EXPERIMENTAL STUDY AND NUMERICAL MODELLING OF WOVEN FABRIC KENAF FIBER COMPOSITES HYBRID ADHESIVELY BONDED-BOLTED JOINTS

LEE SIM YEE

A thesis submitted in fulfilment of the requirement for the award of the Doctor of Philosophy

Faculty of Civil and Environmental Engineering
Universiti Tun Hussein Onn Malaysia

MAY 2018
For my beloved mother and father
ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor Assoc. Prof. Dr. Hilton @ Mohd Hilton Bin Ahmad for the continuous support throughout my Ph.D. study. His guidance, motivation, patience, and immense knowledge have helped me in completing this thesis successfully. I would like to extend my gratitude to my co-supervisors, Dr. Zainorizuan Bin Mohd Jaini and Dr. Haris Ahmad Bin Israr Ahmad for their continual professional advices and invaluable supports.

Nevertheless, I would like to thank all the technicians in Textile Laboratory, Faculty of Mechanical and Manufacturing Engineering and Structural Laboratory, Faculty of Civil and Environmental Engineering in Universiti Tun Hussein Onn Malaysia for the guidance provided in utilizing the laboratory equipments. I would also like to acknowledge Ministry of Higher Education, Malaysia for the financial support provided for this research through MyBrain15 (MyPhD) and Research Acculturation Grant Scheme (RAGS) Vot R034. Last but not least, I am forever grateful to my family and friends whom had supported me directly or indirectly throughout this journey.
ABSTRACT

Couple with natural fiber composite parts, hybrid joints provide better joint strength than using separate joints. There are limited studies on structures response and strength prediction work on hybrid joints that limits its applicability. The aim of present study is to conduct experimental datasets on woven fabric kenaf fiber reinforced polymer (KFRP) and carbon fiber reinforced polymer (CFRP) composite hybrid joints under quasi-static testing and to carry out the strength prediction works subsequently by implementing physically-based traction-separation constitutive law. Testing series investigated includes variation of joint types, normalized $W/d = 2$ to $5$, reinforcing fiber composites, lay-up types, plate thickness and bolt loads. Experimental observations and bearing stress at failures were conducted, the datasets were then used as validation works in FEA modelling. All KFRP hybrid joint series demonstrated net-tension failure mode associated to stress concentration at the vicinity of notch tip. Initially, strength prediction works were attempted by implementing various numerical approaches and fully XFEM techniques was adopted to all series as it provides promising results with better physically representation and less computational time. Good agreements between experimental datasets and predicted bearing stress at failure were found in KFRP hybrid joints with average discrepancy of less than 23%. It was found that combinations of thicker and cross-ply lay-up gives the best prediction of less than 2% (where experimental datasets and FEA output were given as 201 N/mm$^2$ and 198 N/mm$^2$ respectively) due to better repetitive lay-up with implementation of smeared-out properties. Less significant effects from bolt loads and reinforcing fibers were found for both joint types. It can be concluded that fully XFEM technique able to provide as a unified prediction tools in hybrid joints of most composite materials with reasonable agreements.
Gabungan komposit gentian semula jadi dengan sambungan hibrid memberikan kekuatan yang lebih baik daripada menggunakan sambungan secara berasingan. Kajian respon struktur dan kerja ramalan kekuatan sedia ada untuk sambungan jenis ini adalah terhad yang membataskan kebolehgunaannya. Objektif kajian projek ini adalah untuk mendapatkan set data eksperimen sambungan hibrid komposit fabrik tenunan gentian kenaf bertetulang polimer (KFRP) dan gentian karbon bertetulang polimer (CFRP) di bawah ujian tegangan kuasi-statik dan kerja ramalan kekuatan dilaksanakan dengan menggunakan model bahan berasaskan fizikal iaitu hubungan daya tarikan -pemisahan. Siri uji terlibat termasuk jenis sambungan, siri nisbah W/d =2 hingga 5, jenis komposit gentian, jenis urutan lapisan, ketebalan plat dan bebanan bolt. Pemerhatian daripada eksperimen dan kekuatan galas telah ditentukan, data tersebut kemudiannya dibandingkan dengan output FEA. Semua sambungan hibrid KFRP menunjukkan mod kegagalan net-tension berkait rapat dengan tumpuan tegasan di sekitar tip bukaan. Percubaan awal dalam kerja ramalan dijalankan dengan pelbagai teknik berbeza dan teknik XFEM penuh diterimapaka kerana keputusan yang lebih memuaskan disamping cenderung secara fizikal dan mengoptimumkan masa pengiraan. Perbandingan kekuatan galas sambungan hybrid KFRP di antara set data eksperimen dan kerja ramalan didapti baik dengan menunjukkan purata percanggahan kurang daripada 23%. Gabungan plat yang lebih tebal dan cross-ply menunjukkan kerja ramalan yang lebih baik iaitu kurang daripada 2% (di mana data eksperimen dan output FEA adalah 201 N/mm² dan 198 N/mm²) disebabkan ulangan lapisan yang ketara disebabkan pelaksanaan smeared out. Perbezaan yang kurang ketara didapti daripada kesan bebanan bolt dan jenis gentian komposit pada kedua-dua jenis gabungan. Secara rumusan, teknik XFEM penuh dapat dijadikan sebagai alat ramalan untuk sambungan hibrid dalam kebanyakan bahan komposit dengan menunjukkan perbandingan yang baik.
CONTENTS

