates based on Puck's criterion. This model prediction was verified by bi-axial fatigue test using a linkage fixture mounted on a universal testing machine (UTM) with a good agreement. Kureemun et al. [43] had conducted bi-axial tension – compressive tests used the same fixture for unnotched and open-hole carbon epoxy cross-ply laminate. A finite element method based on micromechanics had developed and predicted the critical and subcritical damage mechanisms governing the failure of the specimens. Recently, Rashedi et al. [44] investigated the fracture characterization of laminates with pre-cracks under bi-axial loading condition. A mixed-mode fracture criterion had proposed for the cross-ply composite laminate in this study. This study showed a lack of data for bi-axial fracture characterization for a composite material with cruciform geometry.

In addition to in-plane test using cruciform geometry, the Arcan tests have been used to investigate the interlaminar and intralaminar failure behavior of composite laminates under tension – shear loading conditions. The method introduced by Arcan to produce uniform tension and shear stress states for composite materials [12]. The uniform gauge section was verified by the inspection of photoelastic analysis. Later, Hung et al. [13] proposed a finite element analysis of Arcan specimens for unidirectional AS4/PEEK composite laminates under shear and tensile loadings. This study suggested that the butterfly shaped specimen which was bonded to steel grips could provide the much more uniform stresses than the original S-shaped Arcan specimen. Then, this method has become popular to investigate the material properties of the composite laminate such as interlaminar pure and mixed-mode fracture toughness [14, 45-

48], interface properties [49], or shear moduli [50-52]. To investigate the effect of fiber orientation under tension – shear stress, Gning et al. [53] presented work to test the unidirectional AS4/PEEK laminates with notch-to-notch longitudinally and perpendicularly orientation which noted as MAT31 and MAT32. The comparison between the failure envelopes established the MAT31 specimens are more resistant for a combination of bi-axial tension – shear load ratio. Recently, Tan et al. [6] had conducted the tests for carbon FRP laminate containing a notch or a circular hole under tension – shear bi-axial load, or compression load. The sub-critical damage modes and failure envelopes of laminates containing stress raiser features under bi-axial loading were provided. However, this study indicated the lack of fracture mechanisms of notched laminates under a combination of tension and shear.

In summary, the study on fracture behavior of laminates containing a notches/crack under the combination of in-plane tension/compression – tension/compression, tension/compression – shear is lacking. The current study aims to address this shortfall.

2.4. Adhesively bonded joint under tension/compression – shear

Adhesively bonded joints have been widely used in the wind turbine blade components to improve the strength to weight ratio of the structure or to connect complicated geometries. These joints usually operate under the bi-axial tension/compression – shear conditions. Numerical methods have been proposed to characterize the adhesive joint under bi-axial loading conditions [54]. To provide a deep understanding of the test method, Cognard et al. [55] had compared the shear tests of the standard thick adhered shear test (TAST) and tests using a modified Arcan fixture. The result showed modified Arcan fixture generated a more homogeneous stress state. To optimize the joint assembly, the geometry of adhesive layers was investigated by Jean et al. [56] and Cognard [57] using the finite element analysis [56, 58]. Modifications of joint geometry such as using a break, cleaning the edge of the adhesive, and increasing the thickness of the joint near the edge were proposed to cancel the influences of the edge

effects to the experimental scatter. Later, Creachcadec et al. [59] studied on the thick flexible adhesive joint under different monotonic tensile/compression – shear loading. This study indicated that the joint with substrates with break have a reduction of stress concentration. The influence of adhesive thickness was also investigated by Davis et al [60]. The results indicated that the stress concentrations were higher for tension case than tension/shear and lowest in shear, and they increase with the increase of thickness. To provide the properties for predicting the joint failure, fracture toughness has been used as a design parameter which can be computed from Arcan test data [61-64] Recently, Valès et al. characterized the failure of adhesive of bonded assemblies using modified Arcan fixture under dynamic bi-axial loading [65]. An adequate testing device was proposed for testing adhesively bonded joints under dynamic tension/compression – shear loads. Consequently, it is concluded that most investigation had focused on the optimizing the joint geometry as well as determining the fracture properties of adhesively bonded joints under a combination of tension/compression and shear. However, the joints with straight adhesive layer were commonly employed in these investigations. The study on the effect of substrate profiles to the adhesive joint strength under bi-axial conditions is rarely reported in the literature. Therefore, this study aims to fulfill this lack.

2.5. Stress calculation for cruciform specimens

The exact loaded areas are unknown for a cruciform specimen as the geometry of the arm is not straight. This induced a difficult to calculate the applied stress of a cruciform specimen. Two approaches have been proposed to determine the value of applied stress which are using the equivalent areas and using the strain values to compute the stress values based on constitutive law. In the first method, the standard coupon tests are conducted to find out the ultimate strength of materials along the x and y axes respectively. Then the cruciform specimens are loaded uniaxially in two relative perpendicular axes. The equivalent areas are calculated by dividing the critical force to the ultimate

strength. The method is illustrated in Figure 2.2. Another method is using the strain values which are measured from monitor methods such as DIC or ESPI. This values then multiply with the stiffness matrix to determine the stresses. Both methods assume the linear elastic behavior up to failure to provide the accurate values of computed applied stresses.

Figure 2.2 Method to calculate the equivalent areas [29].

2.6. Fracture toughness test of composite materials

Geometric discontinuities such as cracks, notches, holes, etc. are indicated as the main reason of failure in many composite structures. In order to investigate the stability of a crack or a flaw and predicting the possibility of its propagation, the theory of linear elastic fracture mechanics (LEFM) has been developed. The complex behavior of a crack is classified into three independent modes which include mode I (Figure 2.3a); mode II (Figure 2.3b) and mode III (Figure 2.3c). In each mode, the stability of a crack problem was presented by using stress intensity factor K and fracture energy release rate G . If this parameter (K or G) reaches its critical values or satisfy a mixed mode criterion, a crack will start to propagate.

Figure 2.3 Three fracture modes: (a) opening, (b) in-plane shear, (c) out of plane shear.

Numerical methods have been proposed for testing the fracture parameters for three fracture modes and mixed mode conditions. Three of these methods were introduced in ASTM D4762-11a [66] for composite materials include Double cantilever beam (DCB) method (Figure 2.4a); mixed mode bending (MMB) method (Figure 2.4b); and compact tension test (CTT) method (Figure 2.4c). The DCB method has been used to identify the interlaminar fracture toughness in the opening mode of delamination problems by using a flat rectangle specimen under tension. The MMB method is an extension of DCB method to measure mixed mode I/II interlaminar critical energy release rate by using the flat rectangle specimen under bending loads. The CTT method can be used to measure the translaminar critical stress intensity factor.

Figure 2.4 Fracture toughness testing methods: (a) DCB method, (b) MMB method and (c) CCT method [67-69].

In the DCB method, the value of interlaminar fracture toughness is calculated as follows [67]:

$$G_{IC} = \frac{3P_c \delta}{2ba} \quad (2.1)$$

where P_c is critical load at fracture, δ is load point displacement, b is specimen width, and a is the delamination length. Moreover, the mixed mode I/II interlaminar fracture strain energy release rate in mode I in ENF method are given by [68]:

$$G_I = \frac{12P^2(3c - L)^2}{16b^2h^3L^2E_{1f}}(a + xh)^2 \quad (2.2)$$

$$G_{II} = \frac{9P^2(c + L)^2}{16b^2h^3L^2E_{1f}}(a + 0.42xh)^2 \quad (2.3)$$

where P is applied load, a is delamination length, b is specimen width, c is lever length of the test apparatus, L is half-span length of the test apparatus, h is half thickness of test specimen, x is crack length correction parameter, E_{1f} is modulus of elasticity in fiber direction measured in flexure. For translaminar problems, the stress intensity factor in CTT method is calculated from the following expression [69]:

$$K = \frac{P}{BW^{\frac{1}{2}}} \alpha^{\frac{1}{2}} (1.4 + \alpha) (3.97 - 10.88\alpha + 26.25\alpha^2 - 38.9\alpha^3 + 30.15\alpha^4 - 9.27\alpha^5) / (1 - \alpha)^{3/2} \quad (2.4)$$

where P is applied load, α is a/W ratio, a is notch length, B is specimen thickness, W is specimen width.

Recently, Choupani [46] modified the testing method of Arcan et al. [12] to measure the interlaminar fracture toughness in modes I, II and mixed mode I/II of carbon/epoxy cross-ply composite laminates. A test apparatus was fabricated included two separate parts with various holes to change the loading angle (see Figure 2.6). Specimens were fabricated in a butterfly shape and clamped between the two parts. Due to varying the loading angle, the fixture could provide testing conditions of pure mode I ($\alpha = 0^\circ$), pure mode II ($\alpha = 90^\circ$) or mixed mode I/II

($90^\circ > \alpha > 0^\circ$). The critical stress intensity factors K_{IC} , K_{IIC} on the crack tip are calculated as [46]:

$$K_{IC} = \frac{P_{IC}\sqrt{\pi a}}{wt} \cos(\alpha) f_1\left(\frac{a}{w}\right) \quad (2.5)$$

$$K_{IIC} = \frac{P_{IIC}\sqrt{\pi a}}{wt} \sin(\alpha) f_2\left(\frac{a}{w}\right) \quad (2.6)$$

where P_c is critical load at fracture determined from experiment, w is specimen length, t is specimen thickness, α is loading angle, a is crack length, $f_1(a/w)$ and $f_2(a/w)$ are the non-dimensional geometric correction factors in mode I and mode II calculated by FEA respectively.

Figure 2.5 Modification Arcan fixture [46].

2.7. Analysis of composite materials

The behavior of composite laminates under different loading conditions is complicated due to the multilayered, multi-material and anisotropic

characteristics of these materials. Various analytical and numerical solutions are presented to analyze the complex failure behavior of composite materials such as continuum models, fracture mechanics of composites, finite element method, extended finite element method [70]. In conventional continuum laminate models, general assumptions are presented to analysis composite materials; which are; (1) each lamina is considered as an equivalent homogeneous orthotropic continuum laminate, (2) the bond between fiber and matrix in each layer is assumed to be perfect, (3) strain is continuous through the interface and (4) fibers are in regular arrangement. One example of these models is the classical lamination theory which describes the multilayered laminate according to material properties (fiber orientation, stacking sequence, ply elasticity, etc.). Recently, innovative continuum models which cover interactions between fibers, interfaces, and matrixes in each ply have been developed to predict the behavior of composite laminates using micromechanics. However, they are only limited to solve the problems of simplified geometries with specific layup configuration and loading conditions.

Another important analytical solution for composites is fracture mechanics which can determine a state of crack stability and possibility of crack propagation. Fracture-based parameters such as stress intensity factor and energy release rate are used to define the effect of a crack on the behavior of a cracked structure. Numerous studies on near crack tip stress using infinite tension plate with a crack or a hole were conducted [71-73]. These studies indicated the non-uniform bi-axial stress distribution around the crack tip with stress concentration. Irwin et al. [74] presented the concept of stress intensity factor K to describe the strength of the singularity around the crack tip. The stress intensity factors in mode I, mode II and mode III are related to near crack tip stresses by following equations:

$$K_I = \lim_{r \rightarrow 0} \sigma_{yy} \sqrt{2\pi r} \quad (2.7)$$

$$K_{II} = \lim_{r \rightarrow 0} \sigma_{xy} \sqrt{2\pi r} \quad (2.8)$$

$$K_{III} = \lim_{r \rightarrow 0} \sigma_{yz} \sqrt{2\pi r} \quad (2.9)$$

where σ_{yy} , σ_{xy} , σ_{yz} are near crack tip stresses in mode I, mode II and mode III respectively, r is distance the from crack tip. It was indicated that crack propagation occurs when the value of K reaches a critical value K_c termed as fracture toughness. Each fracture mode has its fracture toughness (i.e. K_{IC} , K_{IIC} , and K_{IIIC}); a mixed-mode criterion can be applied to explain the interaction between individual fracture modes.

In an attempt to evaluate the strength of solids of glass rods in different diameters, Griffith et al. [75] proposed a fracture criterion based on the total change in energy of a cracked body in terms of the crack length. Crack growth energy G is defined as the energy release rate per unit crack extension. A crack becomes unstable when the value of G reaches the critical value of surface energy. For linear elastic fracture mechanics (LEFM), the energy release rates are calculated from the following relationships:

$$G = \frac{K^2}{E'} \quad (2.10)$$

where E' is young modulus ($E' = E$ for plane stress and $E' = E/(1 - \nu^2)$ for plane strain, ν is Poisson's ratio). The LEFM theories have been used to solve many problems in composite materials such as predicting delamination of composite laminates or growth of micro crack in the matrixes. For complex structures, the fracture mechanic theories are required to adapt with various techniques to analyze the behavior of the composite materials.

Due to the ability to handle complex geometries and boundary conditions under many types of loading, finite element method (FEM) is well developed and has been extensively employed to solve numerous engineering and research problems. Numerical methods based on FEM framework were introduced to reproduce the singularity stress field at the crack tip or predict the behavior of crack propagation. One of the most common approaches was proposed by Owen and Fawkes [76]. Singular finite elements are defined by shifting the nearby middle nodes to the quarter points without changing other the elements (illustrated in Figure 2.6a). This approach provides the accurate representation of crack-tip singular fields. However, the method may require large computational

resources and long execution time to re-mesh in each step of calculation when cracks propagate. To overcome the re-meshing problem, Belytschko and Black [77] introduced a method to minimize the meshing process during calculating of crack growth. They modified the finite element formulations by adding discontinuous enrichment functions to present a crack (see Figure 2.6b). Later, Moes et al. [78] proposed the mesh-independent method, also called extended finite element method (XFEM), to analyze a crack based on enriched approximation. The advantages of this method are the ability to reproduce singular stress state at the crack tip and to simulate crack propagation path without changing the mesh. Therefore, XFEM has rapidly become an important tool to analyze fracture problems and incorporated in commercial FEM packages such as Abaqus, Ansys, Aster, etc.

Figure 2.6 Numerical methods of failure analysis: (a) Finite element method, (b) Extended finite element method [70].

2.8. Failure criteria for composite materials

Failure theories of composite material have been attracted considerable attention to predicting the failure behavior of composite structures. Generally, the failure occurs in one or any combinations of four modes i.e. matrix failure, interlaminar failure, fiber/matrix debonding and fiber failure (see Figure 2.7).

Numerous failure criteria have been proposed over the last few decades, which can be categorized into three classes [41, 79]: (1) limit or noninteractive theories (e.g. maximum stress, maximum strain); interactive theories (e.g. Tsai-Hill [80], Tsai-Wu [81]); and partially interactive or failure mode-based theories (e.g. Hashin-Rotem [82], Puck [83]) (see Table 2.1). Of these, maximum stress, maximum strain, Tsai-Hill and Tsai-Wu theories are widely applied in engineering problems and have been developed in many FEM codes for composite materials. However, the failure load predictions obtained from these failure theories are not in good agreement with experimental bi-axial testing results [41]. According to the WWFE results, Hilton et al. concluded that the results achieved by using the theories of Zinoviev [84], Bogetti [85], Puck and Cuntze [86] could fit the experimental data well. However, there is a need to integrate these failure criteria into FEM or XFEM to predict damage behavior of composite materials.

Figure 2.7 Illustration of failure mechanisms of composite laminates.

Table 2.1 Common failure criteria for composites materials [80-83].

<i>Criterion name</i>	<i>Equations</i>
Maximum stress	<p>Fiber failure: $\sigma_1 \geq \sigma_{1T}^u$ (tension) or $\sigma_1 \geq \sigma_{1C}^u$ (compression)</p> <p>Matrix failure: $\sigma_2 \geq \sigma_{2T}^u$ (tension) or $\sigma_2 \geq \sigma_{2C}^u$ (compression)</p> <p>Shear failure: $\sigma_{12} \geq \sigma_{12}^u$</p>
Maximum strain	<p>Fiber failure: $\varepsilon_1 \geq \varepsilon_{1T}^u$ (tension) or $\varepsilon_1 \geq \varepsilon_{1C}^u$ (compression)</p> <p>Matrix failure: $\varepsilon_2 \geq \varepsilon_{2T}^u$ (tension) or $\varepsilon_2 \geq \varepsilon_{2C}^u$ (compression)</p> <p>Shear failure: $\varepsilon_{12} \geq \varepsilon_{12}^u$</p>
Tsai-Hill	<p>Plane stress: $\left(\frac{\sigma_1}{S_1}\right)^2 + \left(\frac{\sigma_2}{S_2}\right)^2 - \frac{\sigma_1\sigma_2}{S_1^2} + \left(\frac{\tau_{12}}{S_{12}}\right)^2 = 1$</p> <p>where $S_1 = \sigma_{1T}^u$ (tension) or $S_1 = \sigma_{1C}^u$ (compression)</p> <p>$S_2 = \sigma_{2T}^u$ (tension) or $S_2 = \sigma_{2C}^u$ (compression)</p> <p>$S_{12} = \tau_{12}^u$</p>
Tsai-Wu	<p>Plane stress: $F_1\sigma_1 + F_2\sigma_2 + F_6\tau_{12} + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\tau_{12}^2 + 2F_{12}\sigma_1\sigma_2 + 2F_{16}\sigma_1\tau_{12} + 2F_{26}\sigma_2\tau_{12} = 1$</p> <p>where $F_1 = \frac{1}{\sigma_{1T}^u} - \frac{1}{\sigma_{1C}^u}$, $F_{11} = \frac{1}{\sigma_{1T}^u\sigma_{1C}^u}$</p> <p>$F_2 = \frac{1}{\sigma_{2T}^u} - \frac{1}{\sigma_{2C}^u}$, $F_{11} = \frac{1}{\sigma_{2T}^u\sigma_{2C}^u}$</p>

	$F_6 = 0, F_{66} = \left(\frac{1}{\tau_{12}^u}\right)^2, F_{16} = 0, F_{26} = 0$ $F_{12} = -\frac{1}{2}\sqrt{F_{11}F_{22}}$
Hashin-Rotem	<p>Fiber failure: $\sigma_1 = \sigma_{1T}^u$ (tension) or $-\sigma_1 = \sigma_{1C}^u$ (compression)</p> <p>Matrix failure: $\left(\frac{\sigma_2}{\sigma_{2T}^u}\right)^2 + \left(\frac{\sigma_{12}}{\sigma_{12}^u}\right)^2 = 1$ (tension) or</p> $\left(\frac{\sigma_2}{\sigma_{2C}^u}\right)^2 + \left(\frac{\sigma_{12}}{\sigma_{12}^u}\right)^2 = 1 \text{ (compression)}$
Puck	<p>Fiber fracture:</p> $\frac{1}{\epsilon_{1T}} \left(\epsilon_1 + \frac{\nu_{f12}}{E_{f1}} m_{\sigma f} \sigma_2 \right) = 1 \text{ (tension)}$ $\frac{1}{\epsilon_{1C}} \left \epsilon_1 + \frac{\nu_{f12}}{E_{f1}} m_{\sigma f} \sigma_2 \right = 1 - (10\gamma_{21})^2 \text{ (compression)}$ <p>Inter-fiber fracture:</p> <p>Mode A:</p> $\sqrt{\left(\frac{\tau_{21}}{s_{21}}\right)^2 + \left(1 - p_{\perp\parallel}^{(+)} \frac{Y_T}{s_{21}}\right)^2 \left(\frac{\sigma_2}{Y_T}\right)^2} + p_{\perp\parallel}^{(+)} \frac{\sigma_2}{s_{21}} = 1 - \left \frac{\sigma_1}{\sigma_{1D}}\right \text{ for } \sigma_2 > 0$ <p>Mode B:</p> $\frac{1}{s_{21}} \left(\sqrt{\tau_{21}^2 + \left(p_{\perp\parallel}^{(-)} \sigma_2\right)^2} + p_{\perp\parallel}^{(-)} \sigma_2 \right) = 1 - \left \frac{\sigma_1}{\sigma_{1D}}\right \text{ for } \sigma_2 < 0$ <p>and $0 \leq \left \frac{\sigma_2}{\tau_{21}}\right < \frac{R_{11}^A}{ \tau_{21c} }$</p> <p>Mode C:</p>

$$\left[\left(\frac{\tau_{21}}{2(1+p_{\perp\perp}^{(-)})S_{21}} \right)^2 + \left(\frac{\sigma_2}{Y_C} \right)^2 \right] \frac{Y_C}{(-\sigma_2)} = 1 - \left| \frac{\sigma_1}{\sigma_{1D}} \right| \text{ for } \sigma_2 < 0 \text{ and}$$

$$0 \leq \left| \frac{\sigma_2}{\tau_{21}} \right| < \frac{|\tau_{21c}|}{R_{\perp\perp}^A}$$

where

$$p_{\perp\parallel}^{(+)} = - \left(\frac{d\tau_{21}}{d\sigma_2} \right)_{\sigma_2=0}, \sigma_2 \geq 0 \text{ and } p_{\perp\parallel}^{(-)} = - \left(\frac{d\tau_{21}}{d\sigma_2} \right)_{\sigma_2=0}, \sigma_2 \leq$$

0

$$R_{\perp\perp}^A = \frac{S_{21}}{2 p_{\perp\parallel}^{(-)}} \left(\sqrt{1 + 2 p_{\perp\parallel}^{(-)} \frac{Y_C}{S_{21}}} - 1 \right)$$

$$p_{\perp\perp}^{(-)} = p_{\perp\parallel}^{(-)} \frac{R_{\perp\perp}^A}{S_{21}}$$

Figure 2.8 Inter-fiber fracture mode C, mode B, and mode A respectively [83].

