

# **Fatigue Analysis of Surface Pretreated Adhesively Bonded CFRP using FEM and X-Ray Tomography**

BY

**Hussain Khalifah Al-Dakheel**

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This thesis, written by **Hussain Al-Dakheel** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN MECHANICAL ENGINEERING**

Zuhair  
Gasem

Digitally signed by Zuhair Gasem  
DN: cn=Zuhair Gasem, o=KFUPM,  
ou=Chair, ME Dept.,  
email=zuhair@kfupm.edu.sa,  
c=SA  
Date: 2020.11.23 13:59:47 +03'00'

Dr. Zuhair Gasem  
Department Chairman



Dr. Jafar Albinmoussa  
(Advisor)



Dr. Suliman Saleh Al-Homidan  
Dean of Graduate Studies



Dr. Khaled Al-Athel  
(Co-Advisor)

November, 2020

Date



Dr. Gilles Lubineau  
(Member)

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2020

## *Dedication*

I dedicate this work to a great man who supported me in tough times that is my father **Khalifa Al-Dakheel**. My gratitude is never enough to my life partner, my wife **Bayan Al-Haddad** for her endless encouragement throughout the process. I will always be thankful to my mother, my brothers and sisters for sticking up for me all along the master's degree program.

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# TABLE OF CONTENTS

|                                                          |       |
|----------------------------------------------------------|-------|
| ACKNOWLEDGMENTS .....                                    | III   |
| TABLE OF CONTENTS .....                                  | IV    |
| LIST OF TABLES .....                                     | VIII  |
| LIST OF FIGURES .....                                    | IX    |
| NOMENCLATURE .....                                       | XIII  |
| ABSTRACT .....                                           | XVI   |
| ملخص الرسالة .....                                       | XVIII |
| Chapter 1            INTRODUCTION.....                   | 1     |
| 1.1     Carbon Fiber Reinforced Polymers .....           | 1     |
| 1.2     CFRP Adhesive Joints .....                       | 2     |
| 1.2.1   Applications .....                               | 3     |
| 1.2.2   Loading and Joining Types .....                  | 4     |
| 1.2.3   Mechanical Damage .....                          | 5     |
| 1.2.4   Surface Pretreatment for Joined Substrates ..... | 6     |
| 1.3     Failure Modes In CFRP .....                      | 7     |
| 1.4     Numerical and Analytical Background.....         | 8     |
| 1.4.1   Fatigue Crack Growth in Fracture Mechanics ..... | 8     |

|           |                                                                 |    |
|-----------|-----------------------------------------------------------------|----|
| 1.4.2     | Crack Growth Modeling Techniques.....                           | 10 |
| 1.4.3     | Numerical Analysis Formulations.....                            | 18 |
| 1.5       | Failure Characterizing Using X-Ray Tomography .....             | 22 |
| 1.5.1     | Principle of x-ray emission .....                               | 22 |
| 1.5.2     | X-Ray Tomography.....                                           | 23 |
| 1.5.3     | Image Reconstruction .....                                      | 24 |
| 1.5.4     | Contrast and Resolution.....                                    | 27 |
| Chapter 2 | LITTERATURE REVIEW .....                                        | 28 |
| 2.1       | FEM of Fatigue Crack Growth in Adhesively Bonded Substrate..... | 29 |
| 2.1.1     | FEM Using Fracture Mechanics Approach .....                     | 29 |
| 2.1.2     | FEM Using Cohesive Zone Model.....                              | 30 |
| 2.1.3     | Fatigue Crack Grow Using CZM .....                              | 32 |
| 2.2       | Tomography Observations in CFRP.....                            | 34 |
| 2.2.1     | In Situ Computed Tomography Scanning for CFRP Failure.....      | 35 |
| 2.2.2     | Ex situ computed tomography scanning for CFRP failure .....     | 35 |
| 2.2.3     | In situ vs. ex situ.....                                        | 36 |
| 2.3       | Computed Tomography Observations in Adhesive Joints .....       | 37 |
| 2.4       | Objectives.....                                                 | 38 |
| Chapter 3 | MATERIAL AND EXPERIMENT .....                                   | 39 |
| 3.1       | Material properties and characteristics .....                   | 39 |