TITLE i
DECLARATION ii
DEDICATION iii
ACKNOWLEDGEMENTS iv
ABSTRACT v
ABSTRAK vi

CONTENTS vii
LIST OF TABLES xiv
LIST OF FIGURES xvii
LIST OF SYMBOLS AND ABBREVIATIONS xxiv
LIST OF APPENDICES xxvii

CHAPTER 1 INTRODUCTION 1
1.1 Background 1
1.2 Problem statements 4
1.3 Project objectives 5
1.4 Scope of study 6
1.5 Significant of study 7
1.6 Organization structure of thesis 7

CHAPTER 2 LITERATURE REVIEW 9
2.1 Introduction 9
2.2 Classification of natural fibers in composite productions 9
  2.2.1 Physical and mechanical properties of natural fibers 10
  2.2.2 Features and anatomy of kenaf plant 11
  2.2.3 Comparisons with commercially synthetic

2.3 Woven fabric composites
   2.3.1 Types of woven fabrics 16
   2.3.2 Lay-up types 19

2.4 Experimental study on joining techniques of composite plates
   2.4.1 Plates with an open hole 20
   2.4.2 Bolted joints 23
   2.4.3 Adhesively-bonded joints 27
   2.4.4 Hybrid adhesively bonded-bolted joints 30
   2.4.5 Summary of previous research in various joining techniques 32

2.5 Stress analysis associated with stress concentrations 37
   2.5.1 Stress analysis in open hole 37
   2.5.2 Stress analysis in bolted joints 40
   2.5.3 Stress analysis in bonded joints 44
   2.5.4 Stress analysis in hybrid joints 45

2.6 Strength prediction works 47
   2.6.1 Strength prediction of hybrid joint by using analytical approach 47
   2.6.2 Fracture mechanics 49
   2.6.3 2-D progressive damage modelling 52
   2.6.4 3-D progressive damage modelling 53
   2.6.5 Virtual crack closure techniques (VCCT) 55
   2.6.6 Cohesive zone model (CZM) 57
   2.6.7 Extended finite element method (XFEM) 59
   2.6.8 Summary of numerical approaches available on various joining techniques 63

2.7 Summary 64

CHAPTER 3 RESEARCH METHODOLOGY 66

3.1 Introduction 66
3.2 Composite materials preparations 69
   3.2.1 Woven fabric kenaf fiber weaving process 69
   3.2.2 Twill weave carbon fiber 71
CHAPTER 4 EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1 Introduction

4.2 KFRP/CFRP independent elastic and material properties

4.2.1 In-plane elastic properties and unnotched strength determination

4.2.2 Shear modulus measurements

4.2.3 Composite laminate compliance calibration and fracture energy determination

4.3 Experimental results and observations on KFRP bonded SLJs

4.3.1 Load-displacement profiles
5.3.2.1 Extended finite element method (XFEM) 142
5.3.2.2 Virtual crack closure technique (VCCT) 144
5.3.2.3 Cohesive zone model (CZM) 146
5.3.2.4 Comparison of strength prediction works by using different modelling approaches 148

5.4 Superposition method in hybrid SLJs 149
5.4.1 Overview of XFEM modelling framework on bolted SLJ from Romanye’s work (2016) 150
5.4.2 Strength prediction results by using superposition method 152