$\sigma_{1T}^u, \sigma_{2T}^u, \sigma_{1C}^u, \sigma_{2C}^u$ are normal strengths of a lamina in the 1,2 direction under tension and compression respectively. τ_{12}^u is shear strength of the material in 12 plane.

$\varepsilon_{1T}^u, \varepsilon_{2T}^u, \varepsilon_{1C}^u, \varepsilon_{2C}^u$ are failure strain of the lamina in the 1,2 directions under tension and compression respectively. ε_{12}^u is shear failure strain of the material in 12 plane.

$\epsilon_{1T}, \epsilon_{1C}$ are tensile failure strain and compression failure strain of a lamina in 1 direction.

ν_{f12} is Poisson's ratio of fibers; E_{f1} is Poisson's ratio of fibers; $m_{\sigma f}$ is mean stress magnification factor.

Y_T, Y_C are tensile strength and compressive strength of a lamina transverse to the fiber direction; S_{21} is shear strength of a lamina transverse and parallel to the fiber direction; σ_{1D} is stress value for linear degradation.

Besides, crack propagation criteria were also introduced to predict the possibility of crack propagation based on the fracture mechanic theory. Erdogan et al. [87] first developed mixed mode stress intensity factor based on the solution of stress conditions near crack tips called maximum circumferential/hoop tensile stress. It was indicated that crack propagated in the direction which was perpendicular to the direction of maximum tension within a plane when the maximum circumferential tensile stress reached a critical value. The mixed mode criterion was defined as:

$$K_{\theta\theta} = \sigma_{\theta\theta} \sqrt{2\pi r} = K_I \cos^3 \frac{\theta}{2} - K_{II} \cos \frac{\theta}{2} \sin \theta = K_{IC} \quad (2.11)$$

where $K_{\theta\theta}$ is hoop stress intensity factor, $\sigma_{\theta\theta}$ is hoop stress, θ is crack angle, and K_{IC} is critical stress intensity factor.

Another criterion named minimum strain energy density criterion was presented by Sih et al. [88] and then was developed by Chang et al. [89]; which determined the crack propagated along a path with minimum strain energy density. The final form of this criterion was given by:

$$W_s = \frac{1}{16\pi\mu r} (a_{11}K_I^2 + 2a_{12}K_I K_{II} + a_{22}K_{II}^2) \quad (2.12)$$

where

$$\begin{aligned} a_{11} &= (1 + \cos \theta)(\kappa - \cos \theta) \\ a_{12} &= \sin \theta (2 \cos \theta + 1 - \kappa) \end{aligned}$$

$$a_{22} = (\kappa + 1)(1 - \cos \theta) + (1 + \cos \theta)(3 \cos \theta - 1)$$

κ is material parameter.

The crack propagates when:

$$\begin{cases} \frac{\partial^2 W_s(\theta)}{\partial \theta^2} > 0 \\ \frac{\partial W_s(\theta)}{\partial \theta} = 0 \end{cases} \quad (2.12)$$

By extending the solution of stress intensity factors, Hussain et al. [90] proposed a maximum energy release rate criterion; which assumed that propagation occurred when the value of energy release rate was maximum. An expression of the energy release rate was defined as:

$$\begin{aligned} G(\theta) &= \frac{1}{E'} (K_I^2(\theta) + K_{II}^2(\theta)) \\ &= \frac{1}{4E'} g^2(\theta) [(1 + 3 \cos^2 \theta) K_I^2 + 8 \sin \theta \cos \theta K_I K_{II} \\ &\quad + (9 - 5 \cos^2 \theta) K_{II}^2] \end{aligned} \quad (2.13)$$

where

$$g(\theta) = \left(\frac{4}{3 + \cos^2 \theta} \right) \left(\frac{1 - \theta/\pi}{1 + \theta/\pi} \right)^{\frac{\theta}{2\pi}}$$

The criterion of crack propagation is:

$$\begin{cases} \frac{\partial^2 G(\theta)}{\partial \theta^2} < 0 \\ \frac{\partial G(\theta)}{\partial \theta} = 0 \end{cases} \quad (2.14)$$

For general mixed mode problems, an empirical criterion was developed and has the following form [91]:

$$a_1 \left(\frac{K_I}{K_{IC}} \right)^{b_1} + a_2 \left(\frac{K_I K_{II}}{K_{IC} K_{IIc}} \right)^{b_2} + a_3 \left(\frac{K_{II}}{K_{IIc}} \right)^{b_3} + a_4 \left(\frac{K_{II}}{K_{IC}} \right)^{b_4} = 1 \quad (2.15)$$

where

$a_1, a_2, a_3, a_4, b_1, b_2, b_3, b_4$ are the coefficients which are obtained from experiments.

K_I, K_{II} is the stress intensity factor in mode I and mode II respectively.

K_{IC}, K_{IIC} is the fracture toughness in mode I and mode II respectively.

2.9. Summary

In this chapter, the design and applications of bi-axial testing and background knowledge of composite material analysis based on strength and fracture mechanic approaches were represented. It is shown that the tests using cruciform specimens and Arcan testing fixture can be potentially applied for investigation of failure behavior of FRP composites under in-plane bi-axial loading conditions. This review also described limitations of bi-axial testing equipment and the lack of composite bi-axial testing data for FRP composites laminates with notches/cracks. Besides, although literature on the characteristics of adhesively bonded joints under bi-axial loading is rapidly growing, there is insufficient research on the influence of adherend contours to adhesively bonded joint strength. Finally, common and innovative approaches for failure analysis and failure theories were reviewed. The literature has provided a better understanding of the analytical and numerical solutions to predict the behavior of composite materials.

References

- [1] M. S. Found, "A review of the multiaxial fatigue testing of fiber reinforced plastics," in *Multiaxial Fatigue*, ed: ASTM International, 1985.
- [2] A. S. Chen and F. L. Matthews, "A review of multiaxial/biaxial loading tests for composite materials," *Composites*, vol. 24, pp. 395-406, 7// 1993.
- [3] M. Hinton, A. Kaddour, and P. Soden, "The world-wide failure exercise: Its origin, concept and content," *Failure criteria in fiber reinforced polymer composites: the world wide failure exercise*. Elsevier, Amsterdam, pp. 2-28, 2004.

- [4] A. Kaddour and M. Hinton, "The background to the second world-wide failure exercise (WWFE-II)," *J Compos Mater*, vol. 46, pp. 2283-2294, 2012.
- [5] A. Kaddour, M. Hinton, P. Smith, and S. Li, "The background to the third world-wide failure exercise," *Journal of Composite Materials*, vol. 47, pp. 2417-2426, 2013.
- [6] J. L. Y. Tan, V. S. Deshpande, and N. A. Fleck, "Failure mechanisms of a notched CFRP laminate under multi-axial loading," *Composites Part A: Applied Science and Manufacturing*, vol. 77, pp. 56-66, 2015/10/01/ 2015.
- [7] A. Smits, C. Ramault, A. Makris, D. Van Hemelrijck, A. Clarke, C. Williamson, *et al.*, "A review of biaxial test methods for composites," in *Experimental Analysis of Nano and Engineering Materials and Structures*, ed: Springer, 2007, pp. 933-934.
- [8] A. Makris, C. Ramault, D. Van Hemelrijck, A. Clarke, C. Williamson, M. Gower, *et al.*, "A review of biaxial test methods for composites," *Experimental Analysis of Nano and Engineering Materials and Structures*, pp. 933-940, 2007.
- [9] H. Thom, "A review of the biaxial strength of fibre-reinforced plastics," *Composites Part A: Applied Science and Manufacturing*, vol. 29, pp. 869-886, 8// 1998.
- [10] R. Olsson, "A survey of test methods for multiaxial and out-of-plane strength of composite laminates," *Composites Science and Technology*, vol. 71, pp. 773-783, 4/12/ 2011.
- [11] C. Bert, B. Mayberry, and J. Ray, "Behavior of fiber-reinforced plastic laminates under biaxial loading," in *Composite Materials: Testing and Design*, ed: ASTM International, 1969.
- [12] M. Arcan, Z. Hashin, and A. Voloshin, "A method to produce uniform plane-stress states with applications to fiber-reinforced materials," *Experimental Mechanics*, vol. 18, pp. 141-146, 1978/04/01 1978.

- [13] S. C. Hung and K. M. Liechti, "Finite Element Analysis of the Arcan Specimen for Fiber Reinforced Composites under Pure Shear and Biaxial Loading," *Journal of Composite Materials*, vol. 33, pp. 1288-1317, 1999/07/01 1999.
- [14] M. Nikbakht and N. Choupani, "Fracture toughness characterization of carbon-epoxy composite using arcan specimen," *World Academy of Science, Engineering and Technology*, vol. 41, pp. 738-744, 2008.
- [15] R. R. de Sousa Junior, J. R. Gouveia, N. M. Ito, and D. J. dos Santos, "Failure prediction of hybrid composite using Arcan's device and Drucker-Prager model," *Polymer Testing*, vol. 58, pp. 256-261, 2017/04/01/ 2017.
- [16] S. T. Taher, O. T. Thomsen, and J. M. Dulieu-Barton, "Bidirectional Thermo-Mechanical Properties of Foam Core Materials Using DIC," in *Thermomechanics and Infra-Red Imaging, Volume 7: Proceedings of the 2011 Annual Conference on Experimental and Applied Mechanics*, ed New York, NY: Springer New York, 2011, pp. 67-74.
- [17] S. T. Taher, O. T. Thomsen, J. M. Dulieu-Barton, and S. Zhang, "Determination of mechanical properties of PVC foam using a modified Arcan fixture," *Composites Part A: Applied Science and Manufacturing*, vol. 43, pp. 1698-1708, 2012/10/01/ 2012.
- [18] A. Kossa, "A new biaxial compression fixture for polymeric foams," *Polymer Testing*, vol. 45, pp. 47-51, 2015/08/01/ 2015.
- [19] X. S. Sun, A. Haris, V. B. C. Tan, T. E. Tay, S. Narasimalu, and C. N. Della, "A multi-axial fatigue model for fiber-reinforced composite laminates based on Puck's criterion," *Journal of Composite Materials*, vol. 46, pp. 449-469, 2012.
- [20] N. Bhatnagar, R. Bhardwaj, P. Selvakumar, and M. Brieu, "Development of a biaxial tensile test fixture for reinforced thermoplastic composites," *Polymer Testing*, vol. 26, pp. 154-161, 2007/04/01/ 2007.

- [21] S. S. H. Muhsin J. Jweeg, Yassr Y. Kahtan, "Experimental Investigations of the Cruciform Specimen of GFRP16 under Biaxial Monotonic and Cyclic Loading," *International Journal of Scientific & Engineering Research*, vol. 4, December-2013 2013.
- [22] G. Ferron and A. Makinde, "Design and development of a biaxial strength testing device," *Journal of Testing and Evaluation*, vol. 16, pp. 253-256, 1988.
- [23] J. S. Welsh and D. F. Adams, "Development of an electromechanical triaxial test facility for composite materials," *Experimental Mechanics*, vol. 40, pp. 312-320, 2000/09/01 2000.
- [24] H. Kumazawa, H. Hayashi, I. Susuki, and T. Utsunomiya, "Damage and permeability evolution in CFRP cross-ply laminates," *Composite Structures*, vol. 76, pp. 73-81, 10// 2006.
- [25] S. Demmerle and J. P. Boehler, "Optimal design of biaxial tensile cruciform specimens," *Journal of the Mechanics and Physics of Solids*, vol. 41, pp. 143-181, 1// 1993.
- [26] J. S. Welsh and D. F. Adams, "An experimental investigation of the biaxial strength of IM6/3501-6 carbon/epoxy cross-ply laminates using cruciform specimens," *Composites Part A: Applied Science and Manufacturing*, vol. 33, pp. 829-839, 6// 2002.
- [27] A. Smits, D. Van Hemelrijck, T. P. Philippidis, and A. Cardon, "Design of a cruciform specimen for biaxial testing of fibre reinforced composite laminates," *Composites Science and Technology*, vol. 66, pp. 964-975, 2006/06/01/ 2006.
- [28] D. Van Hemelrijck, A. Smits, and T. Philippidis, "Study of the behaviour of a glass fibre reinforced epoxy composite system used for wind turbine rotor blades under biaxial load conditions," 2006.
- [29] D. Van Hemelrijck, A. Makris, C. Ramault, E. Lamkanfi, W. Van Paepegem, and D. Lecompte, "Biaxial testing of fibre-reinforced composite laminates," *Proceedings of the Institution of Mechanical*

- Engineers, Part L: Journal of Materials Design and Applications*, vol. 222, pp. 231-239, 2008.
- [30] A. Makris, T. Vandenberg, C. Ramault, D. Van Hemelrijck, E. Lamkanfi, and W. Van Paepegem, "Shape optimisation of a biaxially loaded cruciform specimen," *Polymer Testing*, vol. 29, pp. 216-223, 4// 2010.
- [31] N. Deng, T. Kuwabara, and Y. P. Korkolis, "Cruciform Specimen Design and Verification for Constitutive Identification of Anisotropic Sheets," *Experimental Mechanics*, vol. 55, pp. 1005-1022, 2015/07/01 2015.
- [32] D. Dawicke and W. Pollock, "Biaxial testing of 2219-T87 aluminum alloy using cruciform specimens," 1997.
- [33] Y. M. Tarnopol'skii and V. L. Kulakov, "Tests Methods for Composites. Survey of Investigations Carried out in the PMI of Latvian Academy of Sciences in 1964-2000," *Mechanics of Composite Materials*, vol. 37, pp. 431-448, 2001/09/01 2001.
- [34] J. S. Welsh, J. S. Mayes, and A. C. Biskner, "2-D biaxial testing and failure predictions of IM7/977-2 carbon/epoxy quasi-isotropic laminates," *Composite Structures*, vol. 75, pp. 60-66, 9// 2006.
- [35] A. Smits, D. Lecompte, D. Hemelrijck, H. Sol, and W. Paepegem, "Inverse Method for Parameter Determination of Biaxially Loaded Cruciform Composite Specimens," in *Experimental Analysis of Nano and Engineering Materials and Structures*, E. E. Gdoutos, Ed., ed: Springer Netherlands, 2007, pp. 931-932.
- [36] D. Lecompte, A. Smits, H. Sol, J. Vantomme, and D. Van Hemelrijck, "Mixed numerical-experimental technique for orthotropic parameter identification using biaxial tensile tests on cruciform specimens," *International Journal of Solids and Structures*, vol. 44, pp. 1643-1656, 3/1/ 2007.

- [37] C. W. Bert, B. L. Mayberry, and J. D. Ray, "Behavior of fiber reinforced plastic laminates under uniaxial, biaxial, and shear loadings," DTIC Document 1969.
- [38] I. Daniel, "Behavior of graphite/epoxy plates with holes under biaxial loading," *Experimental Mechanics*, vol. 20, pp. 1-8, 1980/01/01 1980.
- [39] D. L. Jones, P. Poulos, and H. Liebowitz, "Effect of biaxial loads on the static and fatigue properties of composite materials," *Multiaxial Fatigue, ASTM STP*, vol. 853, pp. 413-427, 1985.
- [40] E. Smith and K. Pascoe, *Biaxial Fatigue of a Glass-Fibre Reinforced Composite. Part I—Fatigue and Fracture behavior*, 1989.
- [41] M. J. Hinton, A. S. Kaddour, and P. D. Soden, *Failure criteria in fibre reinforced polymer composites: the world-wide failure exercise*: Elsevier, 2004.
- [42] X. Sun, A. Haris, V. Tan, T. Tay, S. Narasimalu, and C. Della, "A multi-axial fatigue model for fiber-reinforced composite laminates based on Puck's criterion," *Journal of Composite Materials*, vol. 46, pp. 449-469, 2012.
- [43] U. Kureemun, M. Ridha, and T. E. Tay, "Biaxial tensile-compressive loading of unnotched and open-hole carbon epoxy crossply laminates," *Journal of Composite Materials*, vol. 49, pp. 2817-2837, 2015/09/01 2014.
- [44] A. Rashedi, I. Sridhar, and K. J. Tseng, "Fracture characterization of glass fiber composite laminate under experimental biaxial loading," *Composite Structures*, vol. 138, pp. 17-29, 2016/03/15/ 2016.
- [45] S. H. Yoon and C. S. Hong, "Interlaminar fracture toughness of graphite/epoxy composite under mixed-mode deformations," *Experimental Mechanics*, vol. 30, pp. 234-239, 1990/09/01 1990.
- [46] N. Choupani, "Experimental and numerical investigation of the mixed-mode delamination in Arcan laminated specimens," *Materials Science and Engineering: A*, vol. 478, pp. 229-242, 2008/04/15/ 2008.

- [47] R. A. Jurf and R. B. Pipes, "Interlaminar Fracture of Composite Materials," *Journal of Composite Materials*, vol. 16, pp. 386-394, 1982/09/01 1982.
- [48] R. Rikards, F. G. Buchholz, H. Wang, A. K. Bledzki, A. Korjakin, and H. A. Richard, "Investigation of mixed mode I/II interlaminar fracture toughness of laminated composites by using a CTS type specimen," *Engineering Fracture Mechanics*, vol. 61, pp. 325-342, 1998/09/01/ 1998.
- [49] D. DELSART and J. M. MORTIER, "Identification of the Interface Properties of Fibre Reinforced Composite Materials," in *Proceedings of SEM XIth international congress and exposition on experimental & applied mechanics. Orlando (June, 2008)*, 2008.
- [50] A. Voloshin and M. Arcan, "Pure shear moduli of unidirectional fibre-reinforced materials (FRM)," *Fibre Science and Technology*, vol. 13, pp. 125-134, 1980/03/01/ 1980.
- [51] S. C. Hung and K. M. Liechti, "An evaluation of the arcan specimen for determining the shear moduli of fiber-reinforced composites," *Experimental Mechanics*, vol. 37, pp. 460-468, 1997/12/01 1997.
- [52] R. El-Hajjar and R. Haj-Ali, "In-plane shear testing of thick-section pultruded FRP composites using a modified Arcan fixture," *Composites Part B: Engineering*, vol. 35, pp. 421-428, 2004/07/01/ 2004.
- [53] P. B. Gning, D. Delsart, J. M. Mortier, and D. Coutellier, "Through-thickness strength measurements using Arcan's method," *Composites Part B: Engineering*, vol. 41, pp. 308-316, 2010/06/01/ 2010.
- [54] M. Costa, R. Carbas, E. Marques, G. Viana, and L. F. M. da Silva, "An apparatus for mixed-mode fracture characterization of adhesive joints," *Theoretical and Applied Fracture Mechanics*, 2017/04/25/ 2017.
- [55] J.-Y. Cognard, R. Créac'hcadec, L. Sohier, and P. Davies, "Analysis of the nonlinear behavior of adhesives in bonded assemblies—Comparison of TAST and Arcan tests," *International Journal of Adhesion and Adhesives*, vol. 28, pp. 393-404, 2008.

- [56] J. Y. Cognard, "Numerical analysis of edge effects in adhesively-bonded assemblies application to the determination of the adhesive behaviour," *Computers & Structures*, vol. 86, pp. 1704-1717, 2008/09/01/ 2008.
- [57] J. Y. Cognard, L. Sohier, and P. Davies, "A modified Arcan test to analyze the behavior of composites and their assemblies under out-of-plane loadings," *Composites Part A: Applied Science and Manufacturing*, vol. 42, pp. 111-121, 2011/01/01/ 2011.
- [58] J.-Y. Cognard, L. Sohier, and P. Davies, "A modified Arcan test to analyze the behavior of composites and their assemblies under out-of-plane loadings," *Composites Part A: Applied science and manufacturing*, vol. 42, pp. 111-121, 2011.
- [59] R. Créac'hcadec, G. Jamin, J. Y. Cognard, and P. Jousset, "Experimental analysis of the mechanical behaviour of a thick flexible adhesive under tensile/compression-shear loads," *International Journal of Adhesion and Adhesives*, vol. 48, pp. 258-267, 2014/01/01/ 2014.
- [60] P. Davies, L. Sohier, J. Y. Cognard, A. Bourmaud, D. Choqueuse, E. Rinnert, *et al.*, "Influence of adhesive bond line thickness on joint strength," *International Journal of Adhesion and Adhesives*, vol. 29, pp. 724-736, 2009/10/01/ 2009.
- [61] V. Weissberg and M. Arcan, "A uniform pure shear testing specimen for adhesive characterization," in *Adhesively Bonded Joints: Testing, Analysis, and Design*, ed: ASTM International, 1988.
- [62] N. Choupani, "Interfacial mixed-mode fracture characterization of adhesively bonded joints," *International Journal of Adhesion and Adhesives*, vol. 28, pp. 267-282, 2008/09/01/ 2008.
- [63] N. Choupani, "Mixed-mode cohesive fracture of adhesive joints: Experimental and numerical studies," *Engineering Fracture Mechanics*, vol. 75, pp. 4363-4382, 2008/10/01/ 2008.