|           |                                               |    |
|-----------|-----------------------------------------------|----|
| 3.1.1     | Carbon Fiber Reinforced Polymers (CFRP) ..... | 39 |
| 3.1.2     | Adhesive Properties .....                     | 40 |
| 3.2       | Sample Preparation.....                       | 41 |
| 3.3       | Mechanical Tests .....                        | 43 |
| 3.4       | X-Ray Tomography Test .....                   | 46 |
| 3.4.1     | X-Ray Tomography Scanner.....                 | 46 |
| 3.4.2     | Sample Loading and Scanning .....             | 46 |
| 3.4.3     | Reconstruction.....                           | 47 |
| 3.4.4     | Image Segmentation .....                      | 47 |
| Chapter 4 | FINITE ELEMENT ANALYSIS USING CZM .....       | 49 |
| 4.1       | Strategy and Methodology .....                | 49 |
| 4.2       | Finite element modeling inputs .....          | 51 |
| 4.2.1     | Material Models .....                         | 51 |
| 4.2.2     | Geometry.....                                 | 52 |
| 4.2.3     | Loading and Boundary Condition.....           | 52 |
| 4.2.4     | Energy release rate.....                      | 53 |
| 4.2.5     | Substrate Elements Type.....                  | 56 |
| 4.3       | Details of the Finite Element Modeling.....   | 57 |
| 4.3.1     | Virtual Crack Closure Technique (VCCT).....   | 57 |
| 4.3.2     | Bilinear Cohesive Zone Model .....            | 59 |

|                                                                          |     |
|--------------------------------------------------------------------------|-----|
| 4.3.3 Fatigue Crack Grow Using Bilinear CZM.....                         | 61  |
| 4.3.4 Exponential Cohesive Zone Model .....                              | 66  |
| 4.3.5 Fatigue Crack Grow Using Exponential CZM.....                      | 69  |
| Chapter 5 RESULTS AND DISSCUSSION.....                                   | 72  |
| 5.1 Bilinear CZM Results .....                                           | 72  |
| 5.2 Exponential CZM Results .....                                        | 78  |
| 5.3 Computed Tomography Images .....                                     | 84  |
| Chapter 6 CONCLUSION AND RECOMMENDATIONS.....                            | 90  |
| 6.1 Conclusion .....                                                     | 90  |
| 6.2 Recommendations .....                                                | 91  |
| Appendix A.....                                                          | 93  |
| CZM model for a numerical simulation using finite element analysis ..... | 93  |
| Appendix B.....                                                          | 101 |
| EXPERIMENTAL WORK SOFTWARES .....                                        | 101 |
| References .....                                                         | 105 |
| Author Vitae .....                                                       | 117 |

## LIST OF TABLES

|                                                                                |    |
|--------------------------------------------------------------------------------|----|
| Table 3.1. CFRP mechanical properties <sup>89</sup> . .....                    | 40 |
| Table 3.2. Araldite 420 A/B mechanical properties <sup>1</sup> . .....         | 40 |
| Table 3.3. General properties of the adhesive components <sup>90</sup> . ..... | 41 |
| Table 3.4. CFRP mechanical properties <sup>91</sup> .....                      | 51 |
| Table 4. 1 Virtual crack closure technique results .....                       | 58 |
| Table 4. 2 The derived bilinear CZM parameters.....                            | 61 |
| Table 4. 3 The exponential CZM parameters for the LA30 sample. ....            | 68 |
| Table 5. 1 Influence on time increment on the total actual time. ....          | 83 |
| Table A. 1 orthotropic properties used assign to the substrate material. ....  | 96 |
| Table A. 2 Cohesive properties assign to the mating line. ....                 | 96 |
| Table A. 3 Geometric data for the model <sup>68</sup> . ....                   | 98 |
| Table A. 4 Mesh details.....                                                   | 99 |