5.5 Summary 156

CHAPTER 6 STRENGTH PREDICTIONS ON DOUBLE-LAP KFRP HYBRID JOINTS BY USING DIFFERENT FEA TECHNIQUES 157
6.1 Introduction 157
6.2 Pre-processing stage 159
6.2.1 Modelling idealizations 159
6.2.2 Element discretization 161
6.2.3 Generation of materials and geometry properties 162
6.2.4 Loading and boundary conditions 163
6.2.5 Implementation of bolt loads 165
6.3 Modelling techniques and methods 167
6.3.1 Fully extended finite element method (fully XFEM) 168
6.3.2 Combination of XFEM and virtual crack closure technique (XFEM-VCCT) 169
6.3.3 Combination of XFEM and cohesive zone model (XFEM CZM) 170
6.4 Strength prediction in various techniques 171
6.4.1 Structure response and strength prediction from fully XFEM technique
6.4.2 Structure response and strength prediction from XFEM-VCCT technique
6.4.3 Structure response and strength prediction from XFEM-CZM technique
6.4.4 Overview of strength prediction in various techniques

6.5 Summary

CHAPTER 7 STRENGTH PREDICTIONS OF KFRP AND CFRP HYBRID JOINTS BY USING XFEM FRAMEWORK 181
7.1 Introduction 181
7.2 XFEM modelling techniques and approaches 184
7.3 Stress distribution study in woven fabric hybrid joints 188
7.3.1 Stress distribution study with different hybrid joint types 188
7.3.1.1 Peel and shear stress within adhesive layers 188
7.3.1.2 Stress distributions within composite coupons 191
7.3.2 Secondary bending effects in hybrid joints 194
7.4 Sensitivity study of FEA modelling 196
7.5 Strength prediction of woven fabric hybrid DLJs 198
7.6 Strength prediction of woven fabric hybrid SLJs 204
7.6.1 Load-displacement characteristics 204
7.6.2 Strength prediction of woven fabric KFRP and CFRP hybrid SLJs 207
7.7 Overview of strength prediction works on hybrid joints by using fully XFEM technique 211
7.8 Summary 212