- [64] A. Pironi and G. Nicoletto, "Mixed mode I/II fracture toughness of bonded joints," *International Journal of Adhesion and Adhesives*, vol. 22, pp. 109-117, 2002.
- [65] B. Valès, S. Marguet, R. Créac'hacdec, L. Sohier, J.-F. Ferrero, and P. Navarro, "Experimental & Numerical Study of the Tensile/Compression-Shear Arcan Test under Dynamic Loading," *International Journal of Adhesion and Adhesives*, 2017.
- [66] ASTM Standard D4762 11a, "Standard guide for testing polymer matrix composite materials," ed. West Conshohocken, Pennsylvania: ASTM International, 2011.
- [67] ASTM Standard D5528 13, "Standard test method for mode I interlaminar fracture toughness of unidirectional fiber-reinforced polymer matrix composites," ed. West Conshohocken, Pennsylvania: ASTM International, 2013.
- [68] ASTM Standard D6671/D6671M 13, "Standard test method for mixed mode I-mode II interlaminar fracture toughness of unidirectional fiber reinforced polymer matrix composites," ed. West Conshohocken, Pennsylvania ASTM International, 2013.
- [69] ASTM Standard E1922 04, "Standard test method for translaminar fracture toughness of laminated and pultruded polymer matrix composite materials," ed. West Conshohocken, Pennsylvania ASTM International, 2004.
- [70] S. Mohammadi, "Introduction," in *XFEM Fracture Analysis of Composites*, ed: John Wiley & Sons, Ltd, 2012, pp. 1-15.
- [71] G. Kirsh, "Infinite plate containing a circular hole (Die theorie der elastizitat und die bedurfnisse der festigkeitslehre)," *Zeitschrift der Vereines Deutscher Ingenieure*, vol. 42, pp. 797–807, 1898.
- [72] C. E. Inglis, "Stresses in a plate due to the presence of cracks and sharp corners," *Transactions of Institute of Naval Architects*, vol. 55, pp. 219–241, 1913.

- [73] M. L. Williams, "Stress singularities resulting from various boundary conditions in angular corners of plates in extension," *Journal of Applied Mechanics, Transactions ASME*, vol. 19, pp. 526–528, 1952.
- [74] G. R. Irwin, "Analysis of stresses and strains near the end of a crack transversing a plate," *Journal of Applied Mechanics, Transactions ASME*, vol. 24, pp. 361–364, 1957.
- [75] A. A. Griffith, "The phenomena of rupture and flow in solids," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering*, vol. 221, pp. 163–197, 1921.
- [76] D. R. J. Owen and A. J. Fawkes, *Engineering fracture mechanics: numerical methods and applications*: Pineridge Press Swansea, UK, 1983.
- [77] T. Belytschko and T. Black, "Elastic crack growth in finite elements with minimal remeshing," *International journal for numerical methods in engineering*, vol. 45, pp. 601-620, 1999.
- [78] N. Moës and T. Belytschko, "Extended finite element method for cohesive crack growth," *Engineering Fracture Mechanics*, vol. 69, pp. 813-833, 5// 2002.
- [79] I. M. Daniel, "Failure of Composite Materials," *Strain*, vol. 43, pp. 4-12, 2007.
- [80] S. W. Tsai, "Strength characteristics of composite materials," DTIC Document, PHILCO CORP NEWPORT BEACH CA.1965.
- [81] S. W. Tsai and E. M. Wu, "A general theory of strength for anisotropic materials," *Journal of composite materials*, vol. 5, pp. 58-80, 1971.
- [82] A. Rotem, "Prediction of laminate failure with the rotem failure criterion," *Composites Science and Technology*, vol. 58, pp. 1083-1094, 7// 1998.
- [83] A. Puck and H. Schürmann, "Failure analysis of frp laminates by means of physically based phenomenological models," *Composites Science and Technology*, vol. 58, pp. 1045-1067, 7// 1998.

- [84] P. A. Zinoviev, S. V. Grigoriev, O. V. Lebedeva, and L. P. Tairova, "The strength of multilayered composites under a plane-stress state," *Composites Science and Technology*, vol. 58, pp. 1209-1223, 7// 1998.
- [85] T. A. Bogetti, C. P. R. Hoppel, V. M. Harik, J. F. Newill, and B. P. Burns, "Predicting the nonlinear response and progressive failure of composite laminates," *Composites Science and Technology*, vol. 64, pp. 329-342, 3// 2004.
- [86] R. G. Cuntze, "The predictive capability of failure mode concept-based strength criteria for multi-directional laminates—part B," *Composites Science and Technology*, vol. 64, pp. 487-516, 3// 2004.
- [87] F. Erdogan and G. Sih, "On the crack extension in plates under plane loading and transverse shear," *Journal of basic engineering*, vol. 85, pp. 519-525, 1963.
- [88] G. C. Sih, "Some elastodynamic problems of cracks," *International Journal of Fracture Mechanics*, vol. 4, pp. 51-68, 1968/03/01 1968.
- [89] J. Chang, J.-q. Xu, and Y. Mutoh, "A general mixed-mode brittle fracture criterion for cracked materials," *Engineering Fracture Mechanics*, vol. 73, pp. 1249-1263, 6// 2006.
- [90] M. Hussain, S. Pu, and J. Underwood, "Strain Energy Release Rate for a Crack Under Combined Mode I and Mode," *Fracture analysis*, vol. 560, 1974.
- [91] S. Mohammadi, "Fracture Mechanics, A Review," in *XFEM Fracture Analysis of Composites*, ed: John Wiley & Sons, Ltd, 2012, pp. 17-55.

Chapter 3

Experimental Methodology

This chapter first presents the details of experimental methods employed in this study included the material system and specimen preparation processes for composite laminates and adhesive bonding composite joints. Likewise, the methods to assess mechanical properties, including bi-axial tension – tension/compression and tension – shear stress conditions, are elaborated. Moreover, the material characterization of bi-axial failure envelope was introduced to present the behavior of the laminate under bi-axial stress state. Finally, analysis technique of the cruciform specimen and adhesively bonded joint specimens is discussed.

3.1 Material information

One important design aspect for wind turbine blades is the selection of material based on operational conditions. The basic requirements for turbine blade materials include (1) high material stiffness to maintain the optimal aerodynamic performance; (2) low density to reduce the effect of inertial forces; (3) long-fatigue life to increase the lifetime under dynamic forces [1]. As FRP composite materials can satisfy all above requirements, they have been extensively chosen as the materials for rotor blades. The two common types of FRP composites are carbon fiber and glass fiber-reinforced polymer matrix composites. Carbon fiber has excellent properties such as high strength, high stiffness, low density, etc. Glass fiber has high strength, moderate stiffness, and moderate density. Compared to carbon fiber, glass fiber is more cost effective, and thus, it is chosen as the primary material for all tests in this study. Unidirectional (UD) G17500 prepreg with a 0.15mm nominal ply thickness provided by Weihai Guangwei Composites was used to fabricate the specimens for all experiments. The uniaxial elastic properties of this composite measured by using ASTM standard D3039/3039M, D3410/3410M and D3518/3518M are listed in Table 3.1.

Table 3.1 Material elastic properties of G17500 unidirectional lamina [2].

Engineering constant		Value
<i>Longitudinal modulus</i> E_{11}	[GPa]	46
<i>Transverse modulus</i> $E_{22} = E_{33}$	[GPa]	13
<i>Poisson's Coefficient</i> ν_{12}	–	0.26
<i>Shear modulus</i> $G_{12} = G_{13}$	[GPa]	7
<i>Shear modulus</i> G_{23}	[GPa]	4.48

3.2 Mechanical testing method

As most of the wind turbine blades are constructed on a large scale, in-plane bi-axial stress distribution is generated in their flat or gently curved structural surfaces. These bi-axial stress states can be the combination of two distinct normal stress components or one normal stress component with shear stress. Two popular bi-axial testing methods for in-plane loadings are the Arcan tests in butterfly configuration and the test of the cruciform specimen under loaded along two perpendicular directions. Therefore, these bi-axial tests have been used in this study to characterize the composite laminates properties. The testing methods are briefly discussed in the next section.

3.2.1 Tension – Shear Mixed mode test

Over the last decades, outstanding efforts have been made to develop proper equipment for composite laminate failure under bi-axial stress conditions. Recently, Choupani [3] modified the testing method of Arcan et al. [4] to measure the interlaminar fracture toughness in modes I, II and mixed mode I/II of carbon/epoxy cross-ply composite laminates. This fixture can generate a combination of in-plane tensile and shear stresses in the testing sample. Therefore, a test apparatus was fabricated based on the Arcan fixture included two separate parts which are made of mild steel and have seven holes separated by 15° to change the loading angle α (see Figure 3.1). Specimens were clamped between the two parts with bolt tightening. By varying the loading angle, the fixture could provide testing conditions of pure mode I ($\alpha = 0^\circ$), pure mode II ($\alpha = 90^\circ$) or mixed mode I/II ($90^\circ > \alpha > 0^\circ$). This fixture is used to conduct two types of tests which are for determining fracture toughness properties of cross-ply and UD composite laminate, and for characterizing the behavior of adhesive bonded composite joint under tension – shear loadings.

Figure 3.1 A modified Arcan fixture.

3.2.2 Tension – tension and tension – compression bi-axial test

To investigate the behavior of composite laminates under in-plane bi-axial axial and transverse principal stress, cruciform shape specimens have been widely utilized in the composite community. The multi-axial stress states are produced by stretching or pressing the specimen arms as illustrated in Figure 3.2. In this study, bi-axial tension – tension and tension - compression tests have been conducted for cross-ply laminate for cruciform specimens which have a pre-crack at various orientations and transverse to axial stress ratios. Two fixtures are applied to obtain the material characteristics under bi-axial loading conditions. The first one is developed in a joint research projected between Energy Research Institute @NTU (ERI@N), Vestas®, DNV GL®, and Instron® as an add-on

fixture of an Instron Universal Testing Machine (UTM). This frame has extended the capability of the uniaxial testing system to bi-axial testing system with load carrying capacity in primary (axial) axis up to 250 kN and secondary (transverse) axis up to 10 kN. It can also be flexibly installed into various types of Instron traditional UTM frame, particularly Instron 8800, Instron 5985 and Instron 8502.

Figure 3.2 Cruciform specimen on the static bi-axial testing fixture.

An illustration of this test setup is shown in Figure 3.3. In the axial axis, the testing specimen is clamped by two fixtures. The upper fixture is attached to an axial load cell of 250 kN transducer which is fixed to the machine frame, and the lower one is mounted to the machine's hydraulic actuator. In the transverse axis, the left clasper is attached to a 10 kN load cell, and the right clasper is attached to the float fixture frame. A complementary pneumatic actuator is installed at one side of the float frame to provide tension forces in the transverse axis. Two sliders are used to prevent undesired moments acting on the test specimen. The controller of secondary axis actuator is linked to Instron Fast Track 8800D controller of the UTM testing machine. The ratio of transverse force and axial force is controlled by Bluehill 2 software. The bi-axial jig is set up on the Instron UTM servo-hydraulic dynamic testing system. This design can be applied in the static test of composite materials for tension – tension and compression – compression loading conditions.

Figure 3.3 Schematic diagram of the bi-axial testing system with a photograph of test set-up.

The second fixture can produce the various stress ratios which are detailed in Chapter 4.

3.3 Specimen preparation

3.3.1 GFRP laminate preparation

Prior to the curing process, the prepreg glass FRP sheets were first to cut into rectangle shape which was bigger than the actual specimen size. These sheets were retained at room temperature of 25° C with humidity of 50% for 24 hours. Later, the laminate was stacked by hand lay-up in the right lay-up sequence

depend on each test. They were cured in an oven following the thermal curing cycle as a recommendation from the supplier at a maximum temperature of 130° C for 2.5 h and cooled to the room temperature of 25° C. Then, the cured specimens were precisely machined to the desired geometry by the water jet cutting method. Finally, the holes in specimens were drilled and the pre-crack was created using a CNC milling machine with carbide tools. The same method was used to fabricate the UD specimens. The Arcan specimen and cruciform specimen geometry are shown in Figure 3.4.

Figure 3.4 Schematic illustration of (a) Arcan specimen, and (b) Cruciform specimen.

3.3.2 Adhesive bonding composite joint preparation

The adhesive bonding composite joint specimen was designed in a rectangle shape included two composite adherends joined by a layer of adhesive. The adhesive adherends were stacked with quasi-isotropic fiber direction. Later, these adherends had a similar curing process which was mentioned in the Section 3.3.1 at a maximum temperature of 130° C for 2.5 h. Between two adherends, a 2mm layer of 3M Epoxy adhesive was applied. An acrylic mold was made to keep the consistent thickness in all specimens. The specimens were left to fully cure for 48 hours. The specimens were schematically detailed in Figure 3.5.

Figure 3.5 Schematic illustration of adhesive bonding composite joints with different adherend geometries.

3.4 Material characterization

3.4.1 Bi-axial failure envelope

For bi-axial tests, the bi-axial critical stress surface is an important data to characterize the failure of composite laminates under bi-axial stress states. A typical failure envelope of composite laminate under two principal normal stress σ_1 and σ_2 is illustrated in Figure 3.6. The actual stress which is distributed over the cross-section of a testing sample is important to plot the failure surface of composite laminates. However, the cruciform specimens had a non-uniform shape which can affect the calculation of stress in axial and transverse directions if the stress area is calculated by multiplying the length and the thickness of cruciform arm. The methods to calculate the applied stress are introduced in Chapter 2. In this study, applied stress is computed using the equivalent area method.

Figure 3.6 Illustration of bi-axial failure envelope for the IM7/997-2 carbon/epoxy quasi-isotropic laminate [5].

Moreover, the results were also represented in the values of mode I and mode II critical stress intensity factors whereas the testing specimen contained a crack which acted as a stress riser feature. These fracture toughness values were calculated based on the linear elastic fracture mechanic with the aid of geometric correction factors which were determined using finite element analysis. Finally, the results were plotted in a K_I/K_{IC} and K_{II}/K_{IIC} surface when K_I , K_{II} were the mode I and mode II critical stress intensity factors from the experimental results and K_{IC} , K_{IIC} was the mode I and mode II fracture toughness of the material. From this surface, a failure criterion could be introduced to predict the fracture of a composite laminate with a crack under bi-axial loading conditions.

3.4.2 Digital image correlation for surface strain

Digital Image Correlation (DIC) is an optical-numerical method to provide the full-field strain distribution data of experiments. Groups of pixels known as subsets in different pictures taken during the experiments are compared to generate the deformation of the object surface. To apply DIC technique in the present study, a digital single-lens reflex camera Canon 60D/100D, 18.1

megapixels (5184 x 3456 pixels) using CMOS Sensor was used to capture images of testing specimens with speed up to 5 frames per second. The specimen surfaces were sprayed with black paint on a background of white paint to create speckle patterns. To minimize the effect of camera vibration and noise, the camera was fixed on a tripod, and a camera remote controller was used. Images of testing processes were analyzed by VIC2D DIC® software, and then the strain fields were calculated. The experimental set-up of DIC system with instruments was illustrated in Figure 3.4.

Figure 3.7 A digital image correlation system using the single-lens reflex camera.

3.5 Analysis of composite laminate

3.5.1 Finite element models of composite laminates

The finite element analysis in this study was performed using the ABAQUS package software. The main purpose of the simulation was determined the non-dimensional geometric correction factors of the composite specimen which was used to calculate the fracture toughness value [2]. The model elements were registered as quadric 8-node reduced integration (S8R5) shell elements using the orthotropic equivalent effective elastic properties. Depend on the model, different boundary conditions were applied which were detailed in the relative chapter. To generate the singularity, the element around the crack tips was assigned as

quarter-point singular elements with the focused mesh to increase the accuracy from the analysis as present in Figure 3.8.

Figure 3.8 Finite element model of the cruciform specimen.

3.5.2 Finite element models of adhesive bonding composite joint

Samples of the adhesively bonded joints with GFRP quasi-isotropic adherends and 3M® DP460 epoxy adhesive were modeled three dimensionally by using ABAQUS package software. In the 3D analysis, two adherends were meshed using Continuum shell element SC8R with lamina properties from Table 3.1. Apart from this, the adhesive was modeled by 3D stress element hourglass control C3D8R the properties generating from standard tensile tests. Two 0.01mm thin cohesive layers meshing with the cohesive element COH3D8 were added on two sides of the adhesive which were connected to the fixture. Fracture

criterion was applied for the cohesive layer properties which were determined by from pure mode I and mode II tensile tests, DCB, and ENF tests. The Arcan fixture was registered as a rigid body as the maximum applied force was not enough to significantly deform the fixture. Moreover, the fine mesh was used in the adhesive and cohesive layers where stress distribution is critical and coarse mesh was used at the side of an adherend to decrease the duration of the numeric solution. The details of mesh geometry and boundary condition are shown in Figure 3.9.

Figure 3.9 Finite element model of the adhesively bonded joint with the Arcan fixture.

3.6 Summary

This chapter provides methodological details of bi-axial testing experiments used in this study. The rationale of selection for material, testing methods, characterization techniques were also discussed to provide useful information for pursuing further research on this topic.

References

- [1] P. Brøndsted, H. Lilholt, and A. Lystrup, "Composite materials for wind power turbine blades," *Annu. Rev. Mater. Res.*, vol. 35, pp. 505-538, 2005.
- [2] A. Rashedi, I. Sridhar, and K. J. Tseng, "Fracture characterization of glass fiber composite laminate under experimental biaxial loading," *Composite Structures*, vol. 138, pp. 17-29, 2016/03/15/ 2016.
- [3] N. Choupani, "Experimental and numerical investigation of the mixed-mode delamination in Arcan laminated specimens," *Materials Science and Engineering: A*, vol. 478, pp. 229-242, 2008/04/15/ 2008.
- [4] M. Arcan, Z. Hashin, and A. Voloshin, "A method to produce uniform plane-stress states with applications to fiber-reinforced materials," *Experimental Mechanics*, vol. 18, pp. 141-146, 1978/04/01 1978.
- [5] J. S. Welsh, J. S. Mayes, and A. C. Biskner, "2-D biaxial testing and failure predictions of IM7/977-2 carbon/epoxy quasi-isotropic laminates," *Composite Structures*, vol. 75, pp. 60-66, 2006/09/01/ 2006.

Chapter 4

Bi-axial Fixture Design and Development

This chapter presents design and development of a novel bi-axial fixture. Initially, existing planar bi-axial fixture designs are reviewed with their advantages and disadvantages. Secondly, design and development of new bi-axial fixture are elaborated which can generate numerous bi-axial ratios in tension – tension, tension – compression, compression – compression loading conditions. Finally, experiments are conducted to verify the operation and generation of bi-axial loading in the fixture.

4.1 Introduction

Composite materials are commonly used in many industrial fields, especially in aerospace and wind energy. Composite components such as aircraft wings or wind turbine blades have been operated under the combination of tension, compression, and shear loading conditions which generate complex multi-axial stress state in the composite parts. To predict the initiation and final failure of fiber-reinforced plastics material, many of the analytical and numerous approaches have been introduced recently. Although, the composite community has many efforts to evaluate the suitable failure theory which can be used for design process [1-3]. However, there is still a lack of accurate multi-axial experimental data to verify failure initiation and propagation [4]. This data is commonly created by bi-axial tests, which generate bi-axial stress states. Bi-axial loading conditions are combinations of tension, compression or shear stress state, i.e. tension – tension ($\sigma_{T1} - \sigma_{T2}$), compression – compression ($\sigma_{C1} - \sigma_{C2}$), tension – compression ($\sigma_{T1} - \sigma_{C2}$), and tension/compression – shear ($\sigma_{T/C} - \tau$) which are applied to specimens.

Figure 4.1 Common bi-axial testing specimens (a)(b) thin-wall tube specimen, (b) cruciform specimen and (d) punching plate.

Bi-axial tests have been conducted under many systems with different testing sample geometries as schematically shown in Figure 4.1. Among these specimens, thin-wall tube specimen subjected to internal pressure is the most popular method to generate bi-axial stress with any load ratio. However, this method has some disadvantages related to radial effects, which cannot be negligible [4]. Therefore, bi-axial tests using in-plane load systems have been applied to create more realistic data for the composite design process currently. Typical systems which use cruciform or butterfly specimen are introduced in Figure 4.2 with the general information showed in Table 4.1.

The planar bi-axial testing systems may be classified into two categories:

- (i) One actuator loading system
- (ii) Two or four actuators loading system

In the first category, a fixture is mounted on a universal uniaxial tension/compression testing machine. The fixture is assembled from various parts in geometrical relations which create links between an axial movement and its perpendicular movement or shearing movement. Typical types of this category are picture frame type or scissor type linkage fixtures, which generate planar tensile/compressive – tensile/compressive stress state (Figure 4.2f, g) and Arcan fixtures, which generate in-plane tensile/compressive – shear stress state (Figure 4.2 b, c). Most parts of these fixtures can be fabricated by conventional machining methods at moderate position accuracy and tolerances, which provide a low-cost solution for bi-axial testing of composites. However, it presents some drawbacks; (i) deformation of components may change to the actual displacement ratio which affects directly to stress ratio during testing progress, especially in case of high stiffness specimen, i.e. small deformation under high loading; (ii) clearances between parts influence dynamic behavior of the fixture under cyclic loading; and (iii) limitation to change the bi-axial displacement ratio.

Figure 4.2 (a) Frame fixture (b)(c) Tensile/Compressive - shear loading Arcan fixture (d) Four independent hydraulic actuator system (e) Add-on actuator fixture (f)(g) Linkage fixture and (h)(i) Tan relation fixtures.