## LIST OF FIGURES

|                                                                                                                                                       |    |
|-------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1.1 CFRP basic structure <sup>4</sup> .....                                                                                                    | 2  |
| Figure 1.2 Adhesive joint type of loadings where a) Tensile loading, b) shear loading,<br>c) Cleavage loading and d) peel loading <sup>14</sup> ..... | 5  |
| Figure 1. 3 Adhesively bonded substrate formed in DCB. ....                                                                                           | 10 |
| Figure 1. 4 Cohesive zone traction separation law <sup>22</sup> .....                                                                                 | 12 |
| Figure 1. 5 Exponential cohesive zone traction-separation behavior. ....                                                                              | 17 |
| Figure 1.6 The signal of both continuous and characteristics X-ray emissions <sup>48</sup> .....                                                      | 23 |
| Figure 1.7 Flow chart shows the process of generation and reconstruction<br>x-ray tomography <sup>48</sup> .....                                      | 24 |
| Figure 1.8 Platform with column resulting from multiple incidents and filtration<br>can be seen in the right side <sup>52</sup> . ....                | 25 |
| Figure 1.9 Image of a dot resulting from multiple projection with a blurred reconstructed<br>image <sup>52</sup> .....                                | 26 |
| Figure 1.10 The dot image after Fourier transform filtration <sup>52</sup> . ....                                                                     | 26 |
| Figure 1.11 Radon method to reconstruct an image for a) four pixels and b) nine pixels <sup>52</sup> ...                                              | 27 |
| Figure 2.1 Paris law dependent FCG model based on CZM results <sup>20</sup> . ....                                                                    | 32 |
| Figure 2.2 procedure similar to Morvarid et al and Pironi et al published flowcharts <sup>30,32</sup> ...                                             | 33 |

|                                                                                                                               |    |
|-------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 3.1 Dimensions and geometry of the sample.....                                                                         | 42 |
| Figure 3.2 prepared samples formed in DCB for an adhesively bonded CFRP beams. ....                                           | 43 |
| Figure 3.3. The sample is placed in the cyclic loading machine and ready to be tested.....                                    | 44 |
| Figure 3.4 Sample gripping fixture that was manufactured and fabricated by KFUPM<br>machine shop. ....                        | 45 |
| Figure 3.5 Sample is standing on the stage ready for scanning. ....                                                           | 47 |
| Figure 4. 1 Summary of the strategy implemented to model fatigue crack grow.....                                              | 50 |
| Figure 4. 2 Load and boundary conditions .....                                                                                | 53 |
| Figure 4. 3 Energy release rate obtained by MBT and SBT. ....                                                                 | 55 |
| Figure 4. 4 Logarithmic relation constants obtain by fitting the curve to the associate<br>relation for the LA10 sample. .... | 56 |
| Figure 4. 5 PLANE182 element <sup>96</sup> .....                                                                              | 57 |
| Figure 4. 6 INTER202 element <sup>96</sup> .....                                                                              | 58 |
| Figure 4. 7 Load-displacement response for a) BT, b) LA10, c) SB and d) PP samples. ....                                      | 59 |
| Figure 4. 8 Bilinear traction-separation law .....                                                                            | 60 |
| Figure 4. 9 CONTA171 element <sup>96</sup> .....                                                                              | 62 |
| Figure 4. 10 FCG by damage accumulation mechanism .....                                                                       | 63 |
| Figure 4. 11 Flowchart of bilinear CZM for fatigue crack grow <sup>20</sup> . ....                                            | 64 |
| Figure 4. 12 Flowchart of the damage-based model <sup>30,32</sup> .....                                                       | 65 |
| Figure 4. 13 Load-displacement response for the LA30 sample .....                                                             | 66 |