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS 213
8.1 Conclusions 213
8.2 Recommendations for future works 215
REFERENCES 216
APPENDICES 228
APPENDIX A 228
APPENDIX B 230
APPENDIX C 233
APPENDIX D 235
APPENDIX E 237
APPENDIX F 245
LIST OF PUBLICATIONS 246
VITA 248
### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Physical and mechanical properties of natural fibers (Sanjay et al., 2015, Tong et al., 2017)</td>
<td>11</td>
</tr>
<tr>
<td>2.2</td>
<td>Typical tensile mechanical properties of carbon fiber, glass fiber and kenaf fiber (Prasad and Ramachandran, 2017)</td>
<td>13</td>
</tr>
<tr>
<td>2.3</td>
<td>Tensile properties on GFRP and various natural fiber composite</td>
<td>14</td>
</tr>
<tr>
<td>2.4</td>
<td>Parameter understudied on bolted joints by previous researchers</td>
<td>33</td>
</tr>
<tr>
<td>2.5</td>
<td>Parameter understudied on bonded joints by previous researchers</td>
<td>34</td>
</tr>
<tr>
<td>2.6</td>
<td>Parameter understudied on hybrid joints by previous researchers</td>
<td>35</td>
</tr>
<tr>
<td>2.7</td>
<td>Finding summary on bolted joints reported by previous researchers</td>
<td>36</td>
</tr>
<tr>
<td>2.8</td>
<td>Finding summary on bonded joints reported by previous researchers</td>
<td>36</td>
</tr>
<tr>
<td>2.9</td>
<td>Finding summary on hybrid joints reported by previous researchers</td>
<td>37</td>
</tr>
<tr>
<td>2.10</td>
<td>Hashin’s (1980) failure criterion with associated failure mode</td>
<td>54</td>
</tr>
<tr>
<td>2.11</td>
<td>Numerical approaches on various joining techniques reported by previous researchers</td>
<td>63</td>
</tr>
<tr>
<td>3.1</td>
<td>Physical properties of kenaf yarn and plain weave woven kenaf fiber</td>
<td>70</td>
</tr>
<tr>
<td>3.2</td>
<td>Laminate lay-up, thickness and designation code</td>
<td>82</td>
</tr>
<tr>
<td>3.3</td>
<td>Range of test parameters investigated for unnotched coupons</td>
<td>84</td>
</tr>
<tr>
<td>3.4</td>
<td>Range of test parameters investigated for SEN coupons</td>
<td>84</td>
</tr>
<tr>
<td>3.5</td>
<td>Geometry dimensions of the composite plates</td>
<td>85</td>
</tr>
<tr>
<td>3.6</td>
<td>Range of test parameters investigated for hybrid SLJ and DLJ tests</td>
<td>86</td>
</tr>
<tr>
<td>3.7</td>
<td>Range of tests carried out on every laminate lay-up series for hybrid joints</td>
<td>86</td>
</tr>
</tbody>
</table>
4.1 Independent properties for unnotched KFRP coupons
4.2 Independently determined elastic properties for CFRP lay-ups
4.3 Shear modulus for KFRP
4.4 Shear modulus for CFRP
4.5 KFRP SEN fracture energy measurements
4.6 CFRP SEN fracture energy measurements
4.7 Maximum load at failure at different variables of bonded SLJs
4.8 Maximum bearing stress with different KFRP lay-up orientation
4.9 Comparison of coupon thickness on bearing stress at failure
4.10 Comparison of lay-up type on bearing stress at failure
4.11 Comparison of bolt load on bearing stress at failure
4.12 Maximum bearing stress with different CFRP lay-up orientation
4.13 Comparison of coupon thickness on bearing stress at failure
4.14 Comparison of lay-up type on bearing stress at failure
4.15 Comparison of bolt load on bearing stress at failure
5.1 The in-plane elastic material properties of KFRP composite plate
5.2 Nominal stress and fracture energy for adhesive layer (Sugiman & Ahmad, 2017)
5.3 Damage initiation criterion of CZM (Sugiman & Ahmad, 2017)
5.4 Comparison of strength prediction results from different techniques
5.5 Range of test parameters studied
5.6 Material properties implemented in physically-based constitutive model (Romanye, 2016)
5.7 Comparison of experimental and simulation work in KFRP SLJ
6.1 Elastic properties for KFRP composite coupon
6.2 Unnotched strength and fracture energy for KFRP and CFRP coupons
6.3 Nominal stress and fracture energy for adhesive layer
6.4 Comparison of experimental work and modelling predictions by using various modelling models
7.1 Elastic properties for KFRP composite coupon
7.2 Elastic properties for CFRP composite coupon
7.3 Unnotched strength and fracture energy for KFRP and CFRP coupons
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.4</td>
<td>Nominal stress and fracture energy for adhesive layer</td>
<td>186</td>
</tr>
<tr>
<td>7.5</td>
<td>Comparison of experimental and simulation work in KFRP hybrid DLJs</td>
<td>200</td>
</tr>
<tr>
<td>7.6</td>
<td>Comparison of experimental and simulation work in CFRP hybrid DLJs</td>
<td>201</td>
</tr>
<tr>
<td>7.7</td>
<td>Comparison of experimental and simulation work in KFRP hybrid SLJs</td>
<td>207</td>
</tr>
<tr>
<td>7.8</td>
<td>Comparison of experimental and simulation work in CFRP hybrid SLJ</td>
<td>208</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Kenaf crops planted in Asia (after Akil et al., 2011)</td>
<td>12</td>
</tr>
<tr>
<td>2.2</td>
<td>Kenaf processing for fiber production (a) retting process, (b) kenaf stem with fiber, (c) kenaf fiber (Kumar &amp; Sekaran, 2014)</td>
<td>13</td>
</tr>
<tr>
<td>2.3</td>
<td>Fibers twisted as yarn to weave as fabric type</td>
<td>15</td>
</tr>
<tr>
<td>2.4</td>
<td>Basic arrangement of fiber in composite lamina</td>
<td>16</td>
</tr>
<tr>
<td>2.5</td>
<td>2-D plain weave woven fabric reinforcement with woven fabric density</td>
<td>17</td>
</tr>
<tr>
<td>2.6</td>
<td>Common weaving patterns for 2-D woven fabrics</td>
<td>18</td>
</tr>
<tr>
<td>2.7</td>
<td>High damage intensity at hole edge (Manger, 1999)</td>
<td>21</td>
</tr>
<tr>
<td>2.8</td>
<td>Hole edge plain view in 8 layers eight harness satin weave with 2.5 mm circular hole (Manger, 1999)</td>
<td>22</td>
</tr>
<tr>
<td>2.9</td>
<td>Hole edge fiber manage from SEM image at different layer of 2.5 mm circular hole of 8-layer eight harness satin weave (Manger, 1999)</td>
<td>22</td>
</tr>
<tr>
<td>2.10</td>
<td>Damage observation at hole edge of 5 mm diameter hole size using SEM in each layer (after Belmonte et al., 2004)</td>
<td>23</td>
</tr>
<tr>
<td>2.11</td>
<td>Types of mechanical lap joint in structural assembly</td>
<td>24</td>
</tr>
<tr>
<td>2.12</td>
<td>Geometry of notched composite coupon</td>
<td>24</td>
</tr>
<tr>
<td>2.13</td>
<td>Failure modes in mechanical-fastened composite joints for ASTM D 5961/ D 5961 M-05</td>
<td>25</td>
</tr>
<tr>
<td>2.14</td>
<td>Macroscopic damage zone of GFRP bolted joint with W/d = 4 leading to catastrophic failure after exceeding critical damage zone (Kontolatis, 2000)</td>