In the second category, testing systems may be divided into three types: (i) the two-independent actuator system which has limited application because of its asymmetry displacement/loading during testing process [4, 5]; (ii) the add-on fixture on transverse axis showed in Figure 4.2e and (iii) the four-independent actuator system showed in Figure 4.2g. Add-on systems have moderate low fabrication cost with one pneumatic/hydraulic actuator on the transverse axis. This system collects the displacement/force data from the main testing axis then apply close loop control to keep the displacement/force of transverse axis following the desired ratio. However, its accuracy and response speed depends upon the stiffness of mounting parts and transferring data process between controllers of master and slave axes. The last bi-axial test system (see Figure 4.2d) is a complete machine which uses four servo-hydraulic actuators with four control units, load cells, and displacement sensors. Hence, it can generate various combinations of in-plane tensile or compressive static and cyclic stress state. Although this system has a high capacity to conduct most planar bi-axial tests for composite materials, it is complex and expensive.

In the present study, a novel bi-axial testing device is proposed, which can be mounted on a universal uniaxial testing machine. Besides, it can produce different in-plane displacement ratios in axial and transverse axes. Furthermore, the design of this fixture is analyzed with advantage and disadvantage compared to the recent in-plane bi-axial system. Lastly, validity tests are conducted to check the ability of the fixture in actual bi-axial tests using FRP composite cruciform specimens.

Table 4.1 General information of in-plane bi-axial testing systems.

Name	Stress state	Fabrication/control	Description	Cost
Frame fixture [6]	σ_{T1} – σ_{T2} σ_{C1} – σ_{C2}	Simple to fabricate Displacement control	Unable to change displacement ratio Unattended shear stress	Low
Arcan fixture [7, 8]	$\sigma_{T/C}$ – τ	Simple to fabricate Displacement control	Change displacement ratio by changing pin position Unattended out of plane force between two plates	Low
Linkage fixture [9-11]	σ_{T1} – σ_{T2} σ_{C1} – σ_{C2} σ_{T1} – σ_{C2}	Simple to fabricate Displacement control	Change displacement ratio by changing link angle or link length Deformation of parts Assembly clearance Displacement movement of transverse axis related to sin/cos value of angle between linkage (non-linear)	Low
Tan relation fixture [4, 12, 13]	σ_{T1} – σ_{T2} σ_{C1} – σ_{C2} σ_{T1} – σ_{C2}	Moderate to fabricate Displacement control	Change displacement ratio by adjusting slider angle Deformation of parts Assembly clearance Linear relation between two axis displacement movement	Moderate low

Table 4.1 continued

Addon fixture on transverse axis [14, 15]	σ_{T1} $-\sigma_{T2}$ σ_{C1} $-\sigma_{C2}$ σ_{T1} $-\sigma_{C2}$	Complex to fabricate and control Displacement/load control	Change displacement/load ratio by close/open loop control of displacement/force between transverse and axial axis Two independent actuators Add-on fixture is installed on the main uniaxial testing machine	High
Four-independent actuator system [5]	σ_{T1} $-\sigma_{T2}$ σ_{C1} $-\sigma_{C2}$ σ_{T1} $-\sigma_{C2}$	Very complex to fabricate and control Displacement/load control	Change displacement/load ratio by close/open loop control of displacement/force between transverse and axial axis Four independent hydraulic actuators with load cells LVDT sensor	Very high

4.2 Design and development of bi-axial tensile fixture

4.2.1 Design criteria

The summary of the above literature survey of in-plane bi-axial fixture designs acknowledged some issues:

- (i) Four-independent actuator system is costly to install and maintain.
- (ii) Linkage attachments have limited capabilities of given any combination of bi-axial stress ratios especially changing between tensile to compressive stress and vice versa. Moreover, these designs may not generate proportionate motion except few cases, i.e. equal ratio tensile – tensile and compressive – compressive stress state.

- (iii) Test sample deformation, geometry imperfection, and assembly clearance affect directly to the displacement ratio of the fixture which generates bi-axial displacement ratio based on geometry relation.

Armed with this information, several design criteria are proposed to develop a new fixture:

- (i) Use a cruciform specimen which is commonly used in the most in-plane bi-axial systems.
- (ii) Can mount on any universal uniaxial testing machines.
- (iii) Ability to change many displacement ratios and generate tensile – tensile, compressive – compressive and tensile – compressive stress state.
- (iv) Produce proportionate displacement.
- (v) Ability to measure force and displacement along the axial and transverse direction.

4.2.2 Assembly of the fixture

The structure of the fixture is conceived based on the above criteria. The mechanism is mounted on a universal uniaxial testing machine INSTRON 8801 as shown in Figure 4.3 with a description of mechanical parts. The fixture dimensions are presented in Appendix A.

The fixture parts were made from mild steel and coated using Nickel electroplating. The lower crosshead (3) is connected directly to the hydraulic actuator head (1) of the testing machine through an adaptor (2). The upper crosshead is mounted on the Instron load cell (9) with the same type of adapter. Therefore, the upper crosshead is fixed, and the lower cross head is movable. Moreover, the movement of this crosshead is detected by the linear variable differential transformer (LVDT) position sensor of INSTRON 8801 machine, and a total load through the fixture is measured by a load cell (9).

Figure 4.3 Schematic illustration of a bi-axial fixture at (a) front view and (b) back view.

In both moving crosshead (3) and fixed crosshead (4), four grooved cylinders (7) located at four sides. Each cylinder has a straight guiding path to lead roller

bearings (6) to run inside. These roller bearings are linked to the side bars (4) at the front of the crosshead and linkages (10) at back of the crosshead by precision pivot pins. The linkage mechanism is designed to keep the side bars parallel and two limited blocks (11) retain the side bars perpendicular to the crossheads. Two horizontal clampers (8) are connected to the side bars through two shafts (5) and two vertical clampers are mounted on the moving crosshead and the fixed crosshead.

Strain gauges are attached to these parts to measure strain values, which transduce into a shaft axial load up to 50 kN as shown in Figure 4.4 (a). Moreover, a displacement magnetic location sensor which has a resolution of 0.00195 mm is employed to determine the distance between two side bars as shown in Figure 4.4 (b). Displacement and force data of the transverse axis are collected every 0.01 s. Both the axial and transverse loading data collection is synchronized.

Figure 4.4 (a) Loadcell set-up and (b) Displacement magnetic location sensor.

4.2.3 Kinematic relation

The kinematic relation of this fixture is shown in Figure 4.5. When the hydraulic actuator head moves a distance of “ $2h$ ” along the vertical direction, this motion is transferred to the side bars through the roller bearings and cylinders. Roller bearings are pushed by the guide paths of the cylinders and then move a distance of “ h ” in both upper cylinder and lower cylinder along the vertical

direction. Because the path is inclined at an angle " θ ", the side bar then moves a distance of " v " along the horizontal direction in the relation which showed below:

$$v = h \times \tan(\theta)$$

Therefore, each side bar makes a move of " v " if the actuator head moves a distance of " $2h$ ". This relation works from both sides of the sample then the sample is stretched or compressed a distance of " $2v$ ". The cylinder is specially designed to provide many of the inclined angles " θ " which is determined by the pin position. The pin shear strength is calculated to stand the shear load caused by the normal force from roller bearings multiply by out of center distance. The selected angle " θ " are 18.4° , 33.7° , 45° , 56.3° and 71.6° which relate to $1/3$, $2/3$, 1 , $3/2$ and $3/1$ displacement ratio respectively. Moreover, changing angle " θ " from positive value to negative value makes the vertical and horizontal motion same direction i.e. tensile – tensile test or compressive – compressive test to different direction i.e. tensile – compressive test. The cylinder inclined angle is illustrated in Figure 4.3b.

Figure 4.5 Schematic illustration of the bi-axial loading fixture.

4.3 Experimental validation

4.3.1 Test sample

To conduct a successful bi-axial test, the failure of composite cruciform specimens must happen inside the gauge area instead of its arms. Because there is no standard for cruciform specimen dimensions, the specimen geometry is then particularly designed for each specific test device using FEM analysis to achieve the uniform strain field [5]. In this study, specimen dimensions are given based on a previous study on the failure of GFRP cruciform samples under bi-axial loading [14]. This typical cruciform specimen is illustrated in Figure 3.6 with important dimensions are arm width and blending radius. All specimens have the total length of 180 mm with arm width of 60 mm and blending radius of 15 mm, which are calculated to match the limits of bi-axial fixture sizes. Each arm of the specimen is clamped to fixture grips, which are designed with five of M8 holes. Either three or five of bolts are used to tighten a rectangle area of 40 x 60 mm² of the specimen. The GFRP material lay-up is 1.2 mm through-thickness [0/90]_{2s} cross-ply with the lamina properties is listed in Table 3.1.

Figure 4.6 Bi-axial cruciform specimen geometry.

A numerical analysis with FEM package software ABAQUS is carried out to guarantee a suitable bi-axial stress in central gauge area of specimens. Three-dimensional deformable shell structure is used for modeling the specimen with the boundary condition, and the mesh model is shown in Figure 4.7. Finite element is 6-node triangular continuum shell wedge 2C6R. Therefore, stress and strain distribution are predicted to assess the area which has uniform stress are around the center of the specimen.

Figure 4.7 (a) Mesh and (b) Boundary condition of the cruciform specimen.

Figure 4.8 shows that there are uniform stress and strain zones at the center of the cruciform specimen. Strain field is the same for each lamina, but the stress field is a difference depending upon the direction along the fiber. Stress/strain intensity region is observed near the specimen arm which may prevent the failure in gage zone. However, this specimen is designed to test geometry with stress singularity features such as a circle or a notch which promises failure to occur in bi-axial gage area.

Figure 4.8 (a) E11 strain field, (b) E22 strain field, (c) S11 stress field and (d) S22 stress field of a half of the 3D model under equi-biaxial displacement of 1mm for axial and transverse direction.

4.3.2 Experimental validation

The experiments for this study began by recognizing the actual bi-axial ratio during the test using the designed fixture. The cruciform specimens were tested under static tensile – tensile bi-axial loading of different setting angles to a rotation cylinder, i.e., 18.4° , 33.7° , 45° , 56.3° and 71.6° . Each test is conducted to

a limited displacement without failure of the specimen. For compressive – compressive and tensile – compressive loading condition, the behavior is like tensile – tensile loading condition.

Figure (6) shows the results of the bi-axial test which is the axial displacement – transverse displacement variation for unloading and loading state. In the unloading state, the ratios between transverse displacement and axial displacement follow the calculated ratio with good agreement. Therefore, the kinematic relation of the fixture has functioned well for the design without deviation. The bi-axial mechanism can generate five difference displacement ratios, i.e., 1:3, 2:3, 1:1, 3:2 and 3:3 respectively. The slight difference between actual ratios and designed ratios is caused by the inaccuracies of part dimensions or friction.

Figure 4.9 Axial displacement versus transverse displacement for unloading conditions.

Figure 4.10 Axial displacement versus transverse displacement for loading conditions.

In the loading state, the displacement ratios are different from calculated ratios, which show in Figure 4.10. The actual displacement ratio becomes 0.52:1 instead of 0.66:1 for the angle 33.7° . This variation even higher at larger setting angles, i.e. 0.73:1 for 45° , 0.92:1 for 56.3° and 1.12:1 for 71.6° instead of 1:1, 3:2 and 3:1 respectively. This reduction of transverse displacement is produced by effects of part deformation to the kinematics of the fixture. Figure 4.11 shows the force ratios during bi-axial testing. The force ratios and displacement ratios are matched well as the cruciform has the same dimensions along axial and transverse directions. The reduction of transverse force relates directly to the load which applies to the bearing. If the transverse force is 10 kN, the force on the bearing is 31.7 kN for 71.6° , 18 kN for 56.3° , 14.1 kN for 45° , 12 for 33.7° and 10.1 kN for 18.4° . Therefore, the fixture can generate higher accuracy in case of

low transverse force with high transverse displacement. Moreover, it is clear to see the fixture can produce proportionate displacement.

Figure 4.11 Axial force versus transverse force for loading conditions.

4.4 Conclusion

A new bi-axial fixture is designed and fabricated to compensate the bi-axial testing under a static condition with a reasonable cost of 6500 SGD.

The fixture can generate bi-axial test with multiple displacement ratios in both tension – tension, compression – compression and tension – compression loading directions. The cruciform specimen can be used in the bi-axial test with a uniform stress and strain zone at the center of the specimen.

Validation experiments showed that the actual displacement ratio reduced compared to expected ratio. However, the relationship between axial motion and transverse motion is proportionate.

References

- [1] M. Hinton, A. Kaddour, and P. Soden, "The world-wide failure exercise: Its origin, concept and content," *Failure criteria in fiber reinforced polymer composites: the world wide failure exercise*. Elsevier, Amsterdam, pp. 2-28, 2004.
- [2] A. Kaddour and M. Hinton, "The background to the second world-wide failure exercise (WWFE-II)," *J Compos Mater*, vol. 46, pp. 2283-2294, 2012.
- [3] A. Kaddour, M. Hinton, P. Smith, and S. Li, "The background to the third world-wide failure exercise," *Journal of Composite Materials*, vol. 47, pp. 2417-2426, 2013.
- [4] N. Bhatnagar, R. Bhardwaj, P. Selvakumar, and M. Brieu, "Development of a biaxial tensile test fixture for reinforced thermoplastic composites," *Polymer Testing*, vol. 26, pp. 154-161, 2007/04/01/ 2007.
- [5] A. Smits, D. Van Hemelrijck, T. P. Philippidis, and A. Cardon, "Design of a cruciform specimen for biaxial testing of fibre reinforced composite laminates," *Composites Science and Technology*, vol. 66, pp. 964-975, 2006/06/01/ 2006.
- [6] A. Kossa, "A new biaxial compression fixture for polymeric foams," *Polymer Testing*, vol. 45, pp. 47-51, 2015/08/01/ 2015.
- [7] S. C. Yen, J. N. Craddock, and K. T. Teh, "EVALUATION OF A MODIFIED ARCAN FIXTURE FOR THE IN-PLANE SHEAR TEST OF MATERIALS," *Experimental Techniques*, vol. 12, pp. 22-25, 1988.
- [8] S. T. Taher, O. T. Thomsen, and J. M. Dulieu-Barton, "Bidirectional Thermo-Mechanical Properties of Foam Core Materials Using DIC," in *Thermomechanics and Infra-Red Imaging, Volume 7: Proceedings of the 2011 Annual Conference on Experimental and Applied Mechanics*, ed New York, NY: Springer New York, 2011, pp. 67-74.
- [9] X. S. Sun, A. Haris, V. B. C. Tan, T. E. Tay, S. Narasimalu, and C. N. Della, "A multi-axial fatigue model for fiber-reinforced composite

- laminates based on Puck's criterion," *Journal of Composite Materials*, vol. 46, pp. 449-469, 2012.
- [10] A. Hannon and P. Tiernan, "A review of planar biaxial tensile test systems for sheet metal," *Journal of Materials Processing Technology*, vol. 198, pp. 1-13, 2008/03/03/ 2008.
- [11] P. Boisse, A. Gasser, and G. Hivet, "Analyses of fabric tensile behaviour: determination of the biaxial tension-strain surfaces and their use in forming simulations," *Composites Part A: Applied Science and Manufacturing*, vol. 32, pp. 1395-1414, 2001/10/01/ 2001.
- [12] S. S. H. Muhsin J. Jweeg, Yassr Y. Kahtan, "Experimental Investigations of the Cruciform Specimen of GFRP16 under Biaxial Monotonic and Cyclic Loading," *International Journal of Scientific & Engineering Research*, vol. 4, December-2013 2013.
- [13] M. Brieu, J. Diani, and N. Bhatnagar, "A new biaxial tension test fixture for uniaxial testing machine—a validation for hyperelastic behavior of rubber-like materials," *Journal of Testing and Evaluation*, vol. 35, pp. 364-372, 2006.
- [14] A. Rashedi, I. Sridhar, and K. J. Tseng, "Fracture characterization of glass fiber composite laminate under experimental biaxial loading," *Composite Structures*, vol. 138, pp. 17-29, 2016/03/15/ 2016.
- [15] S. Laustsen, E. Lund, L. Kühlmeier, and O. T. Thomsen, "Failure behaviour of grid-scored foam cored composite sandwich panels for wind turbine blades subjected to realistic multiaxial loading conditions," *Journal of Sandwich Structures & Materials*, vol. 16, pp. 481-510, 2014/09/01 2014.

Chapter 5

Fracture of Composite Laminate under Tension and Shear Loading

This chapter focuses on characterizing the intralaminar failure behavior of GFRP composite laminates under bi-axial stress conditions. Unidirectional (UD) and cross-ply butterfly shape specimen, containing a notch, is subjected to the combined in-plane tension and shear. Initially, the crack propagation patterns at different stress ratios are discussed. These critical stress values of the specimens are used to plot a failure stress surface. Moreover, the fracture toughness is calculated using the failure strengths and non-dimensional geometric correction factors which are derived from the FEM analysis. Therefore, a failure envelope in view of fracture mechanic is constructed to provide the relation between mode I and mode II fracture toughness of the laminate. The study contributed to the literature with a damage behavior and fracture toughness envelopes under bi-axial loading in notched composite laminates.

5.1 Introduction

The failure of FRP laminates with stress concentration zones near the cracks, notches, or holes are frequently seen in the composite products and structures. These stress risers are unpreventable as they arise from the geometric discontinuities of the structures. Then, the cracks appear and propagate from the stress concentration localization until whole structure is catastrophically destructed under remote load. When subjected to complex loading conditions, the composite structures have multi-axial stress state. The present study deliveries the experimental data of the composite laminate under bi-axial tension – shear stress states in both failure stress space and fracture toughness space. These experimental results support to characterize the behavior of composite laminate in the actual working conditions.

Many studies have conducted to investigate the behavior of composite under uniaxial tensile load using the standard specimens with central notches [1-5]. These studies highlight the fracture damage mechanisms of fiber, matrix or interface such as matrix cracking, fiber pullout, and delamination near the stress concentration zone at different layup composite laminates. Besides, the pure mode I fracture toughness have been discussed armed with the theory of fracture mechanics [6-10]. The fracture toughness K and energy release rate G are used as the material characteristic parameters to characterize failure. The results explain the effects of crack tip stress intensity to the growth of crack size. Compared to the tension test, the studies of laminates under shear loading is less widespread. In most studies, the shear failure mechanisms under the in-plane shear stress are conducted by using Iosipescu specimen [11-13]. Recently, few studies have addressed the failure behavior of composite laminate under a combination of tension and shear using the Arcan fixture [14-16]. Recently, Tan et al. [17] had conducted the tests for carbon FRP laminate containing a notch or a circular hole under tension – shear bi-axial load, and compression load. The sub-critical damage modes and failure envelopes of laminates containing stress raiser features under bi-axial loading were provided. However, this study

indicated the lack of fracture mechanisms of notched laminates under a combination of tension and shear. The present study aims to address this gap with laboratory tests using a modified Arcan fixture. The butterfly shape samples with a pre-crack were used to produce stress concentration. Finally, the results will be plotted in both failure load surface and critical stress intensity surface to determine the mixed-mode fracture behavior of cross-ply laminates under bi-axial loading.

5.2 Experimental methods

5.2.1 Modified Arcan testing

Arcan setup was originally applied to create the uniform shear stress in test specimens. Recently, Choupani et al. [18] modified the design of Arcan specimens to measure the value of interlaminar fracture toughness in mode I, mode II and mixed-mode. As fracture toughness plays an important role in predicting the fracture behavior of cracked composite laminates, an Arcan fixture has been developed in this study for testing fracture parameters of composite materials.

Figure 5.1 (a) A modified Arcan fixture; (b) Geometry of Arcan testing specimen.

As shown in Figure 5.1a, the modified Arcan fixture has an outside radius of 120 mm and includes two separate parts which are made of stainless steel SS304. Each part is mounted to an adaptor through a located pin and the adaptor is installed to Instron 5569 UTM. The loading angle can be adjusted in a range of 0° to 90° (with a step of 15°) by changing the position of loading pins of two adapters on the fixture. The specimens are fixed in the place between two parts and tightened by screws and bolts. To prevent the buckling effect of thin specimens, clampers were made for both sides of the fixture such that the clearance between two parts is 10 mm.

The Arcan specimen is designed to have a butterfly shape with a pre-crack (with a length of 24 mm and a width of 1 mm) in the middle of the specimen (see Figure 5.1b). The Arcan tests were conducted to the four and eight layers of unidirectional and cross-ply laminates. To fabricate the specimens, glass FRP sheets were first cut into the size of 130 mm by 130 mm and then stacked in the lay-up sequence of $[0]_4$, $[0]_{20}$, $[90]_{20}$, $[0/90]_s$ and $[0/90]_{5s}$. Later, they were cured in an oven following the thermal curing cycle as shown in Figure 5.2. Then, the cured specimens were machined to the desired shape by water jet cutting. Finally, the holes in specimens were drilled and the 24mm pre-crack was created using a conventional milling machine. The same method was used to fabricate the UD specimens.

Figure 5.2 Curing cycle of glass FRP G17500 for Arcan specimen.

The prepared specimens were then used to measure the value of critical loads in tensile tests. Six different angles, i.e. 15° , 30° , 45° , 60° , 75° and 90° , were tested to generate various mixed-mode conditions as shown in Figure 5.3 and listed in Table 5.1. For each angle, three tests were repeated, and then the obtained critical loads were averaged. To minimize the influence of specimen installation, two G-clamps were used to fix the positions of the two fixture parts before starting the test; these clamps were removed when the tests were conducted. The displacement loading rate during the tests was kept constant at 1 mm/min. The tests were conducted for the specimens with layup four plies $[0]_4$, $[0/90]_s$, and 20 plies $[0]_{20}$, $[90]_{20}$, $[0/90]_{5s}$ with the nominal thickness of 0.6 mm and 3 mm. For $[0]_4$, $[0/90]_s$, and $[0/90]_{5s}$, six stress ratios were applied by changing the loading angles. For other layups, pure mode I and pure mode II tests were conducted.