|                                                                                                                                                                                                                      |    |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 4. 14 Exponential traction-separation law. ....                                                                                                                                                               | 67 |
| Figure 4. 15 The exponential traction-separation law for the LA30 sample. ....                                                                                                                                       | 68 |
| Figure 4. 16 INTER202 element <sup>96</sup> . ....                                                                                                                                                                   | 69 |
| Figure 4. 17 Flowchart for Paris law dependent model for FCG exponential CZM <sup>79</sup> . ....                                                                                                                    | 70 |
| Figure 4. 18 Flowchart based on Roe's model for FCG exponential CZM <sup>40,41</sup> . ....                                                                                                                          | 71 |
| Figure 5. 1 Strain energy release rate resulted from the FEM compared with<br>the experimentally computed values for the a) Baseline Teflon,<br>b) laser ablation 10%, c) sandblasting and c) peel ply samples. .... | 73 |
| Figure 5. 2 Fatigue crack grow resulted from the FEM compared with the<br>experimentally computed values for the a) Baseline Teflon, b) laser ablation<br>10%, c) sandblasting and c) peel ply samples. ....         | 74 |
| Figure 5. 3 Strain energy release rate resulted from the FEM compared with the<br>experimentally computed values for the a) Baseline Teflon, b) laser ablation<br>10%, c) sandblasting and c) peel ply samples. .... | 75 |
| Figure 5. 4 Fatigue crack grow resulted from the FEM compared with the<br>experimentally computed values for the a) Baseline Teflon, b) laser ablation<br>10%, c) sandblasting and c) peel ply samples. ....         | 76 |
| Figure 5. 5 A comparison between different element size for the LA10 results. ....                                                                                                                                   | 78 |
| Figure 5. 6 a) Strain energy release rate and b) fatigue crack grow resulted from the<br>exponential CZM compared with the experimentally obtained values for the<br>LA30 sample. ....                               | 79 |
| Figure 5. 7 Strain energy release rate resulted from Roe's model compared with<br>the experimentally computed values for the LA30 sample. ....                                                                       | 80 |

|                                                                                                                                         |     |
|-----------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 5. 8 The resulted fatigue crack growth calibrated by the experimental values<br>based on Roe's model for the LA30 sample.....    | 81  |
| Figure 5. 9 A comparison between two different time increments based on Roe's model.....                                                | 82  |
| Figure 5.10 CT image of the LA10%% showing a crack segment in the top and an<br>orthotropic slice is in the bottom.....                 | 86  |
| Figure 5.11 CT image of the BT sample showing the crack segment. The static<br>region is determined followed by the fatigue region..... | 87  |
| Figure 5. 12 CT image for the BT sample showing the lower side of the crack segment. ....                                               | 88  |
| Figure A. 1 Mesh estimation of DCB. ....                                                                                                | 95  |
| Figure A. 2 Setups for double cantilever beam (DCB) <sup>68</sup> . ....                                                                | 97  |
| Figure A. 3 Von miss stress in DCB. ....                                                                                                | 100 |
| Figure A. 4 Load Vs y-axis displacement for the model and reference. <sup>68</sup> .....                                                | 100 |

## NOMENCLATURE

|                 |                                                          |
|-----------------|----------------------------------------------------------|
| $a$             | Crack length                                             |
| $b$             | The width of the specimen                                |
| $B$             | Strain/Displacement matrix                               |
| $C$             | The compliance                                           |
| $C_1$           | Paris constant associated with stress intensity factor   |
| $C_f$           | Fatigue limit to the maximum stress ratio                |
| $D$             | Constant matrix                                          |
| $\dot{D}$       | Rate of the cyclic damage                                |
| $\delta$        | Crack tip displacement                                   |
| $\Delta$        | Crack length correction factor.                          |
| $\delta_f$      | Final crack tip displacement                             |
| $\Delta G$      | Difference in energy release rate                        |
| $\Delta k$      | Difference in stress intensity factor                    |
| $\delta_0$      | Onset crack tip displacement                             |
|                 | Difference in the maximum crack tip displacement between |
| $\Delta$        | the current and previous time step                       |
| $\delta_\Sigma$ | Accumulated crack tip displacement                       |
| $\Delta t$      | Time increment                                           |
| $D_g$           | Global displacement                                      |
| $D_m$           | Monotonic damage                                         |