<td>26</td>
</tr>
<tr>
<td>2.15</td>
<td>SLJ and DLJ joining technique (Kim &amp; Kedward, 2001)</td>
<td>28</td>
</tr>
<tr>
<td>2.16</td>
<td>Possible failure modes in bonded joints between FRP composite adherends (Banea &amp; Da Silva., 2009)</td>
<td>29</td>
</tr>
</tbody>
</table>
2.17 Fiber tear failure observed for CFRP/aluminum bonded joint (Seong et al., 2008)
2.18 Failure sequence of hybrid joint (Kim et al., 2015)
2.19 Typical load-displacement behavior on bonded, bolted and hybrid joint (Di Franco & Zuccarello, 2014)
2.20 Plate under a remote tensile stress with stress distribution along ligament
2.21 Typical stress distribution along the net-tension plane circular hole plate (Nuismer & Whitney, 1975)
2.22 Superposition of De Jong (1977) load cases
2.23 (a) Radial and tangential stress along the hole boundary (b) tangential stress along the net-tension plane (Ahmad, 2012)
2.24 Hole boundary diagram and location for maximum radial and tangential stress
2.25 Comparison of radial and tangential stress distribution for both top and bottom plane between (a) DLJs and (b) SLJs (Ahmad, 2012)
2.26 (a) Peel and (b) shear stress distribution along the normalized overlap (Campilho & Fernandes, 2015)
2.27 Comparison of shear stress on hybrid and bonded joint at (a) centreline and (b) overlap edge (Di Franco & Zuccarello, 2014)
2.28 Comparison of peel stress on hybrid and bonded joint at (a) centreline and (b) overlap edge (Di Franco & Zuccarello, 2014)
2.29 Damage zone and equivalent crack at notch vicinity (Backlund & Aronsson, 1986)
2.30 Barenblatt cohesive zone concept (Barenblatt, 1962)
2.31 Open hole strength prediction from critical damage growth (CDG) models as proposed by Hitchen et al. (1994)
2.32 Reaction force and separation applied in VCCT analysis based on one evaluation step (Krueger, 2004)
2.33 Linear CZM law under pure-mode and mixed mode laws (Campilho et al., 2012)
2.34 Failure load obtained from experimental and CZM on different overlap length with various adhesive type (Campilho & Fernandes, 2015)
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.35</td>
<td>Normal and tangential coordinates for random crack (Campilho et al., 2011a)</td>
</tr>
<tr>
<td>2.36</td>
<td>Damage propagation using phantom nodes concept (a) before and (b) after partitioning a crack element to sub-elements (Campilho et al., 2011a)</td>
</tr>
<tr>
<td>3.1</td>
<td>Flow chart conducted in current work</td>
</tr>
<tr>
<td>3.2</td>
<td>Flow chart for experimental programme (Stage 1)</td>
</tr>
<tr>
<td>3.3</td>
<td>Woven fabric kenaf yarn weaving process</td>
</tr>
<tr>
<td>3.4</td>
<td>Twill weave carbon fiber ply used as reinforcement</td>
</tr>
<tr>
<td>3.5</td>
<td>Epoxy resin and hardener used as matrix constituent</td>
</tr>
<tr>
<td>3.6</td>
<td>Steel bolts, nuts and washers used as fastener system in current work</td>
</tr>
<tr>
<td>3.7</td>
<td>Fabrication process for KFRP composite plate</td>
</tr>
<tr>
<td>3.8</td>
<td>A sample of KFRP composite panel after 24 hours curing period</td>
</tr>
<tr>
<td>3.9</td>
<td>Geometry of (a) unnotched coupon, (b) SEN coupon, (c) adherend and (d) notched plate</td>
</tr>
<tr>
<td>3.10</td>
<td>Epoxy as adhesive agent used in current study</td>
</tr>
<tr>
<td>3.11</td>
<td>Diagram of bonded joint configuration</td>
</tr>
<tr>
<td>3.12</td>
<td>Diagram of hybrid joint configuration carried out with different joint type</td>
</tr>
<tr>
<td>3.13</td>
<td>Stacking orientations in various lay-ups for KFRP composite plates</td>
</tr>
<tr>
<td>3.14</td>
<td>Stacking orientations in various lay-ups for CFRP composite plates</td>
</tr>
<tr>
<td>3.15</td>
<td>Bonded SLJ geometry</td>
</tr>
<tr>
<td>3.16</td>
<td>Strain gauges was placed in both longitudinal and lateral direction connected to data logger</td>
</tr>
<tr>
<td>3.17</td>
<td>Strain measurement as load applied by using strain gauge</td>
</tr>
<tr>
<td>3.18</td>
<td>(a) Data logger for strain gauge reading (b) UTM tensile test set up connecting to data logger (c) unnotched coupon set up with strain gauges</td>
</tr>
<tr>
<td>3.19</td>
<td>PX4 KFRP bonded SLJ coupon</td>
</tr>
<tr>
<td>3.20</td>
<td>PX4 KFRP hybrid DLJ coupon ready to be test</td>
</tr>
<tr>
<td>4.1</td>
<td>Failure occurred within gauge length on KFRP unnotched coupon</td>
</tr>
<tr>
<td>4.2</td>
<td>Fiber plies directions</td>
</tr>
<tr>
<td>4.3</td>
<td>Stress-strain curve on (a) cross-ply lay-up and (b) quasi-isotropic lay-up unnotched coupon plotted to determine Young’s modulus</td>
</tr>
</tbody>
</table>
4.4 Failure occurred within gauge length on CFRP unnotched plate
4.5 Load-displacement graph plotted to determine stiffness for PS2 lay-up
4.6 Graphs of compliance against notch length for PS2 lay-up coupon
4.7 Load-displacement curve of PX4 and PQ4 lay-up with various adherend width
4.8 Cohesive failure observed within adhesive layer of bonded SLJ
4.9 Representative load-displacement profile: PQ4 hybrid DLJ with W/d = 3, FT condition
4.10 Photograph of PQ4 hybrid DLJs coupons with different W/d (crack at hole edge is enlarged for visual clarity)
4.11 Bearing stress at failure on KFRP hybrid DLJs with various W/d
4.12 Bearing stress at failure on KFRP hybrid DLJs with various W/d
4.13 CFRP joint behaviour for CQ4 lay-up on (a) DLJ and (b) SLJ with clamped condition
4.14 Failed SLJ coupons for CQ4 lay-up with clamped condition (crack at hole edge is enlarged for visual clarity)
4.15 Bearing stress at failure on CFRP hybrid DLJs with various W/d
4.16 Bearing stress at failure on CFRP hybrid DLJs with various W/d
4.17 Secondary bending caused by plate lifting for CX2 hybrid SLJ
5.1 Flow chart on strength prediction work of 2-D bonded joint
5.2 Flow chart on strength prediction work of hybrid joints superposition method
5.3 Components in bonded SLJ configuration
5.4 Meshing in PQ4 bonded SLJ with adherend width = 20 mm
5.5 Loading and boundary conditions applied in bonded SLJs
5.6 Traction-separation constitutive models used within XFEM frameworks in adhesive layer (Sugiman & Ahmad, 2017)
5.7 Traction separation constitutive models used in CZM frameworks in adhesive layer (Sugiman & Ahmad, 2017)
5.8 Predefined crack edge assigned within adhesive layer
5.9 Predefined bonding region assigned between contact surface of adhesive layer and its adjacent adherend
5.10 Cohesive element assigned within adhesive layer
5.11 Path across adhesive layer investigated in current work