Figure 5.3 Arcan testing fixture at different loading angles: (a) 0°; (b) 15°; (c) 30°; (d) 45°; (e) 60°; and (g) 90°.

Table 5.1 Ratio between tension and shear loads

Loading angle	0°	15 °	30 °	45 °	60°	75 °	90 °
Tension	1.00	0.97	0.87	0.71	0.50	0.26	0.00
Shear	0.00	0.26	0.50	0.71	0.87	0.97	1.00
Tension: shear ratio	1:0	1:0.27	1:0.58	1:1	0.58:1	0.27:1	0:1

5.2.2 Fracture toughness calculation

Mode I and mode II fracture toughness were calculated using Equation 2.5 and 2.6. In these equations, critical loads were obtained from experiments, and the non-dimensional geometric correction factors were calculated from FEA of

Arcan specimen. Therefore, FEM models of Arcan fixture with the attached specimen were proposed using ABAQUS package software. In these models, the fixture was assumed to be undeformed and registered as two separated rigid bodies. The specimen was assigned as orthotropic material using equivalent effective elastic properties. Quadric 8-node reduced integration (S8R5) thin shell elements were used to model the specimen. Boundary conditions were applied at the center of two holes which were used in the test. All displacements were fixed except the rotation movements around the left and right holes and the axial movement of the right hole (Figure 5.4). Displacement of 1 mm was applied to the hole of the moving part. The elements around the crack tip were assigned as quarter-point singular elements to generate the crack-tip singular stress fields. In addition, the focused mesh was used in the area around the crack-tip to increase the accuracy of J-integral values from the analysis.

ABAQUS provides a procedure to compute values of J-integral which is equivalent to energy release rate values in the case of linear elastic fracture mechanic based on virtual crack extension method. The stress intensity factors for all modes can be related to J-integral.

After the analyzing process, these values were applied to calculate the geometrical correction factor by following equations:

$$Y_1 = \frac{K_I wt}{P_I \sqrt{\pi a}} \quad (5.1)$$

$$Y_2 = \frac{K_{II} wt}{P_{II} \sqrt{\pi a}} \quad (5.2)$$

where P_I , P_{II} is the force in FEA for tensile and shear load, w is the specimen gauge length, t is the specimen thickness, a is the crack length, K_I and K_{II} are the stress intensity factor of mode I and mode II in FEA respectively.

Figure 5.4 Finite element model of mode I Arcan testing.

5.3 Result and discussion

5.3.1 Load vs displacement curve

The load-displacement curves for the thick UD specimens and cross-ply specimens are shown in Figure 5.5. For the UD specimens and cross-ply specimens at the loading angles from 0° to 45° , the specimens failed from the crack tips in the reduced section in a sudden catastrophic manner. For these tests, the peak loads were recorded, and the critical stresses were calculated to generate the failure space under tension and shear stress conditions. For the $[90]_{20}$ UD specimens, there are points which the crack already propagated, but the curve was still increasing. This behavior was explained by the crack grew in the direction which separated the specimen into two parts; one part contained the crack was failed and another part was undamaged which could withstand the applied force. For the $[0/90]_{5s}$ specimens, it is evident that different failure behavior occur in the 0° and 90° loading angle cases. The load – displacement

increase linearly until the failure point for the 0° but showed a nonlinear behavior for the 90° . Moreover, the response patterns from 15° to 75° shown a transformation from the 0° to 90° response. This means the mixed mode loading conditions are successfully generated using Arcan tests.

(a)

(b)

Figure 5.5 Load-displacement plot for (a) UD specimens at 0° and 90° loading angles and (b) cross-ply $[0/90]_{5s}$ specimens from 0° to 90° loading angles.

The failure of cross-ply for loading angles of 60° to 90° were more complex with the development of transverse crack under shear loading. Figure 5.6 shows the crack evolution at various load values. It is understood that the load when the crack starts propagating is different from the peak load and the failure load. Therefore, the load when the crack starts propagating is used as the critical load to calculate failure stress and stress intensity factor values. This load was captured by comparing the load when the crack is visible and the gradient of load-displacement curves. It is assumed that the crack propagation produces a significant change in the load-displacement curves.

Figure 5.6 The crack patterns for $[0/90]_{5s}$ laminate during the pure mode II test.

5.3.2 Critical load

The main purpose of this study is to generate failure envelope in the stress space, and the stress intensity factor space for the GFRP UD and cross-ply laminates using Arcan tests at many loading angles. As mentioned in the previous section, calculation of the stress intensity factor requires the value of critical load from experiments and geometrical factors from the finite element analysis. The critical load obtained from the experiments for GFRP UD $[90]_4$ and cross-ply

$[0/90]_s$ composite materials using Arcan fixture is detailed in Figure 5.7. It is shown that the cross-ply laminates had higher critical loads than UD laminates for all loading angles. Critical loads of cross-ply laminates experienced a decrease when loaded from 0° to 90° . The critical loading kept decreasing for the UD laminates from 0° to 90° loading angles and started to increase when loaded from 60° to 90° . The lowest critical load was 177 N at 60° for the UD laminates and 680 N at 90° for the cross-ply laminates.

Figure 5.7 Average critical load vs. loading angle of $[90]_4$ and $[0/90]_s$ laminates.

The critical load obtained from experiments for GFRP UD $[0]_{20}$, $[90]_{20}$ and cross-ply $[0/90]_{5s}$ laminates was shown in Figure 5.8. Similarly, the cross-ply laminates had much higher load-bearing capability than UD laminates for pure mode I and pure mode II test. Critical loads of cross-ply laminates kept changing slenderly when loaded from 0° to 90° . For UD laminates, the critical loading of $[90]_{20}$ at 0° was around a half of this value for the cross-ply laminates whereas this value for $[0]_{20}$ was very low. In contrast, the pure mode I (90°) critical value of $[0]_{20}$ was higher than this value for $[90]_{20}$. Then, these critical loads will be discussed with the crack propagation patterns in the next section.

Figure 5.8 Average critical load vs. loading angle of [0]₂₀, [90]₂₀ and [0/90]_{5s} laminates.

The crack propagation patterns were also considered in these experiments which were highlighted in Figure 5.9 and Figure 5.10. In the tests for UD laminates specimens of varying thickness [0]₄, [0]₂₀, and [90]₂₀ layups, the crack always propagated along the direction of fiber (Figure 5.9a, b and Figure 5.10a to 5.10d). This phenomenon was explained by the occurrence of transverse intralaminar matrix cracking which starts growing from the stress concentration fields near crack-tip. Different crack propagation behavior were observed in the test of cross-ply specimens at [0/90]_s, and [0/90]_{5s}. In both layups, the cracks propagated along the crack direction in the loading angles of 0°, 15°, 30° and 45° (Figure 5.9c to 5.9f and Figure 5.10e to 5.10h) and deviated to the perpendicular direction in other loading angles i.e. 60°, 75°, and 90° (Figure 5.9g to 5.9i and Figure 5.10i to 5.10k). This suggested that different fracture mechanisms operated when the loading angle changed from 40° (1:1 load ratio) to 60° (0.58:1 load ratio). These performances may have been classified to the mode I dominating in which the crack was followed the crack opening failure behavior

and mode II active in which the crack was followed the shear failure behavior. This behavior will be discussed in the following section.

Figure 5.9 GFRP Arcan specimens in the testing conditions of $[90]_4$ and $[0/90]_s$ laminates in (a) 0° , (b) 90° loading angles and cross-ply laminates in (c) 0° , (d) 15° , (e) 30° , (f) 45° , (g) 60° , (h) 75° and (i) 90° loading angles.

Figure 5.10 Arcan specimens in the testing conditions of $[0]_{20}$, $[90]_{20}$ and (a, c) 0° , (b, d) 90° loading angles and cross-ply laminates $[0/90]_{5s}$ in (e) 0° , (f) 15° , (g) 30° , (h) 45° , (i) 60° , (j) 75° and (k) 90° loading angles.

The fracture mechanisms of the laminate in mode I is shown in Figure 5.11a, the failure occurred by a combination of matrix and fiber failure included fiber pull-out, fiber bridging, matrix cracking. The details of each failure mode are illustrated in Figure 5.11b. The 90° ply-split first appeared around the crack tip. Then, the cracks start propagating in the matrix zone between fibers of 0° at the crack tip. Finally, the fibers were pulled out with associated fiber bridging. These behavior acted for all mode I dominant cases. The similar behavior has been observed in the laminate under opening mode [19].

(a)

(b)

Figure 5.11 (a) Photograph and (b) schematic of mode I dominant failure under bi-axial tension – shear loading condition of the cross-ply laminate.

(a)

(b)

Figure 5.12 (a) Photograph and (b) schematic of mode II dominant failure under bi-axial tension – shear loading condition of the cross-ply laminate.

For the mode II loading case, a different crack pattern was observed compared to the mode I dominant case (Figure 5.12a). Both 0° and 90° plies were

pulled up and then rose the crack propagation in the direction which was perpendicular to crack orientation. This crack propagation happened in both directions from the crack tips. The mechanisms of fractures were illustrated in Figure 5.12b. The fiber and matrix split first happened in the 90° ply near the crack tips along the fiber direction. Then, the fiber and matrix split happened in the 0° ply which resulted in a bending part of lamina and matrix cracking along the inferior crack tip alignment. This bending part of 0° ply brought about the 90° ply. Later, the fibers of 90° plies were pulled out with the quick decrease in laminate load bearing capacity. The detailed information about interface failure can only be obtained through the X-ray computer tomography scan, to which author does not have access to.

Figure 5.13 The mixed mode effect to the crack pattern for 45° and 60° loading angle tests.

Moreover, the mixed mode effect is observed in the crack pattern for the specimen at 45° and 60° loading angles as shown in Figure 5.13. It is noticeable that the crack pattern in the 45° and 60° had both characteristics of mode I and

mode II effect. For 45° , the crack propagated along the crack direction like pure crack opening mode I but the 90° ply fiber matrix split appeared showing in-plane shear displacement. For 60° , the crack propagated perpendicular to crack direction like pure mode II, but the damaged region was difficult to observe compared to the pure mode II crack pattern. For 15° and 30° cases, the crack patterns were similar to the 0° loading angles test pattern. Likewise, for the 75° , a crack pattern followed pure mode II failure with smaller damaged region size.

5.3.3 Fracture toughness

To calculate the stress intensity factor, non-dimensional geometric correction factors are determined using the results from finite element analysis based on equations (5.1) and (5.2). The results were presented in Figure 5.14. The geometrical factors for cross-ply and UD laminates are slightly different. In addition, these factors remain almost unchanged for all angles, except that Y_I in pure mode II and Y_2 for pure mode I are equal to zero. The difference in values of non-dimensional geometric correction factors may be due to the FEA approximation.

Table 5.2 Fracture toughness of GFRP laminates.

Layup	K_I (MPa.m ^{1/2})	K_{II} (MPa.m ^{1/2})
[90] ₄	14.76	2.76
[90] ₂₀	8.92	2.12
[0] ₂₀	1.92	6.27
[0/90] _s	32.3	7.40
[0/90] _{5s}	28.00	8.84

Figure 5.14 Geometrical factor vs. loading angle for GFRP UD and cross-ply laminates for the crack length 24 mm for different loading angles.

After the values of average critical loads and geometrical factors were obtained, the experimental values of the stress intensity factors can be determined. The critical stress intensity factors for pure mode I (0° loading angle) and mode II (90° loading angle) were used as the fracture toughness which was considered as a material property. For both laminate thicknesses, critical stress intensity factors for cross-ply laminates were consistently higher than these values of UD laminates in both mode I and mode II. The fracture toughness in mode I was much higher than mode II except the laminate of $[0]_{20}$. This means the samples failed by intralaminar cracking had the higher tensile load bearing capacity than the shear loading. The values of fracture toughness of mode I and mode II are summarised in Table 5.2.

Figure 5.15 shows the values of critical stress intensity factor for different loading angles. The thickness influences the mode I fracture toughness while the stress distribution changed from plane stress to plane strain condition. For the cross-ply laminates, mode I fracture toughness of thin specimens $[0/90]_s$ is

higher than this value of thick specimen $[0/90]_{5s}$. For the mode II fracture toughness, the value for thick laminate is higher than the thin one. However, the mode II critical stress intensity values of both thin and thick laminates are quite consistent at the loading angles from 0° to 45° . The reason is the out-of-plane shear during the tests which has more effect on the thin laminate. Therefore, the mode II fracture toughness of thick laminate was used as the material property instead of the thin laminate value.

Figure 5.15 Critical stress intensity factor vs. loading angle for GFRP UD and cross-ply laminates for the crack length 24 mm for different loading angles.

Lastly, the mixed-mode fracture behavior of cross-ply laminates was described in Figure 5.16 with the combination of K_I/K_{IC} and K_{II}/K_{IIC} values. It is seen that the cross-ply laminates are failed in three modes under the bi-axial tension and shear condition. In the mode I dominate part, the tensile opening loading condition induced the propagation pattern along crack orientation. Furthermore, the specimens under the mode II dominant part is failed by the in-plane shear stress. In the tests, the crack opening mode I had dominated 0° and 15° loading angles and the mode II dominated for 60° , 75° , and 90° loading angles. For the mixed mode case of 30° and 45° loading angles, the crack grows along its orientation.

Figure 5.16 The mixed-mode fracture condition for $[0/90]_{5s}$ and $[0/90]_s$ laminates.

5.4 Conclusion

In this study, the mixed-mode intralaminar failure of UD and cross-ply laminates was investigated using a modified Arcan fixture. The numerous combinations of tension-shear loads can be generated to observe the mixed-mode behavior of the specimens under bi-axial loading condition. The crack patterns for each test case were discussed and the failure regions were analyzed to identify mode I dominant or mode II dominant. Later, the critical stress intensity factors were determined and plotted in a fracture envelope.

Based on the results and discussion above, the following conclusions can be made:

- The cross-ply specimens under tensile stress failed from the crack tips in a sudden catastrophic manner while the fracture of these specimens occurred gradually in the direction which was perpendicular to the crack orientation.

- The UD specimens failed along the fiber direction in all test cases. Matrix cracking was considered as the main failure mode for crack growth in the UD laminates.
- For the cross-ply specimens, two failure modes were observed as mode I dominant and mode II dominant conditions. The mode I dominant fracture happened for the loading angle from 0° to 45° and the specimens fractured under mode II for the loading angles from 60° to 90° .
- Fracture toughness of GFRP composite materials depends on the lay-up sequence. With the same number of plies, the cross-ply $[0/90]_s$ laminates have greater fracture toughness than the UD $[0_2]_s$ laminates. The average fracture toughness of GFRP were calculated as $K_{IC} = 32.1 \text{ MPa.m}^{1/2}$ and $K_{IIC} = 8.84 \text{ MPa.m}^{1/2}$ for cross-ply laminates and $K_{IC} = 14.76 \text{ MPa.m}^{1/2}$ and $K_{IIC} = 2.12 \text{ MPa.m}^{1/2}$ for UD $[90]_n$ laminates. The opening mode fracture toughness was much higher than the shearing mode result. The increase of specimen thickness decreases the mode I fracture toughness due to the change from plane stress to plane strain condition.

References

- [1] A. C. Garg, "The fracture mechanics of some graphite fibre-reinforced epoxy laminates, Part 1: quasi-isotropic laminates," *Composites*, vol. 17, pp. 141-149, 1986/04/01/ 1986.
- [2] A. E. Scott, M. Mavrogordato, P. Wright, I. Sinclair, and S. M. Spearing, "In situ fibre fracture measurement in carbon–epoxy laminates using high resolution computed tomography," *Composites Science and Technology*, vol. 71, pp. 1471-1477, 2011/08/19/ 2011.
- [3] F. Sket, R. Seltzer, J. M. Molina-Aldareguía, C. Gonzalez, and J. Llorca, "Determination of damage micromechanisms and fracture resistance of glass fiber/epoxy cross-ply laminate by means of X-ray computed microtomography," *Composites Science and Technology*, vol. 72, pp. 350-359, 2012/01/18/ 2012.

- [4] X. Xu, M. R. Wisnom, Y. Mahadik, and S. R. Hallett, "An experimental investigation into size effects in quasi-isotropic carbon/epoxy laminates with sharp and blunt notches," *Composites Science and Technology*, vol. 100, pp. 220-227, 2014/08/21/ 2014.
- [5] J. Awerbuch and M. S. Madhukar, "Notched Strength of Composite Laminates: Predictions and Experiments—A Review," *Journal of Reinforced Plastics and Composites*, vol. 4, pp. 3-159, 1985/01/01 1985.
- [6] L. Ye, "Evaluation of Mode-I interlaminar fracture toughness for fiber-reinforced composite materials," *Composites Science and Technology*, vol. 43, pp. 49-54, 1992/01/01/ 1992.
- [7] S. Jose, R. Ramesh Kumar, M. K. Jana, and G. Venkateswara Rao, "Intralaminar fracture toughness of a cross-ply laminate and its constituent sub-laminates," *Composites Science and Technology*, vol. 61, pp. 1115-1122, 2001/06/01/ 2001.
- [8] S. T. Pinho, P. Robinson, and L. Iannucci, "Fracture toughness of the tensile and compressive fibre failure modes in laminated composites," *Composites Science and Technology*, vol. 66, pp. 2069-2079, 2006/10/01/ 2006.
- [9] B. G. Falzon and P. Apruzzese, "Numerical analysis of intralaminar failure mechanisms in composite structures. Part I: FE implementation," *Composite Structures*, vol. 93, pp. 1039-1046, 2011/01/01/ 2011.
- [10] M. W. Czabaj and J. G. Ratcliffe, "Comparison of intralaminar and interlaminar mode I fracture toughnesses of a unidirectional IM7/8552 carbon/epoxy composite," *Composites Science and Technology*, vol. 89, pp. 15-23, 2013/12/13/ 2013.
- [11] W. R. Broughton, M. Kumosa, and D. Hull, "Analysis of the Iosipescu shear test as applied to unidirectional carbon-fibre reinforced composites," *Composites Science and Technology*, vol. 38, pp. 299-325, 1990/01/01/ 1990.

- [12] K. Hollmann, "In-plane shear failure analysis of notched composites," *Composites Science and Technology*, vol. 41, pp. 257-285, 1991/01/01/ 1991.
- [13] E. Totry, J. M. Molina-Aldareguía, C. González, and J. Llorca, "Effect of fiber, matrix and interface properties on the in-plane shear deformation of carbon-fiber reinforced composites," *Composites Science and Technology*, vol. 70, pp. 970-980, 2010/06/01/ 2010.
- [14] M. Arcan, Z. Hashin, and A. Voloshin, "A method to produce uniform plane-stress states with applications to fiber-reinforced materials," *Experimental Mechanics*, vol. 18, pp. 141-146, 1978/04/01 1978.
- [15] P. B. Gning, D. Delsart, J. M. Mortier, and D. Coutellier, "Through-thickness strength measurements using Arcan's method," *Composites Part B: Engineering*, vol. 41, pp. 308-316, 2010/06/01/ 2010.
- [16] X. S. Sun, A. Haris, V. B. C. Tan, T. E. Tay, S. Narasimalu, and C. N. Della, "A multi-axial fatigue model for fiber-reinforced composite laminates based on Puck's criterion," *Journal of Composite Materials*, vol. 46, pp. 449-469, 2012.
- [17] J. L. Y. Tan, V. S. Deshpande, and N. A. Fleck, "Failure mechanisms of a notched CFRP laminate under multi-axial loading," *Composites Part A: Applied Science and Manufacturing*, vol. 77, pp. 56-66, 2015/10/01/ 2015.
- [18] N. Choupani, "Experimental and numerical investigation of the mixed-mode delamination in Arcan laminated specimens," *Materials Science and Engineering: A*, vol. 478, pp. 229-242, 2008/04/15/ 2008.
- [19] A. J. Moffat, P. Wright, J. Y. Buffière, I. Sinclair, and S. M. Spearing, "Micromechanisms of damage in 0° splits in a [90/0]_s composite material using synchrotron radiation computed tomography," *Scripta Materialia*, vol. 59, pp. 1043-1046, 2008/11/01/ 2008.

Chapter 6

Fracture Capacity of Composite Laminate under Bi-axial Loading

Cruciform type specimens with pre-crack of different sizes and orientation were tested under different in-plane tension-tension and tension - compression bi-axial loading ratios. The material system was glass fiber-reinforced epoxy composite laminate with layup $[0/90]_s$ and $[0/90]_{2s}$. During the tests, critical axial and transverse stresses are recorded to find out the failure envelopes of composite laminates. Finite element simulations were carried out to determine the non-dimensional geometric correction factors of the test specimens with. Then, the stress intensity factors were computed and plotted in a fracture toughness surface. The result showed that the composite laminates can stand at higher load-bearing capability and the mode I fracture was the main fracture mode of the laminate failure.

6.1 Introduction

Wind turbines have been widely used to convert wind mechanical energy, which is an important renewable energy source, into electrical power. Turbine blades, which drive the turbine shaft to spin and thus generate electricity, are among the most important components of a wind turbine. The blades are subjected to complex loads, i.e., unsteady aerodynamic, gravitational and centrifugal forces during their service life which causes bi-axial or tri-axial stress and strain distribution on the blade surface. However, the uniaxial test data of composite laminates is normally applied during the design processes which can lead to misrepresenting the behavior of the composite structure. Therefore, the bi-axial response of composite samples is investigated in this study which provides more realistic data for the design processes of the composite wind turbine blade under complex loading situations.