|               |                                                        |
|---------------|--------------------------------------------------------|
| $D_{max}$     | Maximum displacement                                   |
| $D_T$         | Total damage                                           |
| $E$           | Modulus of elasticity                                  |
| $E_f$         | Equivalent effective modulus of elasticity is given    |
| $\varepsilon$ | Strain matrix                                          |
| $\mathbf{f}$  | Load matrix                                            |
| $f'$          | Cyclic load frequency                                  |
| $F_{yI}$      | Crack tip nodal force                                  |
| $G$           | Shear modulus                                          |
| $G_c$         | The critical strain energy release rate.               |
| $G_{Ic}$      | Fracture toughness                                     |
| $G_{LR}$      | Shear modulus in the XY direction                      |
| $G_{max}$     | Maximum energy release rate                            |
| $h$           | Thickness of the specimen                              |
| $i$           | Index                                                  |
| $\eta$        | Paris exponent associated with stress intensity factor |
| $K_0$         | Initial CZM stiffness                                  |
| $\kappa$      | Element Stiffness matrix                               |
| $L$           | Longitudinal length of the specimen                    |
| $\lambda$     | Logarithmic function constant                          |
| $L_{cz}$      | Process zone length                                    |
| $M$           | Paris law Exponent                                     |
| $\mu$         | Logarithmic function constant                          |
| $N$           | Number of cycles                                       |
| $\mathbf{N}$  | Shape function                                         |

|            |                                           |
|------------|-------------------------------------------|
| $n_{FPZ}$  | Number of the integration points          |
| $\nu$      | Poisson ratio                             |
| $P$        | Applied load                              |
| $\Phi$     | Area of the exponential CZM curve         |
| $\varphi$  | Turon number                              |
| $P_{max}$  | Maximum applied load                      |
| $Q$        | Orthotropic stiffness term                |
| $\rho$     | The notch radius                          |
| $r_w$      | Relative weight of each integration point |
| $S$        | Normal stress                             |
| $\sigma$   | Stress matrix                             |
| $\sigma_0$ | Maximum achievable CZM stress             |
| $\sigma_y$ | Stress in y-axis                          |
| $T_n$      | Exponential CZM stress                    |
| $u$        | Displacement matrix                       |
| $V$        | Volume                                    |
| $x$        | Dependent variable along x-axis           |
| $y$        | Dependent variable along y-axis           |

# **ABSTRACT**

Full Name : Hussain Khalifah Al-Dakheel

Thesis Title : Fatigue Analysis of Surface Pretreated Adhesively Bonded CFRP using FEM and X-Ray Tomography

Major Field : Mechanical Engineering

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Carbon fiber reinforced polymers (CFRP) is a composite material that has been reliably implemented in engineering structures. The development of CFRP has been crucial for many industries due to their superior material properties. In countable applications, their strength and stiffness are comparable to metals alloys and yet has the advantage of lighter weight and higher corrosion resistance. Typically, materials are joined to assemble structural components by bolts and rivets. However, such joining methods raise difficulties keeping the structural integrity. Screw holes are stress concentration locations that are considered as weak points in CFRP where cracks may develop causing splits and delamination. Hence, adhesive bonding is utilized to join CFRP substrates. To ensure proper mating, surface pretreatments are performed to increase the surface roughness and to enhance the surface bonding energy. Mechanical surface pretreatments are conventionally used to roughen the surface; however, they are crucially dependent on the skill of the labor and may leave traces of contaminations. Chemical pretreatments are reliable due to the high bonding of the reacted surfaces; however, their disposed components are harmful to the environment. Unconventional methods like plasma are applied but they are not sufficient to cause deep cuttings which is needed to create a rough surface. Laser pretreatment is another unconventional method that has the advantage to

overcome all the disadvantages of the previously mentioned techniques beside its controllability.

Previous work has been done to compare different pretreatment methods. Laser irradiation in monotonic loading has shown higher toughness and better surface profile. However, fatigue performance of laser irradiation method has not been investigated.