5.12 Peel stress, $\sigma_{22}$ and shear stress, $\tau_{12}$ across path 2

5.13 Path 1 and 3 for shear stress, $\tau_{12}$

5.14 Path 1 and 3 for peel stress, $\sigma_{22}$

5.15 Load-displacement profile from XFEM results

5.16 Damage plot at specified location from load-displacement profile as labelled in Figure 5.15 (overlapped region is enlarged for visual clarity)

5.17 Load-displacement profile from VCCT results

5.18 Damage plot at specified location from load-displacement profile as labelled in Figure 5.17 (overlapped region is enlarged for visual clarity)

5.19 Load-displacement profile from CZM results

5.20 Damage plot at specified location from load-displacement profile as labelled in Figure 5.19 (overlapped region is enlarged for visual clarity)

5.21 Load-displacement curve on PX4 (with 15 mm adherend width) bonded joint determined from experimental and various numerical works

5.22 Superposition method approach used by combining 2-D adhesive SLJs and 3-D bolted SLJs

5.23 SLJ model used by Romanye (2016)

5.24 Final failure mode observed in PQ4, $W/d = 3$, SLJ bolted SLJ model by using XFEM technique (Romanye, 2016)

5.25 Comparison on stress at failure of PQ4 hybrid SLJ obtained from experimental work and combined bolted and bonded SLJ obtained from FEA works