Bi-axial testing methods using cruciform specimen on composite materials have improved due to the development of bi-axial testing facilities, process monitoring methods and numerical tools [1, 2]. However, the bi-axial data from these methods are limited because of the expensive costs of the testing equipment, sample preparation, and experiment operation compared to standard uniaxial tests. It is observed that there is a lack of bi-axial experimental data results of damaged FRP composite materials with imperfections such as cracks or notches. A previous experimental investigation by Rashedi et al. [3] studied fracture characterization of the composite cruciform sample with varies of length and angular orientation of the through-thickness central cracks. The current study is focussed on further experimental work on cruciform specimens with central cracks under tension – tension and tension – compression bi-axial loading conditions. Then, the damage and failure behavior for each arrangement were categorized with failure envelopes in stress space and fracture toughness space. The results will be used to validate the capacity of linear fracture mechanics to GFRP composite laminates under bi-axial stress states.

Figure 6.1 Flowchart of bi-axial testing experiment and simulation.

6.2 Experimental methods

6.2.1 Material system

In this study, glass fiber-reinforced epoxy matrix unidirectional (UD) G17500 prepreg with a 0.15mm nominal ply thickness supplied by Weihai Guangwei Composites was selected as the material for all the experiments. The uniaxial elastic properties of this composite measured by using ASTM standard D3039/3039M, D3410/3410M and D3518/3518M are listed in Table 5.1.

Table 6.1 Material elastic properties of G1750 unidirectional lamina

Engineering constant		Value
<i>Longitudinal modulus</i> E_{11}	[GPa]	46
<i>Transverse modulus</i> $E_{22} = E_{33}$	[GPa]	13
<i>Poisson's Coefficient</i> ν_{12}	–	0.26
<i>Shear modulus</i> $G_{12} = G_{13}$	[GPa]	7
<i>Shear modulus</i> G_{23}	[GPa]	4.48

6.2.2 Tension – tension test method

Cruciform specimens with the dimensions and orientation shown in Figure 6.2 are used for the testing. The specimen geometry was optimally designed to

obtain a uniform far-field stress around the gauge zone of the specimen by using FEM simulation. This specimen has cruciform shape with a corner radius of 25 mm and a through-thickness central crack of 1 mm width. The crack lengths are 40 mm and 45 mm with an orientation angle of 0° , 30° , and 45° . Due to the limited dimension of the bi-axial fixture, specimen geometry is asymmetric with the axial length of 320 mm and a transverse length of 200 mm. Eight 16mm diameter holes in the axial tabs and five 8 mm diameter holes in the transverse tabs were machined to support the bolt clamping in bi-axial tests.

Figure 6.2 Cruciform specimen dimensions and orientation. All dimensions are in mm.

Sample preparation process is illustrated in Figure 6.3. GFRP composite laminate samples were manufactured by using hand layup. The composite panels were stacked together at the right sequence of $[0/90]_s$ with the size of 320 mm by 200 mm and the thickness of 0.6 mm. To prevent edge effect during the testing process, eight composite tabs including four tabs of 100 mm x 80mm and four tabs of 100 mm x 45 mm were prepared to obtain a symmetric pattern $[0/90]_{2s}$ by using the stacking process. Then these tabs were attached to the sample at the four arms. After the stacking process, the samples were cured in an oven according to manufacturer instructions suggested curing cycle of 130°C for 2.5

hours and then cooled to the room temperature in the furnace. Water jet cutting machine was used to cut the composite panel to the final geometry of samples. Finally, 40 mm and 45 mm notches were machined using 1mm diameter milling tool. To measure the strain distribution on the specimen during the bi-axial tests, the surface of specimens were coated by a speckle pattern for DIC measurements.

Figure 6.3 Fabrication process steps of GFRP specimens.

All specimens were tested using the Instron Universal Testing Machine (UTM) with add-on fixture as shown in Figure 6.4. This fixture has an extended the capability of the uniaxial testing system to bi-axial testing system with load carrying capacity in axial axis up to 250 kN and transverse axis up to 10 kN (Figure 5.4) for tension – tension bi-axial loading conditions. Each specimen was loaded at a constant displacement rate of 1 mm/min. The ratio between the axial force and transverse force was electrically interlocked controlled by the Instron controller with Bluehill software.

Transverse to axial load ratios were 0:1, 0.4:1, 0.8:1, 1:1, 1:0.8, 1:0.4, and 1:0. For the 45° crack specimens, only half of load ratios were done because of the symmetrical shape of the specimen. For high transverse load cases, the crack was rotated 90° to swap the transverse direction and axial direction. Then, the vertical direction was transverse and the horizontal direction was axial. This

method was applied to bypass the 10 kN limitation of the pneumatic actuator.

Figure 6.4 Photograph of the bi-axial testing set-up.

6.2.3 Tension – Compression test method

A cruciform sample also is subjected to the tension-compression bi-axial tests. These tests were conducted with a novel fixture which was detailed in the previous chapter. Therefore, a new specimen was designed based on the optimal specimen geometry of the tension – tension test with the scaled size which is shown in Figure 6.5. The composite panels were stacked at the sequence of $[0/90]_{2s}$ with the size of 180 mm by 180 mm and thickness of 1.2 mm. Each arm of the specimen was strengthened with $[0/90]_{2s}$ tabs of 40 mm x 60 mm for both sizes. All specimens were cured in the same process steps as the tension – tension samples. The cracks of 20 mm length and 1 mm width were machined on the sample.

Figure 6.5 Cruciform specimen dimensions and orientation. All dimensions are in mm.

The bi-axial fixture is mounted to Instron 8801 universal testing machine as seen in Figure 6.6. Specimens were clamping into plates which were secured with three to five M10 bolts depending on the maximum applied force. The fastening torque was kept at 50 Nm by using a torque wrench. Axial displacement rate was set at 1 mm/min. Transverse displacement was captured by a magnetic location sensor. The current time of Instron computer was used to sync the axial and transverse force and displacement data. Both axial and transverse force and displacement data were collected every 0.01s. The setting angles for the bi-axial test were 45° , 33.7° , and 18.4° which generate the transverse to axial load ratios are set as 0:1, 0.14:1, 0.48:1, and 0.65:1. The bi-axial specimens were used with through-thickness center cracks of 20 mm length with orientations of 0° and 45° . To prevent the effect of laminate buckling under compression loading, an anti-buckling plate was designed to keep in-plane bi-axial condition during the tests.

Figure 6.6 The bi-axial testing fixture set-up.

6.2.4 DIC method

DIC is an optical-numerical method to provide the full-field strain distribution data of experiments. To apply DIC technique in the present study, a digital single-lens reflex camera Canon, 18.1 megapixels APS-C CMOS Sensor was used to capture images of testing specimens with every second. The specimen surfaces were covered with a black paint to create speckle patterns. The camera was mounted on a tripod, and a remote camera controller was used to set the time duration. Images of testing processes were analyzed by VIC2D DIC software, and then the displacement fields were generated. The experimental set-up of DIC system was illustrated in Figure 6.7.

Figure 6.7 Photograph of digital image correlation setup using the single-lens reflex camera.

6.3 Data reduction

6.3.1 Equivalent loaded area

The actual stress which is distributed over the cross-section of a testing sample is important to determine the behavior of a composite panel under bi-axial loadings. However, the cruciform geometry of specimens is non-uniform which can affect the calculation of stress in axial and transverse directions. To bypass this problem, a method to calculate the equivalent area in the both directions was proposed. The tensile strength of the testing composite material is determined by uniaxial tensile testing according to ASTM standard D3039/3039M. The bi-axial samples are then separately tested in uniaxial axial and transverse direction under tensile loading. Ultimate load when the sample failed was used to calculate the equivalent loaded area.

$$A_{equiv} = P/\sigma_{ult} \quad (6.1)$$

where A_{equiv} is equivalent load area (mm^2), P is the ultimate load at axial/transverse direction (N) and σ_{ult} is tensile strength (MPa).

After the equivalent load areas in both axial and transverse are determined, these values were used to calculate the stress in the specimen during the bi-axial test.

6.3.2 Failure surface in stress space

The axial and transverse stress is calculated from axial and transverse load using equivalent load areas which are detailed in the above section. For each test, the peak load is recorded then used to compute the ultimate stress value. For an inclined crack, the axial and transverse stress may be used to express the crack opening and crack shear behavior. Then, the stress components were transformed to the crack orientation which is illustrated in Figure 6.8. Finally, the transformation stress components are plotted in one graph with their stress ratios to obtain the failure envelope.

The stress transformation equation is written as

$$\sigma_{x'} = \sigma_x \cos^2 \theta + \sigma_y \sin^2 \theta + 2\tau_{xy} \sin \theta \cos \theta \quad (6.2)$$

$$\sigma_{y'} = \sigma_x \sin^2 \theta + \sigma_y \cos^2 \theta - 2\tau_{xy} \sin \theta \cos \theta \quad (6.3)$$

$$\tau_{x'y'} = (\sigma_y - \sigma_x) \sin \theta \cos \theta + 2\tau_{xy}(\cos^2 \theta - \sin^2 \theta) \quad (6.4)$$

where σ_x , σ_y , τ_{xy} are the original stress components, $\sigma_{x'}$, $\sigma_{y'}$, $\tau_{x'y'}$ are the transformation stress components and θ is the transformation angle.

Figure 6.8 Illustration of stress transformation in a bi-axial sample.

6.3.3 Fracture toughness surface

In linear elastic fracture mechanic, stress intensity factor (K) is applied to predict the stress states which are near the crack tips. The mode I and mode II stress intensity factor values for a crack under bi-axial stress field can be express as:

$$K_I = Y_1 \sigma_{axial} \sqrt{\pi a} \quad (6.5)$$

$$K_{II} = Y_2 \sigma_{axial} \sqrt{\pi a} \quad (6.6)$$

where K_I and K_{II} are the mode I and mode II stress intensity factors, σ_{axial} is axial critical stress value, $2a$ is crack length, Y_1, Y_2 are mode I and mode II non-dimensional geometric correction factors.

However, the non-dimensional geometric correction factor Y_1, Y_2 are unknown components from the equations. These factors are commonly determined by using an analytical equation or calculated from finite element analysis results. In this study, the simulation from finite element code named

ABAQUS was performed to find out the non-dimensional geometric correction factor value of cruciform specimens under bi-axial loading conditions.

Figure 6.9 FEM model of a bi-axial cruciform specimen under bi-axial loading.

For the FE modeling of the bi-axial specimen, an eight-node doubly curved thin shell element with reduced integration S8R5 available in ABAQUS is used. Focus mesh refinements are defined around the crack to archive a better result in simulation. The equivalent elastic properties of $[0/90]_s$ laminate is calculated using MATLAB and the properties were then assigned to the material properties of FE model. The FEM model of the bi-axial specimen is shown in Figure 6.9 with the details of mesh around the crack notch and boundary condition. The stress intensity factor value is computed from J-integral values for node paths around the crack tips. Then are non-dimensional geometric correction factors are

calculated from the FEA stress intensity factor value using the equation which is derived from (6.5) and (6.6).

$$Y_I = K_{IFEM} / (\sigma_{axialFEM} \sqrt{\pi a})$$

$$Y_2 = K_{IIFEM} / (\sigma_{axialFEM} \sqrt{\pi a})$$

In the case of α° orientation crack, the kinked crack stress intensity factors are calculated by the below expressions [4]:

$$K_{Ik} = \frac{1}{4} \left(3 \cos \frac{\alpha}{2} + \cos \frac{3\alpha}{2} \right) K_I + \frac{3}{4} \left(\sin \frac{\alpha}{2} + \sin \frac{3\alpha}{2} \right) K_{II} \quad (6.7)$$

$$K_{IIk} = -\frac{1}{4} \left(\sin \frac{\alpha}{2} + \sin \frac{3\alpha}{2} \right) K_I + \frac{1}{4} \left(\cos \frac{\alpha}{2} + 3 \cos \frac{3\alpha}{2} \right) K_{II} \quad (6.8)$$

6.4 Results and discussion

6.4.1 Tension – tension bi-axial test

6.4.1.1 Load versus displacement plots and crack paths

The study of cruciform specimens with a central crack under bi-axial tensile-tensile loading had been conducted for 0° and 45° crack from 1:0 to 1:1 ratio by Rashedi et al. [3]. In addition to the bi-axial tensile-tensile test result of 0° and 45° crack specimens, Figure 6.10 presents the load versus displacement curves for 40 mm 0° crack and 45 mm 45° crack which has high transverse load by axial load ratio i.e. 1:0, 1:0.8 and 1:0.4. For 0° 40mm crack with the ratio of 1:0.8, the axial force reached the limitation of 10 kN then the test was finished without specimen failure. Figure 6.11 and 6.12 demonstrate the load versus displacement curves for 40 mm 30° crack, 45 mm 30° crack from load ratio 1:0 to 0:1. The specimen positions on these graphs show the axial and transverse direction during the test. To provide a clear view of the graph, the axial load vs displacement curves are shown with positive displacement values and the transverse load vs displacement curves are shown with negative displacement value. For both 0° and 30° cracks, the plot of the experimental results highlights brittle fracture of composite laminates as the curve has a linear gradient up then suddenly drop with catastrophic failure. Similar behaviors were observed for the 0° and 45° crack tests. For each test, the peak load is recorded then critical stress is calculated with the equivalent areas which are 50.6 mm^2 for transverse direction and 61.1 mm^2 for axial direction. Therefore, the stress ratios are 1:0, 1:0.33, 1:0.67, 1:0.83, 0.83:1, 0.67:1, 0.33:1 and 0:1, respectively.

(a)

(b)

Figure 6.10 Load -displacement plot for 0° , (a) 40 mm cracks and (b) 45 mm cracks for bi-axial tension-tension loading.

(a)

(b)

Figure 6.11 Load-displacement plot for 30°, 40 mm cracks under (a) ratios from 1:0 to 1:1 and (b) ratios from 0.4:1 to 0:1 bi-axial tension-tension loading.

(a)

(b)

Figure 6.12 Load-displacement plot for 30° , 45 mm cracks under (a) ratios from 1:0 to 1:1 and (b) ratios from 0.4:1 to 0:1 bi-axial tension-tension loading.

The crack propagation patterns of four samples with 0° crack are shown in Figure 6.13. For 0:1 and 0.4:1 load ratios, similar propagation direction through the arm section were observed (Figure 6.13a). This notch-insensitive response was different from the failure pattern of the previous study for 1:0 to 1:1 load ratios which show the failure occurred from the crack tips i.e. notch-sensitive response. For 0.8:1 load ratio, the crack started from crack tips then propagate until the sample was broken (Figure 6.13b).

Figure 6.13 Crack propagation direction (a) for load ratio of 0:1 and 0.4:1; (b) for load ratio of 0.8:1.

The crack propagation directions for 30° degree crack samples are shown in Figure 6.14. The cracks propagated in the directions which are perpendicular to the direction of dominant load. For 1:0 to 1:1 load ratio, the cracks followed the transverse direction in the axial load condition (Figure 6.14a). For 0.8:1 to 0:1 load ratio, the cracks propagated along the axial direction in the transverse load

dominant condition (Figure 6.14b). In both cases, the cracks were simultaneously growth from both ends.

(a)

(b)

Figure 6.14 Crack propagation direction (a) for load ratios from 1:0 to 0.8:1; (b) for load ratio from 0.8:1 to 1:1.

Crack propagation patterns are shown in Figure 6.15. Several composite failure behaviors were observed in 0° and 90° plies through the fracture surface. Firstly, the intralaminar damage in the 0° laminates was the matrix cracking which happened in the space between fibers i.e. transverse matrix crack. Then, the fibers in the 90° plies which is adjacent the fractured zone of 0° plies were stretched. Fiber fracture occurred with the fiber pull-out in 90° plies. Later, fiber-bridged zone can be observed in the 0° plies. The fracture happened initially in the 0° plies and then propagated into the 90° plies. The similar behavior were also recorded in the mode I test for composite laminate [5].

Figure 6.15 Crack patterns of (a) 30° crack 1:0.4 load ratio; (b) 30° crack 0.4:1 load ratio; and (c) 45° crack 0.8:1 load ratio.

6.4.1.2 Failure response of axial and transverse stress

The critical axial stress and transverse stress values for 40 mm and 45mm cracks are presented in Figure 6.15 with respective load ratios and crack angles. The axial stress to transverse stress ratios become 1:0, 1:0.33, 1:0.67, 1:0.83, 0.67:1, 0.33:1 and 0:1, respectively because of the different equivalent areas which were used to calculate ultimate stress from the peak loads. All tests were conducted under tensile – tensile bi-axial loading conditions. The 0° crack specimens were subjected to pure crack opening force which was pure mode I loading condition.

Figure 6.16 Failure graph of axial and transverse stress of (a) 40 mm cracks and (b) 45 mm cracks under bi-axial tension – tension loading conditions.

For 0° and 45° crack, specimens can withstand a higher amount of axial stress with the increase of transverse stress from uniaxial 1:0 ratio to bi-axial 1:0.86 ratio. Similarly, for 30° cracks, the axial critical stress increases by 3.4% for the 40mm crack and 14.2% for the 45mm crack and the critical axial stress under bi-axial tensile failure always was higher than uniaxial value whereas the load ratio was increased from 1:0 to 1:0.83 (Figure 5.17a, b). However, a positive gradient was not maintained whereas the highest axial stress was from 155 MPa for 1:0.33 stress ratio for 40 mm crack and 162.6 MPa for 1:0.67 stress ratio for 45 mm crack, respectively. Therefore, for the stress ratio from 1:0 to 1:0.83, the specimens could achieve a greater load bearing capacity under bi-axial tensile –

tensile stress conditions. For 0° degree crack, this strengthen effect is caused by the transverse load which induced a crack closure response as shown in Figure 5.18.

Figure 6.17 Critical stress against increasing stress ratio (a) for stress ratio from 1:0 to 1:0.83 of 40 mm crack; (b) for stress ratio from 1:0 to 1:0.83 of 45 mm crack; (c) for stress ratio from 1:0.67 to 0:1 of 40 mm crack; and (d) for stress ratio from 1:0.67 to 0:1 of 45 mm crack (the stress ratios for a and b are drawn in transverse stress to axial stress ratios; the stress ratios for c and d are drawn in axial stress to transverse stress ratios).

For 0° crack with stress ratio 0:1, the specimens are failed when the transverse stresses reach 282.8 MPa for 40 mm crack and 290.6 MPa for 45 mm which is near the ultimate stress value of the cross-ply laminates i.e. 288 MPa. When the

stress ratio is 0.33:1, the transverse critical stress increases to 315.5 MPa for 40 mm crack and 296.9 MPa for 45 mm crack (Figure 6.17 c,d). In both stress ratios, the specimens were failed by crack growth through its arm. It is understood that at the high transverse stress and low axial stress, crack closure force will be more dominating rather than the crack opening forces (Figure 6.18). Hence, cross-ply GFRP laminates are likely more insensitive to the crack. For the stress ratio 0.67:1, the failure mode is unclear because of limitation of the bi-axial testing system. However, it is suggested that a transition from notch-sensitive failure to notch-insensitive failure will occur when the stress ratio is over 0.67:1.

Figure 6.18 Crack closure and crack opening effects of cracks under tension or compression loading.

As in the case of 30° crack, for high transverse stress i.e. stress ratio of 0:1, 0.33:1 and 0.67:1, the transverse stress show different trends for 40 mm crack and 45 mm crack as shown in Figure 6.17c, d. The crack propagation paths are perpendicular to the transverse force direction at these ratios. For 40 mm crack, the transverse stress decreases from 178.8 MPa to 160.1 MPa while the axial stress increase from 0 MPa to 104.2 MPa. In another scenario, for 45 mm crack, the transverse stress increases from 171.4 MPa to 203.3 MPa then decreases to 177.2 MPa whereas the transverse stress rises from 0 MPa to 66.6 MPa then to

114.9 MPa. Therefore, the increase of axial stress affected differently to the laminate failure when the crack length was changed.

6.4.1.3 Failure graph of transformation stress components

To provide a better understanding, the stress was transformed along the crack direction using the Equation 6.2 to 6.4 in which the shear stress orientation is parallel to crack orientation i.e. 30° for 30° cracks and 45° for 45° cracks respectively. The results are illustrated in Figure 5.19 which shear stress $\tau_{xy'}$ and transformation stress components $\sigma_{y'}$ are plotted against transverse to axial stress ratio for 30° and 45° cracks for respective load ratios. Similar behavior can be observed for both 30° crack and 45° crack in the plot. In-plane shear changed from negative to positive near 1:1 stress ratio and reached highest values at the stress ratios 1:0 and 0:1 i.e. unidirectional loading. Resolved axial stress $\sigma_{y'}$ increases for the stress ratios from 0:1 to 1:1 then decrease in the rest ratios. It shows fairly symmetric shape about the y-axis around the ratio 1:1. The consistency of the experiment result suggests a relation between in-plane shear $\tau_{xy'}$ and crack opening stress $\sigma_{y'}$ to the fracture behavior of the specimens. In this space, the resolved axial stress $\sigma_{y'}$ causes mode I crack opening separation and shear stress $\tau_{xy'}$ caused mode II in-plane sliding effect.

Figure 6.19 Plot of transformation stress components against stress ratio.