The purpose of this research is to investigate fatigue failures in CFRP adhesively joined substrates treated by laser irradiation. Samples with five different types of surface pretreatments were examined. A finite element model is implemented to simulate fatigue crack growth using cohesive zone model (CZM). The model is used to obtain the energy release rate and the crack growth due to the increment of the number of cycles. The unique physics of the crack growth in the high-power laser ablation required different type of cohesive zone constitutive behavior than the rest of the samples as it induced fiber bridging phenomena within the crack surface. The resulted energy release rate from the model for both types of constitutive behaviors has shown a small scatter of within 10% of the analytically obtained values while the predicted crack length was accurately matching the experimentally estimated values. It was found that the mesh size plays an important rule in obtaining rational and persuasive numerical outcomes. Similarly, when the exponential constitutive behavior is implemented in the cohesive zone model to simulate the crack growth in the high-power laser sample, the time increment is observed to be vital in Roe model. In order to visualize the fatigue damage accumulation in the adhesively bonded substrate, computed tomography was used to observe crack surface for static and fatigue tests. When the x-ray intensity threshold value was adjusted, the segment of the crack surface was isolated and became presentable. The observations have supported the previous studies which stated that the fatigue crack growth is caused by immergence of the main crack with the microcracks ahead of the crack tip. Those microcracks are believed to be generated from the adhesive cavities, which are experiencing strain concentrations around them as the cyclic loading is being applied.

## ملخص الرسالة

الاسم الكامل: حسين خليفة الدخيل

عنوان الرسالة: تحليل الاجهاد الناتج عن الاوزان المتكررة لمادة البوليمرات المدعمة بالألياف الكربونية المركبة بلواصق صناعية باستخدام طريقة العناصر المتناهية والأشعة المقطعية

التخصص: هندسة ميكانيكية

تاريخ الدرجة العلمية: أغسطس 2020

البوليمرات المدعمة بالألياف الكربونية هي مادة مبركة تم توظيفها بجدارة في الهياكل الهندسية. العمل على تطوير مادة البوليمرات المدعمة بالألياف الكربونية لاقى اهتماماً واسعاً في الأوساط العلمية والبحثية لما تحمله من مواصفات تناسب العديد من التطبيقات الهندسية والعملية. قوة تحملها العالية بالإضافة إلى قدرتها الفائقة على مقاومة التآكل جعلها مرشحة لتكون بديلاً للمعادن. التطبيقات الهندسية التي يمثل وزن المواد فيها معياراً مهماً تفضل استخدامها على المعادن نظراً لخفتها. عادةً تستخدم المثبتات المعدنية مثل الأقفال والمسامير للتجميع والتركيب لبناء الهياكل المركبة لكنها تخلق نقاط ضعف للبوليمرات المدعمة بالألياف وذلك لتسببها في إنشاء مواقع يتركز فيها الضغط مما يؤدي إلى نشوء التشوهات والتفكك. لذلك تستخدم اللواصق الصناعية عالية القوة بدلاً عنها. لتثبيت اللواصق هناك أهمية كبرى لتعزيز الالتصاق عن طريق تجهيز سطح المادة بالتقنيات الميدانية قبل إضافة اللاصق. يتم ذلك عندما تقوم المعالجة السطحية بزيادة خشونة السطح مما يزيد طاقة وسطح الترابط. المعالجة الميكانيكية عادةً تستخدم لكنها تعتمد على مهارة العامل القائم عليها وهناك شواهد على تركها للشوائب على السطح المعالج. المعالجة الكيميائية تعتبر فعالة لكونها تعتمد على التفاعل الكيميائي بين اللاصق والسطح لكنها عادة تترك مواد كيميائية مضرّة تحتاج إلى تصريف. بالمقابل تستخدم تقنية الليزر للمعالجة وهي تقنية فعالة وتنتج سطح نظيف ومنتظم بدون شوائب بالإضافة إلى كونها سهلة التحكم.

المقارنة بين تقنية الليزر والتقنيات الأخرى في دراسة سابقة أكدت على صلابة المعالجة الليزرية مقارنة بالطرق الأخرى تحت الأحمال الثابتة. للحصول على منظور متكامل حول افضلية المعالجة الليزرية من وجهة نظر ميكانيكية يجب أن تقام دراسة لاختبار قدرة تحملها للأوزان المتكررة بتردد عالي. هذه الدراسة من المقترض أن تشمل نموذج هندسي يحاكي العملية الميكانيكية ويؤكد نتائجها.