6.1 Flow chart on strength prediction of hybrid joints using different FEA techniques

6.2 All components in hybrid DLJ model implemented in current work

6.3 Geometry of notched coupon implemented in current work

6.4 Assembled component parts for KFRP hybrid DLJ

6.5 Meshing implemented in ABAQUS CAE for hybrid DLJ model

6.6 Two steps implemented in DLJ model
6.7 Boundary condition and applied loading assigned in current hybrid DLJ model 164
6.8 Boundary condition at y-symmetry axis (given as red colour region) to idealize hybrid DLJ half model 165
6.9 Occurrence of bearing interaction in DLJ configurations 165
6.10 Sliding load on PQ4 KFRP hybrid DLJ with various $W/d$ 166
6.11 Bolt load applied near the nut region in current model 166
6.12 Assignment of XFEM region within composite coupon 167
6.13 Interaction between contact surfaces on hybrid DLJ model 168
6.14 Friction coefficient determination by simple experiment 169
6.15 Tie constraint between adherend contact surfaces and adhesive layer contact surfaces 169
6.16 Two contact bonding were assigned as possible region of delamination 170
6.17 Adhesive layer with appropriate mesh element size 171
6.18 Typical load-displacement profile on PQ4 KFRP hybrid DLJ determined by using fully XFEM 172
6.19 Damage plot with crack growth on associated model (fully-XFEM) 173
6.20 Typical load-displacement profile on PQ4 KFRP hybrid DLJ determined by using XFEM-VCCT 174
6.21 Damage plot with crack growth on associated model (XFEM-VCCT) 175
6.22 Typical load-displacement profile on PQ4 KFRP hybrid DLJ determined by using XFEM-CZM 177
6.23 Damage plot with crack growth on associated model (XFEM-CZM) 178
6.24 Comparison of bearing stress at failure on PQ4 KFRP hybrid DLJ of all technique implemented 179
7.1 Flow chart on strength prediction work on hybrid joints using fully XFEM 182
7.2 Pre-processing stage on fully XFEM framework 183
7.3 Components in SLJs configurations 184
7.4 Meshing implemented in ABAQUS CAE for hybrid SLJ model 187
7.5 Surface interaction between contact pairs in hybrid SLJ model 187
7.6 Predefined crack assignment within adhesive layer as cohesive failure and XFEM within composite coupon

7.7 Peel and shear stresses analysis on SLJ and DLJ within adhesive layer

7.8 Angle direction along the hole boundary and definition of bearing region

7.9 Tangential and radial stresses analysis on DLJ and SLJ within PX2 KFRP coupon around hole boundary

7.10 Secondary bending effect on SLJ due to bending

7.11 Effect of secondary bending in (a) bolted joint and (b) hybrid joints

7.12 Crack initiated at tensile surface and propagated through coupon thickness observed from (a) numerical and (b) experimental works

7.13 Failure mode observed in hybrid DLJ with cohesive failure exhibited within adhesive layers and net-tension failure within composite coupon