6.4.1.4 DIC and FEM analysis

To verify the suitability of FEM analysis, a comparison between DIC results and the corresponding FEM is shown in Figure 6.20 for 40 mm 30° crack under bi-axial stress ratio 1:0.33 at the axial load 3498.63N which is 90% of the fracture load. The strain value limitations are set from -0.05% to 0.5%. The area with higher strain is plotted in red color. From the images, symmetrical strain field patterns can be observed, especially around the crack tips. Moreover, high strain regions are prominent near the crack tips which highlight the strain intensity. The results show a good agreement between the simulation and experimental data whereas the similar patterns appear in the distribution of all stress components. The measurements depict comparable strain field shape, especially near the crack tips.

(a)

(b)

(c)

Figure 6.20 Comparison between FEM analysis (left) and DIC results (right) for (a) ϵ_x ; (b) ϵ_y ; and (c) ϵ_{xy} of 40 mm 30° crack under stress ratio 1:0.33.

6.4.1.5 Fracture toughness

To determine the fracture toughness, the non-dimensional geometric correction factors were calculated using the FEM analysis which was mentioned in the the previous section. These non-dimensional geometric correction factor values are shown in Figure 6.20. After wards, mode I and mode II fracture toughness are calculated according to the Equation 6.5 to 6.8.

Figure 6.21 non-dimensional geometric correction factors Y1 and Y2 of bi-axial testing specimens.

The variations of fracture toughness for different stress ratios of 0° crack are shown in Figure 6.21. The cracks were subjected to the pure mode I at the 0° case. The mode I stress intensity factor values are around $32 \text{ MPa} \cdot \sqrt{\text{m}}$. These values are matched well with the fracture toughness which is calculated from previous chapter ($32.3 \text{ MPa} \cdot \sqrt{\text{m}}$) and is higher than the fracture toughness which mentioned in the previous study in which the translaminar fracture toughness is $15.52 \text{ MPa} \cdot \sqrt{\text{m}}$ [3]. It is comparable between mode I fracture toughness value which is determined from the Arcan test and the mode I critical stress intensity values of cruciform specimens under bi-axial loadings. This suggests a method to predict the failure of composite laminates in which the material fracture properties are found by Arcan tests then this value can be applied to predict the failure of cross-ply laminates under bi-axial loading, especially in the pure mode I.

Figure 6.22 Mode I fracture toughness versus stress ratio for 0° cracks.

Next, the mode I and mode II stress intensity factors are calculated for 30° and 45° cracks. Figure 5.22a illustrates that the variations for K_{IC} and K_{IIC} for 40 mm and 45 mm crack at the stress ratio from 0:1 to 0.83:1. Mode II in-plane shear appeared to decrease from positive values to negative values as the stress ratio increases from 0:1 to 0.83:1. Meanwhile, mode I crack opening is consistent around the $30 \text{ MPa} \cdot \sqrt{\text{m}}$. This mean that mode I crack opening played a dominant role in the failure of composite laminates whereas the transverse stress is smaller than axial stress for both 30° and 45° crack. For the stress ratio from 1:0.83 to 1:0, the critical stress intensity factors are shown in Figure 6.22b with the x-axis is the axial stress to transverse stress ratio. In this case, the mode I values are smaller than the values of stress ratio from 0:1 to 0.83:1. This means that the increase in transverse stress lead to crack opening process of specimens. The reason of this behavior is the change of crack propagation direction which was discussed previously.

Figure 6.23 Mode I and mode II fracture toughness versus stress ratio for 30° cracks and 45° cracks.

To provide a mixed-mode relation, the values of K_I/K_{IC} and K_{II}/K_{IIc} are computed then compared to these values from the Arcan tests which was conducted in the the previous chapter, as showed in Figure 6.23. The results show a good agreement between Arcan test data and cruciform data. Most cruciform

specimens were failed in high mode I stress intensity factor which suggests a mode I dominated fracture of the cross-ply laminates with cracks. There are some failure points which seems to fail in the mixed-mode behavior which is fairly similar to the results from Arcan test.

Figure 6.24 Plot of K_I/K_{IC} against K_{II}/K_{IIc} for cruciform specimens and Arcan specimens under bi-axial tests.

6.4.2 Tension – compression bi-axial test

6.4.2.1 Load versus displacement plots and crack paths

The bi-axial tests were conducted under displacement control for both 0° and 45° cracks. The load against displacement plots is shown in Figures 5.25. For 0° cracks, the load increases linearly with displacement then fail catastrophically for all load ratios. This behavior is similar to the results of tension – tension bi-axial tests.

(a)

(b)

Figure 6.25 Load – displacement plot for 20 mm cracks for (a) 0° cracks; and (b) 45° cracks under bi-axial tension-compression loading.

Also, the same performance is observed for the tests of 45° cracks under bi-axial load ratio 0:1 and 0.14:1. However, for higher load ratio i.e. 0.48:1 and 0.6:1, there are two fracture points which are caused by the failure of samples under compression loading. The crack propagation patterns of samples with 0° crack and 45° crack are shown in Figure 6.26. For 0° cracks with all load ratios and 45° load ratio of 0:1 and 0.14:1, similar propagation direction which is perpendicular to the axial force. This shows consistent failure pattern in both tension – tension and tension – compression bi-axial tests for 0° crack which suggests that the mode I fracture failure occurs in these tests. Therefore, the same crack opening behavior was seen in the bi-axial loading test if the axial force is dominant.

Figure 6.26 Crack propagation direction (a) for 0° cracks at all ratios; (b) for 45° crack at load ratios of 0:1 and 0.14:1.

For 45° cracks at 0.48:1 and 0.65:1 ratios, different crack patterns can be noticed as shown in Figure 6.27. At first, the crack propagated along the direction which was perpendicular to the transverse compressive load. Then, the secondary

crack line appeared in the direction which was perpendicular to the axial tensile load. The traces of this failure can be observed from the load-displacement response in Figure 6.25b. In this graph, the peak load of transverse force was the load for primary crack propagation. Besides, the secondary propagation occurred when the axial force reached its peak.

Figure 6.27 Crack propagation direction for 45° crack at load ratios of 0.48:1 and 0.65:1.

Crack propagation patterns are shown in Figure 6.28. An identical pattern can be observed for the 0° at all tested load ratios and 45° cracks at 0:1 and 0.14:1 load ratios (Figure 6.28a, b) which are similar to that of previous results of 0° crack under tension – tension bi-axial loading. The failure mechanisms included matrix cracking, fiber fracture with the fiber-bridged zone. This again highlights the mode I fracture of cross-ply laminate under bi-axial test with crack. However, in the tension – compression test, the transverse stress may affect the failure behavior of the laminate which will be discussed in the following section. For 45° cracks at 0.65 load ratio, the primary crack pattern is a shear band which can be observed in cross-ply laminate compression tests [6] (Figure 6.28 c). This suggests that the laminate failed under compression load initially. However, the specimen still had the load bearing capacity along the axial direction as the crack parallel to the axial load direction. Therefore, the force kept increasing until the specimen was failed under crack opening mode.

(a)

(b)

(c)

Figure 6.28 Crack patterns of (a) 0° crack; (b) 45° crack 0:1 load ratio; and (c) 45° crack 0.65:1 load ratio.

6.4.2.2 Failure graph of axial and transverse stress

The stress values were calculated by dividing the peak load by the equivalent area. Due to the symmetric shape of the specimen, only one equivalent area value is determined for both axial and transverse axis which is $A_{equiv} = 60.6 \text{ mm}^2$.

Figure 6.29 presents the critical axial and transverse stress values for 0° and 45° crack bi-axial tests. The critical stress values were plotted for both fracture modes which were fracture under compression which occurred initially and mode I crack opening which occurred latterly at the 0.48:1 and 0.65:1 load ratios for 45° cracks. As in the case of 45° crack under compressive failure, the specimen failed because of compressive critical transverse stress. These transverse stress values increase 24.7% whereas the axial stress ratios change from -0.48:1 to -0.65:1. Therefore, the stress ratio affects significantly to the ultimate compressive stress values under bi-axial loadings.

Figure 6.29 Failure graph of axial and transverse stress of 20mm; (a) 0° cracks and (b) 45° cracks under bi-axial tension – compression loading conditions.

From Figure 6.30, specimens load bearing capacity decreases for stress ratio from uniaxial i.e. no transverse force to higher transverse force. In contrary to the tension – tension test results, for 0° cracks, the axial critical stress reduced 6.9% from 169 MPa to 157.5 MPa when the stress ratio changes from 0:1 to 0.8:1. Similarly, this stress value decreases 5.8% from 183.4 MPa to 172.8 MPa when

the stress ratio varies from 0:1 to 0.14:1 for 45° crack. This behavior can be explained by the crack opening mechanism due to transverse force which is illustrated in Figure 6.18. The failure surface appears a linear relation for critical axial stress to the stress ratios for both 0° crack and 45° crack. For 45° crack at the stress ratios higher than 0.14:1, the mode I fracture happened after the failure caused by compression force. However, it is less effective to the mode I fracture as axial stress decreases 3.6% from 172.8 MPa to 166.6 MPa while the stress ratio varies from 0.14:1 to 0.48:1.

Figure 6.30 Critical stress against increasing stress ratios for 0° and 45° crack under tension – compression bi-axial loading.

6.4.2.3 Fracture toughness

The fracture toughness values are calculated using the same methodology for tension – tension bi-axial tests. The non-dimensional geometric correction factors are computed from FEM analysis which are shown in Figure 6.31a. The fracture for 45° crack at stress ratio varies from -0.47:1 to -0.65:1 occurs under compressive failure, the stress intensity values are provided for only 0° crack at all stress ratios and 45° crack at 0:1 and -0.14:1. Like before, the values of mode I critical stress intensity factor of 0° crack is $26.54 \text{ MPa} \cdot \sqrt{m}$ and stress intensity factors for 45° crack is $\sim 25.3 \text{ MPa} \cdot \sqrt{m}$ which are matched well with the

translaminar mode I fracture toughness for $[0/90]_{2s}$ laminates ($26.7 \text{ MPa} \cdot \sqrt{m}$).

This means that mode I fracture is occurred for these tests.

(a)

(b)

Figure 6.31 Mode I and mode II (a) non-dimensional geometric correction factors and (b) fracture toughness versus stress ratios for 0° cracks and 45° cracks under tension – compression bi-axial loadings.

6.4 Conclusion

In this chapter, the failure behavior of cross-ply laminate cruciform specimens was investigated under the in-plane bi-axial tension – tension and tension – compression static loading condition. These tests provide a reliable data for composite structure designs. The results were generated under stress domain and fracture toughness domain. FEM analysis was used to find the non-dimensional geometric correction factors which are important to determine the stress intensity factor values. Then the strain distribution from DIC data is compared to the FEM model to verify the eligibility of the simulation. Crack paths and mode of fracture also discussed for each case of bi-axial stress states.

For 0° crack, the notch – sensitivity behavior can be observed in all tests at the load ratio from uniaxial 0:1 to bi-axial 1:1 under tension – tension and tension – compressive loading. In these tests, the material able to bear higher load bearing capability at higher stress ratio for the tension – tension loading. On the contrary, the specimens are failed at the lower axial stress for tension – compression loading when the transverse stress increased. This is an expected phenomenon, as in case of tensile transverse force produce crack closure effect and compressive transverse force creates crack opening behavior. Moreover, the material becomes notch – insensitive when the tensile transverse stress is much higher than axial tensile stress.

For 30° and 45° crack under tension – tension loading, mixed - mode behavior is observed with the appearance of in-plane shear stress. However, the mode I dominant is noticed in the fracture toughness surface with the calculation for kinked cracks. This finding is verified by investigation of the crack propagation patterns during the tests which are typical for mode I composite failure. This means the crack opening mode is the most important mode for the laminate with cracks under bi-axial loading conditions. Later the K_I/K_{IC} and K_{II}/K_{IIC} values are mapped into a suitable graph and compare to the results from Arcan test. The graph shows a similar trend between data from two in-plane test method results.

For 45° crack under tension – compression loading, the specimens have failed different ways depending on the stress ratio. At the uniaxial and 0.14:1 stress ratio, cracks propagate from crack tip then generate the mode I fracture. However, at higher compressive transverse stress, a compressive failure with a shear band is visible for the bi-axial tests. Therefore, numerous failure scenarios can occur together during the bi-axial tests which are different from uniaxial tests. These realistic behaviors are significant to the composite community to decrease the conservativeness in the design and reduce material usage.

References

- [1] J. S. Welsh and D. F. Adams, "An experimental investigation of the biaxial strength of IM6/3501-6 carbon/epoxy cross-ply laminates using cruciform specimens," *Composites Part A: Applied Science and Manufacturing*, vol. 33, pp. 829-839, 2002/06/01/ 2002.
- [2] A. Smits, D. Van Hemelrijck, T. P. Philippidis, and A. Cardon, "Design of a cruciform specimen for biaxial testing of fibre reinforced composite laminates," *Composites Science and Technology*, vol. 66, pp. 964-975, 2006/06/01/ 2006.
- [3] A. Rashedi, I. Sridhar, and K. J. Tseng, "Fracture characterization of glass fiber composite laminate under experimental biaxial loading," *Composite Structures*, vol. 138, pp. 17-29, 2016/03/15/ 2016.
- [4] T. L. Anderson, "Fracture mechanics : fundamentals and applications," 2005.
- [5] A. E. Scott, M. Mavrogordato, P. Wright, I. Sinclair, and S. M. Spearing, "In situ fibre fracture measurement in carbon–epoxy laminates using high resolution computed tomography," *Composites Science and Technology*, vol. 71, pp. 1471-1477, 2011/08/19/ 2011.
- [6] A. A. Arifin, W.-X. Wang, and T. Matsubara, "Experimental investigation on the compression and crush responses of cross-ply laminates with 0° plies of unidirectionally arrayed chopped strand," *Composites Part B: Engineering*, vol. 98, pp. 182-193, 2016/08/01/ 2016.

Chapter 7

Fracture of Adhesively Bonded Joints under Tension and Shear Loading

In this chapter, the effect of adherend contour on the strength of adhesively bonded joints under combinations of tension and shear loads using were investigated experimentally and numerically. The bi-axial tests were conducted for specimens with three adherend contour types included straight, rectangle shape, and triangle shape bond lines using a modified Arcan fixture with different loading angles. Besides, finite element models of all specimens were also developed to predict the strength of the joints. The experimental results show that the straight contour samples have the highest strength. However, numerical data gathered in this study suggest that the specimens with rectangle shape and triangle shape contours have the higher load-bearing capacity. This inconclusive debate leads to a study of the stress concentration and failure zones during the simulation process. The findings lend support to a good agreement between numerical prediction and the experiment results for the straight bond line specimens. Moreover, the failure behavior of the rectangle shape and triangle shape contour samples also captured a high level of stress concentration which induced the lower strength of these bonded joints.

7.1 Introduction

Complex wind turbine blade geometry is realized through adhesive bonding of composite shells. Further, shear webs are attached to the pressure and suction sides through adhesive bonding. These joints are usually working under a multi-axial condition which are combinations of tension/compression and shear stresses. In order to investigate the behavior of the bonded joints under bi-axial loading conditions, many attempts have been taken using Arcan fixture which can generate the bi-axial tension/compression and shear loads for both metallic and composite joints. The current research is to give a validation of using modified Arcan fixture to produce homogeneous stress state [1, 2] as well as covers the influences of edge effects, bond line thickness, surface treatment, joint configurations to the strength of the adhesively bonded joints [3-8]. However, there is insufficient research on the strength of adhesive assemblies with different adherend contours which are expected to increase the load-bearing capability of these joints. Therefore, the present study aims to address this shortfall.

In this study, the strength of adhesive bonding joints with different adhesive surface contours under bi-axial tension – shear loading condition were experimentally and numerically investigated. In the production of experimental samples, two quasi-isotropic GFRP composite adherends were used with 3M® DP460 adhesive to construct the adhesively bonded joints. Experiments were conducted using a modified Arcan fixture to create the bi-axial loading condition. After the experimental study, three-dimensional finite element models of adhesively bonded joints are developed using cohesive element layers to present the adherend and adhesive interface behavior. Then, the characterization of the joint strength was discussed based on the experimental and numerical results.

7.2 Experimental methods

7.2.1 Material and specimen

Adhesively bonded butt joints were prepared in the experimental tests. The test specimens were rectangular in geometry with 100 mm length, 30mm width,

and the 3mm thickness (two GFRP quasi-isotropic laminate adherends bonded with adhesive in the middle). The composite adherends were fabricated in the lay-up of $[0^\circ/+45^\circ/90^\circ/-45^\circ]_{3s}$ using the similar GFRP material and curing process as in Chapter 5. Apart from the straight two other interface contours triangular and square are used for the comparative study. The adherend contours were cut out using carbide Mill End on a CNC machining center. The gap of the specimen was filled by the 3MTM Scotch WeldTM DP460 epoxy adhesive. The properties of 3MTM DP460 are determined using ASTM D638 and shown in Table 7.1. Properties of unidirectional GFRP laminate are listed in Table 3.1.

Table 7.1 Material properties of the DP460 epoxy adhesive used in the study.

DP460		
Young modulus	E (MPa)	1907.5±76.7
Poisson ratio	ν	0.38
Ultimate tensile strength	σ_t (MPa)	42.3±1.37

In this study, mechanical properties of three types of samples which have different adhesive bonded contours were investigated experimentally and numerically. The joint geometries included straight, rectangle shape, and triangle shape contours named Type I, Type II and Type III specimens. The dimensions and geometrical parameters of the samples are shown in Figure 7.1. The edges of the contours were designed with 3mm radius of curvature to avoid the stress intensity effect. The Type II and Type III adherend dimensions are presented in Appendix B.

Figure 7.1 Geometric parameters of adhesively bonded joints; (a) straight contour (Type I), (b) rectangle shape contour (Type II), and (c) triangle shape contour (Type III).

Figure 7.2 Photographs of (a) adherend in the Acrylic mold with secure tape, (b) testing sample geometry.

Surface preparation is important to increase the adhesively bonded joint quality. Therefore, the adherend bonded surfaces were treated using the grade 60 sandpaper and then were cleaned with acetone before bonding. The surface roughness of composite adherend surface increase from R_a 1.32 μm after milling to R_a 4.04 μm after treatment. Also, the acrylic mold was used to control the thickness of adhesive layer with the dimension check using a caliper. The profile of the mold was created using a laser cutting machine. Composite adherends which were secured by tape were placed into the mold (see Figure 7.2a). The gap between two adherends was checked by a caliper to guarantee the 2 mm thickness. Later, the adhesives were separately applied using a 3M EPX Application gun with plungers. The adhesively bonded joints were then left at the room temperature of 25° for 48 hours to have the full curing strength. The final samples of three bonded adhesive profiles were shown in Figure 7.2b.

7.2.2 Experimental procedure

All experiments were conducted by using a modified Arcan fixture which was mounted on an INSTRON® UTM 5569 machine. The fixture was first placed into the right angle orientation that was set from 0° (pure tensile mode) to 90° (pure shear mode) at 15° interval. The fine adjustment was conducted to guarantee the proper clamped position of the sample. Before starting the test, two G clamps were used to secure two plates of Arcan jig to prevent any unattended loads to the specimens during experimental set-up process and then would be removed when the experiments started. Later, the bolts which locked the sample onto the Arcan fixture were tightened with 30 Nm torque by using TEKTON torque wrench. All experiments were recorded using Canon DSL camera. The experimental setup with the modified Arcan fixture was shown in Figure 7.3.

Figure 7.3 The modified Arcan setup on INSTRON® UTM 5569.

The Arcan experiments for adhesively bonded joints was conducted to determine the adhesive joint strength under tension and shear loads. Seven different angles, i.e. 0° , 15° , 30° , 45° , 60° , 75° and 90° were used to generate different bi-axial load ratios. For each relative angles, three tests were conducted to archive consistent results. The loading was applied under displacement control of 0.5 mm/min. The force-displacement curves were obtained for each combination of the adhesive joint type and testing angle.

7.2.3 Finite element model

In this section, three-dimensional FE models of Arcan fixture for the three different contours used in the experimental studies were described briefly. The basic geometry included the mesh, and the boundary condition is presented in Figure 7.4. Simplified geometry was used for the clamper zone in the Arcan fixture. Therefore, the fixture was modeled two neat plates and connected to the specimen model using the surface to surface tie constraint. Two composite adherends were discretized using 8-node quadrilateral continuum shell with reduced integration and hourglass control SC8R. 2mm width adhesive layer was modeled using 8-node linear brick with reduced integration and hourglass control

three-dimensional stress element C3D8R. Two adhesive layers with 0.01mm thickness were added at the two sides of the adhesive layer which are meshed in the three-dimensional 8-node cohesive element COH3D8. These cohesive elements were set to be deleted when the failure criteria was satisfied. Adhesive and cohesive layers were generated in the uniform fine mesh whereas distinct levels of mesh refinement were used for the adherend models. The element size in the adhesive zone is $0.125 \times 0.125 \times 0.3 \text{ mm}^3$. The boundary condition was applied at the positions which are similar to the positions of the center of located holes in the experiment setup. Also, a displacement of 1 mm was applied to a point with the same location on another plate of Arcan fixture. The step increment was set at 0.001 for all simulations to provide an accurate failure prediction. The force-displacement response of the adhesively bonded joints during each simulation is recorded to determine the computed critical loads.