هذه الدراسة تعتمد الى التحقيق في مقاومة مادة البوليمرات المدعمة بالألياف الكربونية المركبة بلاصق صناعي للتصدع الناتج من الأوزان المتكررة. العينات المتوفرة تحتوي على خمس أنواع من المعالجات السطحية لكل عينة بحيث أن التجربة العملية تهدف إلى متابعة التلف الناجم عن الأوزان المتكررة. تم إنشاء نموذج هندسي يعتمد على التحليل العددي لإيجاد معامل الانشقاق. باستخدام تقنية CZM في طريقة العناصر المتناهية تم حساب معدل الطاقة الكامنة  $G_{max}$  بالإضافة الى تمدد الانشقاق كنتيجة لتراكم الجهد. بسبب وجود ظاهرة فيزيائية مميزة في العينة المعالجة بالليزر، كان هناك حاجة ماسة لاستخدام نموذج خاص لسلوك المادة يعكس التفاعل الفيزيائي فيها والذي يختلف عن بقية العينات. معدل الطاقة الكامنة الناتج عن النماذج الهندسية كان متوافقاً مع معدل الطاقة المحسوب

من المعادلات التحليلية مما يثبت صلاحية النموذج وتوافقه مع سلوك المادة بالإضافة الى قدرته على توقع نمو التصدعات بدقة. حجم العناصر المنتهية ومعدل الزيادة الزمنية المستخدمين في النموذج كان لهم دور كبير في استخراج نتائج منطقية ودقيقة. بالإضافة لذلك تم معاينة تطور الإجهاد والتشقق في بعض من العينات المختارة باستخدام الأشعة المقطعية. تم عزل الانشقاق باستخدام تقنية الانتقاء المقطعي للتصوير والتحليل والشرح. عند تعديل القيمة الرائدة لحدة الاشعة المقطعية أصبح بالإمكان عزل سطح التشقق وعرضه. الملاحظات دعمت الفرضية القائلة بأن سبب تمدد التشققات تحت الاحمال المترددة هو اندماج التصدع الرئيسي مع التشققات الميكروبية الناتجة عن نمو التجويفات في الاصق.

## Chapter 1

## INTRODUCTION

Weight is an important parameter in modern structural components particularly in aerospace and aircraft assemblies. Hence, researchers are interested to investigate materials which has sufficient properties that are comparable to metals but with lower weight. One of these materials is carbon fiber reinforced polymers that are being used in wide range of applications such as pipelines and automobiles. To assemble such material, it is preferred to avoid using fasteners and screws because they are difficult to machine. In addition, holes may create stress concentration sites which are favored for crack nucleation and propagation that lead to delamination <sup>1</sup>. Hence, it is preferred to use adhesive as an alternative because it has proven reliability in many cases. Improving adhesive properties and adhesion strength is becoming a field of interest for many researchers to provide valuable information to the industry. Surface pretreatment is a key to increase the fracture toughness to resist separation of the joint. Usually, it involves techniques to create surface roughness, enhance bonding, increase surface energy and remove contamination. One of such techniques is the laser surface treatment which has an advantage of reducing environmental impact because it does not produce harmful substance to the environment. In addition, it provides variety of surface profiles, it is completely controllable and it requires minimum labor skills <sup>2</sup>.

### 1.1 Carbon Fiber Reinforced Polymers

CFRP is a composite material that consists a binder which known as the matrix. The binder is the main structure material that holds the entire component and form its body. The matrix consists of layers known as plies and hence they stack up to form the component. Each ply is filled with carbon fibers those provide the strength and stiffness to the substrate as shown in Figure 1.1. Consequently, the number of fibers, their directions and orientation determine the material properties based on the load directions. This explains the orthotropic behavior of

composite materials. Nowadays, composite materials are considered as a competitive choice compared to metals due to their lightweight and low corrosion sensitivity. Therefore, they are a convenient choice for aircrafts, spaceships, automotive and pipelines industries <sup>3</sup>.