7.14 Crack initiated and propagated uniformly through coupon thickness in hybrid DLJ

7.15 Damage stabilization on strength prediction

7.16 Mesh sensitivity on strength prediction

7.17 Discrepancy on strength prediction work on KFRP and CFRP hybrid DLJ with various W/d

7.18 Discrepancy on strength prediction work on KFRP hybrid DLJ with various laminate lay-up and plate thickness

7.19 Discrepancy on strength prediction work on PX4 KFRP hybrid DLJ with various bolt load

7.20 Load-displacement profile on PX2 hybrid SLJ with W/d = 3

7.21 Damage plot with crack growth of KFRP hybrid SLJ coupon

7.22 Discrepancy on strength prediction work on KFRP hybrid SLJ with various laminate lay-up and coupon thickness

7.23 Discrepancy on strength prediction work on KFRP and CFRP hybrid SLJ with various W/d

7.24 Discrepancy on strength prediction work on PQ4 KFRP and CFRP hybrid SLJ with various bolt load
**LIST OF SYMBOLS AND ABBREVIATIONS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM</td>
<td>American Society for Testing Materials</td>
</tr>
<tr>
<td>BK</td>
<td>Benzeggagh-Kenane failure criterion</td>
</tr>
<tr>
<td>CQ/CS</td>
<td>Carbon fiber quasi-isotropic</td>
</tr>
<tr>
<td>CX</td>
<td>Carbon fiber cross-ply</td>
</tr>
<tr>
<td>CDG</td>
<td>Critical damage growth</td>
</tr>
<tr>
<td>CGM</td>
<td>Crack growth model</td>
</tr>
<tr>
<td>CZM</td>
<td>Cohesive zone model</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon fiber reinforced polymer</td>
</tr>
<tr>
<td>DLJ</td>
<td>Double-lap joint</td>
</tr>
<tr>
<td>DZM</td>
<td>Damage Zone Model</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite element analysis</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite element method</td>
</tr>
<tr>
<td>FRP</td>
<td>Fiber reinforced polymer</td>
</tr>
<tr>
<td>FT</td>
<td>Finger-tight case</td>
</tr>
<tr>
<td>GFRP</td>
<td>Glass fiber reinforced polymer</td>
</tr>
<tr>
<td>KFRP</td>
<td>Kenaf fiber reinforced polymer</td>
</tr>
<tr>
<td>LEFM</td>
<td>Linear elastic fracture mechanics</td>
</tr>
<tr>
<td>PDM</td>
<td>Progressive damage modelling</td>
</tr>
<tr>
<td>PE</td>
<td>Polyethylene</td>
</tr>
<tr>
<td>PP</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>PS</td>
<td>Polystyrene</td>
</tr>
<tr>
<td>PV</td>
<td>Polyvinyl chloride</td>
</tr>
<tr>
<td>PQ/PS</td>
<td>Plain weave quasi-isotropic</td>
</tr>
<tr>
<td>PX</td>
<td>Plain weave cross-ply</td>
</tr>
<tr>
<td>SEN</td>
<td>Single-edge notch</td>
</tr>
<tr>
<td>SLJ</td>
<td>Single-lap joint</td>
</tr>
</tbody>
</table>
VCCT - Virtual crack closure technique
XFEM - Extended finite element method
2-D - Two-dimensional
3-D - Three-dimensional
a - Longitudinal distance from hole edge/crack length
a_i - Enriched nodal degree of freedom vector
B - Plate width
b_i^e - Nodal enriched degree of freedom vector of nodes
t - Plate thickness
C - Compliance
d - Hole diameter
D - Scalar damage variable
e - End-distance
E_1 - Longitudinal Young’s modulus
E_2 - Transverse Young’s modulus
E_x - Laminate longitudinal Young’s modulus
E_y - Laminate transverse Young’s modulus
\( \varepsilon_{n,max} \) - Maximum nominal strain normal-only mode
\( \varepsilon_{s,max} \) - Maximum nominal strain shear-only mode first-direction
\( \varepsilon_{t,max} \) - Maximum nominal strain shear-only mode second direction
F - Reaction force
F_\alpha(x) - Related elastic asymptotic crack-tip functions
G_{xy} - Laminate shear modulus
G_{12} - In-plane shear modulus (fiber direction)
G_1/G_c - Fracture energy
G_c^* - Apparently fracture energy
G_n - Fracture energy normal-only mode
G_d/G_{IC} - Fracture energy mode first direction
G/G_{IIIC} - Fracture energy mode second direction
H(x) - Discontinuous jump shape function (in enriched element)
K - Elastic stiffness matrix
K_T^\infty /K_T - stress concentration factor
K_r - Crack interior
$K_{\Delta}$ - Crack tip
$L_0$ - Overlap length
$N_i(x)$ - Conventional FE (non-enriched) nodal shape function
$n_i$ - Nodes in an element ($i=1,2,3\ldots$)
$n_i$ - Phantom Nodes in element ($i=1,2,3\ldots$)
$P_{max}/P_m$ - Maximum load
$P/P_{app}$ - Applied load
$P_{bolt}$ - Bolt load
$r$ - Hole radius
$u$ - Displacement vector
$u_i$ - Conventional FE (non-enriched) nodal displacement vector
$\mu$ - Friction coeffiecnt
$(\ )_s$ - Symmetry
$T$ - Torque condition
$T_{n,max}$ - Maximum nominal stress normal-only mode
$T_{s,max}$ - Maximum nominal stress shear-only mode first-direction
$T_{t,max}$ - Maximum nominal stress shear-only mode second direction
$\nu_{xy}$ - Poisson’s ratio
$W$ - Plate width
$X_t$ - Longitudinal tensile strength
$X_c$ - Longitudinal compressive strength
$Y_t$ - Transverse tensile strength
$Y_c$ - Transverse compressive strength
$\sigma_0$ - Unnotched strength
$\sigma_{coh}$ - Cohesive stress
$\sigma_b$ - Bearing stress at failure
$\sigma_y$ - Normal stress
$\bar{\sigma}$ - Uniform tensile stress
$\delta$ - Displacement
$\delta_{max}$ - Displacement at maximum
$\delta_u$ - Distance between displacements of nodal points next to crack tip
$\theta$ - Angle of bearing plane
REFERENCES


Tong, L. (1997), An assessment of failure criteria to predict the strength of adhesively bonded composite double lap joints. *Journal of Reinforced Plastics and Composites*, 16(8), 698-713.