The properties of the cohesive element used in the joint models were presented in Table 7.2. The penalty stiffness values for all modes are considered to be the same. These values were selected to satisfy the requirements that were high enough to avoid the interpenetration into the adherend surface as well as low enough to avoid artificial compliance from the model properties [9]. Also, maximum nominal stress (MAXS) and quadratic nominal stress (QUADS) criteria are used as the damage initiation criteria for the simulation of Type I specimens whereas only quadratic criterion is applied to the models of Type II and Type III. The normal-only nominal stress (mode I), and the first direction and second direction nominal stress (mode II) were determined by computing from the critical loads of the pure tension (0° test angle) and pure shear (90° test angle) Arcan tests using net-section area of the specimen. For damage evolution, the energy-based Benzeggagh – Kenane criterion was used [10]. The mode I and mode II fracture toughness were determined using DCB and ENF tests.

Figure 7.4 Finite element analyses models of adhesively bonded joints; (a) model with Arcan fixture, (b) mesh geometry of Type I specimen, (c) mesh geometry of Type II specimen, and (c) mesh geometry of Type III specimen.

Table 7.2 Interfacial properties of cohesive layer

σ_{Ic} (MPa)	$\tau_{IIc}=\tau_{IIIc}$ (MPa)	G_{Ic} (N/m)	$G_{IIc} = G_{IIIc}$ (N/m)	$E/E_{nn}=G_I/G_{nn}$ $=G_2/E_n$ (Pa)
23.2	18.8	210	900	10e14

7.3 Result and discussion

7.3.1 Force -displacement curve and crack pattern

Figure 7.6 show, respectively, the stress-displacement curves for Type I, Type II, and Type III specimens of Arcan tests. For the sample Type I, there are two typical behavior for the specimens under tension or shear dominant loading. From 0° to 45° , the load increase linearly with displacement then experience a sudden drop. From 60° to 90° , the response showed the shear effect where load was observed gradually decreasing after reaching its peak. The different response patterns were related to the splitting behavior of the adhesive bond line from the adherends. The load dropped catastrophically when the adhesive peeled out of the bonded surface quickly (see Figure 7.5a) whereas the load reduced gently when the adhesive was subjected plastic deformation before failure (see Figure 7.5b). The peak load in each curve were used as critical loads to assess the strength of the adhesively bonded joint.

Figure 7.5 Crack formation and propagation in Type I specimen for (a) 0° and (b) 90° loading angles.

Figure 7.6 Force – displacement curve for (a) Type I specimen, (b) Type II specimen, and (c) Type III specimen.

Figure 7.7 Crack formation and propagation in Type II specimen for (a) 0° and (b) 90° loading angles.

More complex patterns were observed in the force-displacement curves for Type II and Type III specimens (see Figure 7.6b and 7.6c). However, the difference between specimens under tension dominant or shear dominant part could be comprehended. For the Type II specimens, a combination of tensile and shear stresses appeared in the adhesive zone even under pure tensile loading conditions (see Figure 7.7). Moreover, Figure 7.7b shows that the horizontal adhesive bond line at the center of the specimen was subjected to the compressive force while the vertical bond line was subjected to the shear force during the test. For the Type III specimens, similar behavior to Type I failure can be seen in Figure 7.8. For loading angles from 0° to 30° , the adhesive peels off suddenly from the stress concentration points with sudden drop in load. Besides, the load decreased gradually after an undulation for the loading angle from 45° to 90° . The reason was that each part of the bond line was broken separately during the test as seen in Figure 7.8b.

Figure 7.8 Crack formation and propagation in Type III specimen for (a) 0° and (b) 90° loading angles.

From the failure behavior of all specimen types, it is indicated that the failure occurred at the interface between the adherend and adhesive which is considered as the weakest zone in the adhesively bonded joint. The interface properties are different from adherend and adhesive. This suggests a method to define the interface as a cohesive layer with proper properties in the numerical study for the bonded joints. This layer has a small finite thickness as the interface layer is exceedingly thin in the bonded zone.

7.3.2 Strength of adhesively bonded joint

The critical loads of three specimen types for the different loading angles with their relative standard deviation are introduced in Figure 7.9. The graph indicates that the joint strengths of Type I are higher than Type I and Type II for all loading angles. Besides, the strength of Type II and Type III were comparable at 0° and

15° loading angles. For higher angles, i.e., 30° to 90°, the Type II samples had higher load-bearing capacity than the Type III samples. The standard deviation values of the strength of Type III specimens are higher than other test results.

Figure 7.9 Strength of the adhesively bonded joints for the loading angles from 0° to 90°.

The critical tensile and shear loads were presented in Figure 7.8, for various loading angles. As can be seen from the graph, the critical tension loads were higher than the critical shear load. The Type I specimens had the highest critical values of both tension and shear loads. The Type III specimens showed the weakest lowest load bearing response may be due to severe stress singularity from the corners. The critical shear loads were consistent for three specimen types whereas the critical tensile loads of Type II and Type III tests were lower than those for Type I specimens. Quadratic relationship can be reserved for the strength of Type I joints. For the Type II and Type III, a linear relationship is highlighted. The lower strength values of Type II and Type III specimens are unpredicted as the bonded surface area in these types is larger than the Type I

specimens. Therefore, it is needed an in-depth FEM analysis to explain this behavior. The numerical results will be presented next.

Figure 7.10 Critical shear load vs critical tension load for three types of specimens.

7.3.3 Finite element analysis result

The numerical results for critical loads from FEM analysis for three testing specimen types with the corresponding experimental measurements are shown in Figure 7.9. These values were recorded from the peak value of the reaction forces at the boundary condition points. From the simulation analysis, the peak value occurred when the elements started to be deleted from the models when the failure criteria were satisfied. The graph shows a gradual decrease of the critical loads when the loading angles changed from 0° to 90° for all types of specimens.

Figure 7.11 The predicted strength of three types of specimens using finite element models with their relative experimental results.

For the Type I sample, the numerical results are over predicted for the pure tension case in both simulation using MAXS and QUADS criteria and show good agreement for the pure shear case. A closer examination of the data indicates that the models with QUADS criteria induced a better presentation of the experimental data for Type I specimens. This led to the using of QUADS criterion for the simulation of Type II and Type III samples. Apart from that, the data appears to suggest that strength of Type II and Type III specimens were overpredicted in most cases particularly for the Type III specimens.

Figure 7.12 The stress concentration zones of (a) Type I specimen, (b) Type II specimen, and (c) Type III specimen for 0° loading angle and (d) Type I specimen, (e) Type II specimen, and (f) Type III specimen for 90° loading angle.

Figure 7.12 show the stress concentration zones using maximum principal stresses in the adhesive layer of three types of specimens at 0° and 90° loading angles. It appears that the stress concentration values in the Type III specimens were higher than the Type I and Type II specimens. This explains the lowest strength of Type III specimens compared to other type specimens. Moreover, the maximum stresses in the Type III specimens are higher than the ultimate strength of the adhesive materials, i.e. 42.3 MPa. Therefore, the nonlinear behavior that occurred in the adhesive layer overpredicts simulation results of Type III specimens as the models use linear elastic properties. For the Type II specimens, the stress concentration values are comparable to the Type I specimen. However, the stress values at curves of the adhesive layer of the Type II specimens are

higher than these values for straight specimens. Therefore, strength values of Type II specimens were lower than Type I specimens for the 0° loading angle case. Moreover, the low concentration values of maximum principal stresses could be observed in the Type II specimen along the bond line for the 90° loading angle case. As a result, the predicted critical loads for 90° from the simulation was matched well to the experimental result. The similar trend could be seen for the other loading angles.

In summary, the overpredicted values of adhesively bonded joints of Type II and Type III specimens were caused by the stress concentration zones in the adhesive layer which induced the nonlinear behavior in the bond line zones. This suggests the requirement of models which included the nonlinear behavior of the adhesive layer. Besides, the current models can predict well the strength for the traditional butt joints. Therefore, the development of failure zones in the interface between the adherend and adhesive layer were investigated from the simulation results.

Figure 7.13 Deleted element zones in the cohesive element layers of (a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60°, (f) 75°, and (g) 90° loading angles.

Figure 7.13 shows the first failed element of interface cohesive zones with the propagation direction of the cohesive layer of the Type I specimens for the loading angle from 0° to 90°. It is clear that the damaged zones appeared from middle or side of the cohesive layer. For 0° loading angle, the damaged elements appeared from the middle and then propagated to the two sides (see Figure 7.14a). For the loading angles from 15° to 60°, cohesive elements were deleted from the side and then propagate to the centre of the cohesive layer. In addition, damaged elements at the centre were also observed in the 60° loading angle. Finally, the

elements disappeared from the centre of the interface cohesive zone the 75° and 90° loading angles. High damage zones were also seen at the side of the cohesive layer. Therefore, the elements failed at the central and edge simultaneously in these cases. Consequently, the failure patterns for the loading angles from 60° to 90° are similar to Figure 7.6.

7.3 Conclusion

In this study, the influence of the contours of adhesively bonded surfaces to the strength of adhesively bonded joints under bi-axial tension – shear loads was experimentally and numerically investigated. Three different types of specimens with the straight, rectangle shape and triangle shape contours were used in the experiment using a modified Arcan fixture. Using the experimentally measured load displacement results, three-dimensional finite element models were developed to predict the strength of the adhesively bonded joints as well as inspect the stress distribution in the adhesive layers. These models used two cohesive element layers to present the interface layers between adhesive bond line and adherends. The results obtained show that the straight contour specimens give the highest strength for all combination of tension and shear loads. This is unexpected as the rectangle shape and triangle shape contour specimens have a longer bond line which may provide a higher strength. But, there are regions of stress concentrations or singularities, which reduce their load-bearing capability.

The numerical results suggest different trends as the straight contour specimens have the weakest strength among three types of specimens. Considering the influence of stress concentration, the stress distributions in the adhesive layers of rectangle and triangle shape contour specimens express a high level of stress concentration which induces nonlinear behavior of the polymer adhesive. This results in a need for a nonlinear model which can simulate the performance of adhesive layer after the yield point. However, the current models can predict the strength of straight contour specimens in good agreement with the experimental measurements. Moreover, these models also capture the damaged zones inside the interface layer of the adhesively bonded joints, adequately.

References

- [1] J. Y. Cognard, R. Créac'hcadec, L. Sohier, and P. Davies, "Analysis of the nonlinear behavior of adhesives in bonded assemblies—Comparison of TAST and Arcan tests," *International Journal of Adhesion and Adhesives*, vol. 28, pp. 393-404, 2008/12/01/ 2008.
- [2] J. Y. Cognard, P. Davies, B. Gineste, and L. Sohier, "Development of an improved adhesive test method for composite assembly design," *Composites Science and Technology*, vol. 65, pp. 359-368, 2005/03/01/ 2005.
- [3] J. Y. Cognard, "Numerical analysis of edge effects in adhesively-bonded assemblies application to the determination of the adhesive behaviour," *Computers & Structures*, vol. 86, pp. 1704-1717, 2008/09/01/ 2008.
- [4] J. Y. Cognard, L. Sohier, and P. Davies, "A modified Arcan test to analyze the behavior of composites and their assemblies under out-of-plane loadings," *Composites Part A: Applied Science and Manufacturing*, vol. 42, pp. 111-121, 2011/01/01/ 2011.
- [5] P. Davies, L. Sohier, J. Y. Cognard, A. Bourmaud, D. Choqueuse, E. Rinnert, *et al.*, "Influence of adhesive bond line thickness on joint strength," *International Journal of Adhesion and Adhesives*, vol. 29, pp. 724-736, 2009/10/01/ 2009.
- [6] G. Bresson, J. Jumel, M. E. R. Shanahan, and P. Serin, "Strength of adhesively bonded joints under mixed axial and shear loading," *International Journal of Adhesion and Adhesives*, vol. 35, pp. 27-35, 2012/06/01/ 2012.
- [7] D. Thevenet, R. Créac'hcadec, L. Sohier, and J. Y. Cognard, "Experimental analysis of the behavior of adhesively bonded joints under tensile/compression–shear cyclic loadings," *International Journal of Adhesion and Adhesives*, vol. 44, pp. 15-25, 2013/07/01/ 2013.

- [8] J. Y. Cognard, H. Devaux, and L. Sohier, "Numerical analysis and optimisation of cylindrical adhesive joints under tensile loads," *International Journal of Adhesion and Adhesives*, vol. 30, pp. 706-719, 2010/12/01/ 2010.
- [9] M. Moslemi and M. Khoshnavan, "Cohesive zone parameters selection for mode-I prediction of interfacial delamination," *Strojniški vestnik- Journal of Mechanical Engineering*, vol. 61, pp. 507-516, 2015.
- [10] M. Benzeggagh and M. Kenane, "Measurement of mixed-mode delamination fracture toughness of unidirectional glass/epoxy composites with mixed-mode bending apparatus," *Composites science and technology*, vol. 56, pp. 439-449, 1996.

Chapter 8

Conclusions and Recommendations

This research focuses on investigating failure behavior of composite laminates and adhesively bonded joints under bi-axial loading conditions to contribute to a better understanding of the characterization of composite materials and adhesively bonded joints under multi-axial stress states. The objectives of this work were first to design and fabricate the proper fixtures for bi-axial tests. Secondly, the failure initiation and propagation of cross-ply laminates under tension – tension and tension – compression bi-axial condition were investigated. Additionally, the strength of adhesively bonded joints under a combination of tension and shear loads were examined experimentally and numerically. This chapter includes together the main conclusions, and then recommendations for further research.

8.1 Conclusions

8.1.1 Development of a novel bi-axial fixture

A new bi-axial fixture was developed to overcome the intrinsic limitations of the current two actuator fixture with 10 kN transverse load. This jig can be adapted to any conventional universal testing machine using the cruciform specimens with the ability to generate different in-plane displacement ratios in the two distinct perpendicular directions which subject the tension – tension, tension – compression, and compression - compression loading conditions to the test samples. As a result, this device is cost-effective alternative for bi-directional material characterization tests which can be useful for validating of theoretical failure models. Validation experiments were also conducted to verify the actual bi-axial ratio using the designed fixture. The results indicate that the kinematic of this mechanism able to induce different perpendicular movements at specific load or displacement ratios. Though there has been a reduction of transverse displacement under loaded conditions, this fixture show potential to conduct the in-plane bi-axial tests for composite laminates.

8.1.2 Fracture of composite laminate under tension and shear loads

The unidirectional and cross-ply GFRP laminates with cracks were examined using a modified Arcan fixture. Mixed-mode behavior under tension – shear bi-axial loading conditions were investigated with different crack patterns and failure modes. Moreover, failure envelopes of these materials were provided in both stress and fracture toughness spaces. The following conclusions can be drawn:

- Different crack propagation patterns were observed during the bi-axial test based on the test laminate lay-up sequence. The cross-ply specimens under pure tensile stress failed from the crack tips in a sudden catastrophic manner while the fracture of these specimens occurred gradually in the direction which was perpendicular to the crack orientation under pure shear stress. For the mixed-

mode conditions, the crack propagation should follow the pattern suggested by the dominant stress.

- The unidirectional specimens failed in the direction which parallels to the fiber direction in all test cases. Matrix cracking was considered as the main failure mode of crack growth for the unidirectional laminates.

- For the cross-ply specimens, two failure modes were determined which were defined as mode I dominant and mode II dominant modes. Many laminate damage mechanisms were observed included fiber full-out, fiber bridging, matrix crack, 90° ply-split, and fiber bending. The mode I dominant fracture happened for the loading angles from 0° to 45°, and the specimens broke under mode II dominant way for the loading angles from 60° to 90°.

- Fracture toughness of GFRP composite materials depend on the lay-up sequence. With the same number of plies, the cross-ply [0/90]_s laminates had greater fracture toughness than the UD [0]_s laminates. The average fracture toughness of GFRP were calculated as $K_{IC} = 32.1 \text{ MPa.m}^{1/2}$ and $K_{IIC} = 8.84 \text{ MPa.m}^{1/2}$ for cross-ply laminates and $K_{IC} = 14.76 \text{ MPa.m}^{1/2}$ and $K_{IIC} = 2.12 \text{ MPa.m}^{1/2}$ for UD [90]_n laminates. The opening mode fracture toughness was much higher than the shearing mode result. The increase of specimen thickness induced the mode I fracture toughness values.

- The failure envelope in the fracture toughness space shows three regions including mode I dominant, mode II dominant, and mixed-mode dominant. The mode I fracture pattern were likely to occur more frequently than the mode II fracture pattern.

8.1.3 Fracture capacity of composite laminates under bi-axial loads

In this study, the cruciform specimens with pre-crack were used to investigate the fracture behavior of cross-ply composite laminates under bi-axial tension – tension and tension – compression loading condition. The stress intensity factor values were calculated and presented in the fracture toughness space. It was found that:

– For 0° crack, the specimens were failed in notch – sensitive manner which can be observed in all tests at the load ratio from uniaxial 0:1 to bi-axial 1:1 under tension – tension and tension – compressive loading. Moreover, the material becomes notch – insensitive when the transverse tensile stress is much higher than the axial tensile stress. In the tension – tension tests, the closure crack effect of transverse tensile force induces higher load-bearing capacity in the axial direction of the specimens, i.e., around 20% from 1:0 (uniaxial) to 1:1 load ratio. In contrast, the crack opening effect of transverse compressive force makes the critical axial stress to decrease around 7% from 1:0 to 1:0.8 for the tension – compression tests. It appears that the fracture toughness for pure mode I is $32 \text{ MPa} \cdot \sqrt{\text{m}}$ under tension – tension test ($[0/90]_s$ laminates) and is $26 \text{ MPa} \cdot \sqrt{\text{m}}$ under tension – compression test ($[0/90]_{2s}$ laminates) which are comparable to the fracture toughness from the Arcan tests.

– For 30° and 45° crack under tension – tension loading and tension – compression loading for 0:1 and 0.14:1 load ratio, mixed - mode behavior occur with the appearance of in-plane shear stress. Nevertheless, the mode I dominant fracture was noticed for both 30° and 45° test. The crack propagation path and crack pattern investigation also confirm the mode I composite failure. This means the crack opening mode is the most important mode for the laminate with cracks under these bi-axial loading conditions. Later the K_I/K_{IC} and K_{II}/K_{IIC} values are mapped into a suitable graph and compare to the results from the Arcan test. The results show an agreement between data from two in-plane test method results. Besides, the shear failure under compressive load was observed for 0.48:1 and 0.65:1 load ratios.

8.1.4 Fracture of adhesively bonded joints under tension and shear loads

The strength of adhesively bonded joints with three different types of specimens with the straight, rectangle shape, and triangle shape contours under bi-axial tension – shear loads were experimentally and numerically investigated using a modified Arcan fixture. Moreover, three-dimensional finite element

models using cohesive elements were developed to predict the strength of the adhesively bonded joints as well as inspect the stress distribution in the adhesive layers. The results predict that the traditional butt joints have the highest strength for all combination of tension and shear loads. Therefore, the influence of the stress concentration was considered in the finite element analysis. The stress distributions in the adhesive layers of rectangle and triangle shape contour specimens showed a high level of stress concentration which induced the nonlinear behavior of adhesive materials. The finite element model using fracture mechanics approach i.e. stress singularity based calculations should be implemented for further study

8.2 Recommendation

8.2.1 Bi-axial tests of composite materials under static and fatigue loading conditions

In this study, bi-axial tests have been used to determine the failure envelopes of composite material in both stress and fracture toughness space for tension – shear, tension – tension, tension – compression static bi-axial loading conditions. However, the experimental data is required for compression – shear, and compression – compression loading to fulfill all quadrant of failure envelope. Although the bi-axial fixture was developed to produce the bi-axial loading for all quadrants, a proper anti-buckling plate is needed to prevent the buckling effect of thin composite cruciform specimens under compressive loads. Besides, the behavior of composite materials under bi-axial fatigue loading conditions are important to predict the service life of composite structures. The current fixture requires a minor modification to investigate the failure behavior of GFRP laminates under complex bi-axial cyclic loads. Then, fatigue failure envelopes can be generated to define the fatigue failure in a bi-axial stress space by using the fixture in bi-axial fatigue tests. Moreover, the effect of stress intensity factor on failure behavior of composite specimens with a pre-crack under dynamic

loadings is also important. The fatigue data shall further improve the life prediction of composite structures reliably.

8.2.2 Numerical model of composite laminates under bi-axial loading condition

In this study, GFRP cross-ply laminates were modeled in two dimensional as equivalent orthotropic materials by using effective elastic parameters in the finite element study for the in-plane bi-axial tests to determine the geometrical factors which were used to calculate the stress intensity factor values. Also, to investigate the effect of the crack on laminates, XFEM shows potential to provide the detail of stress singularity distribution near the crack tip. Then, failure criteria are integrated during analyzing the process to present the failure mechanisms of the fiber, matrix, and interface layer of composite laminates.

8.2.3 Bi-axial testing of the adhesively bonded joint using thick specimens or tubular specimen

The rectangle composite adhesively bonded joint with the thickness of 3mm was used in the current study. However, the actual bonded joint sizes in the composite structure such as wind turbine generator blades or aircraft wing are much larger. This motivates the need for conducting bi-axial tests for thick adhesively bonded joints with a modified clamp setup for the Arcan fixture. Besides, the tubular specimens with butt joints in the middle area can also be investigated. A tubular specimen under tension/compression – torsion loads, have the bi-axial tensile – shear stress in the joint area.

APPENDIX

Figure A.1 Bi-axial fixture dimensions (all dimensions in mm).

Figure B.2 Adherend dimensions of (a) Type II and (b) Type III specimens (all dimensions in mm).