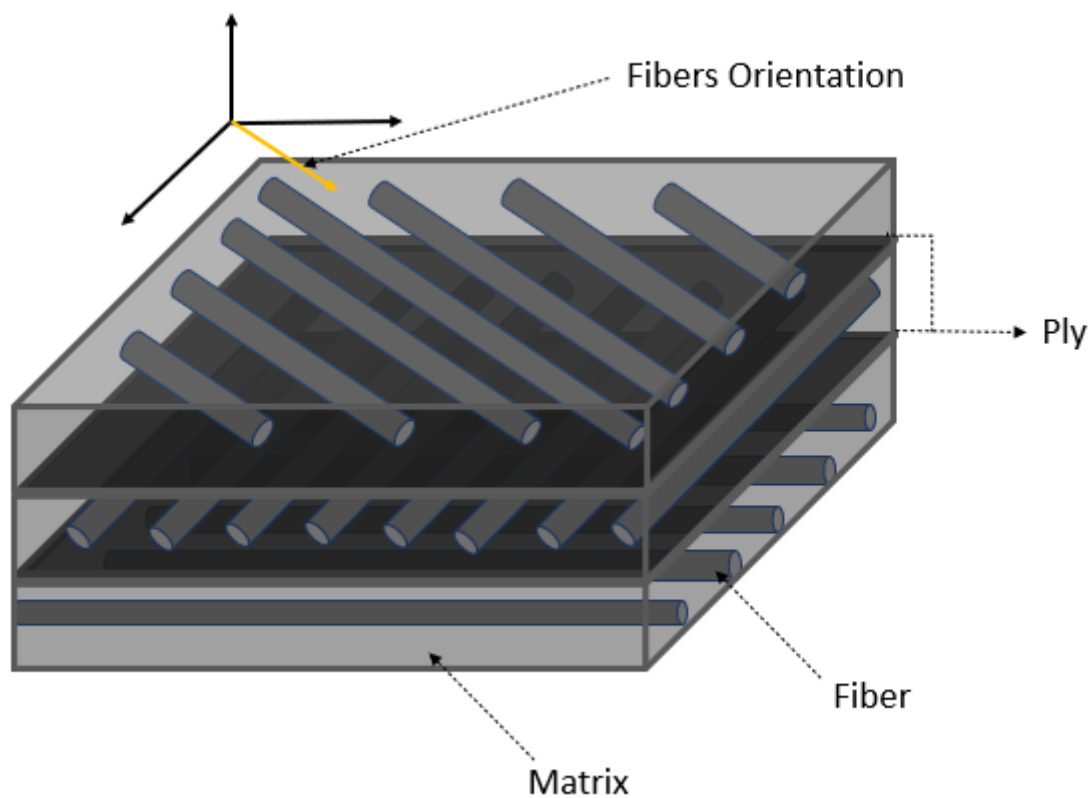


Figure 1.1 CFRP basic structure <sup>4</sup>.

## 1.2 CFRP Adhesive Joints

Fasteners, rivets and bolts are the most used elements to join parts in a structure, however, they add considerable weight because they are made of metals. In addition, the labor work of drilling

the holes and installation of the fasteners require additional labor. Holes are considered as a stress concentration region which could lead to risk of crack nucleation. Hence, adhesives can be used for such applications as they are suitable to join composite materials as well as metals.

### 1.2.1 Applications

The carbon fiber material trace goes back to the late of 1800. Due to its high thermal resistance, it was used for electrical applications. For instant, Thomas Edison made the bulb filaments from it. However, the binder material was made from nonpetroleum products <sup>5</sup>. In the middle of 1900, the material tensile strength was improved dramatically, and the material started to take its current modern shape <sup>6</sup>. Although, the strength-weight ratio was tempting, it was restricted to aerospace industry due to its high cost. At the end of the last century, aviation and automotive started to implement it as a replacement of metals <sup>7</sup>. As industries were growing in the last 30 years, concerns related to corrosion cost and failure have raised. Therefore, the high corrosion resistance of CFRP made it suitable for Pressure vessels and pipelines <sup>8</sup>.

The superior advantages CFRPs have, made them a preferred alternative in an increasing number of applications. By controlling the number of layers and the orientation of the fibers, the properties of the composite can be adjusted to fit certain design need. Thus, composites can be found in a wide range of products such as sports cars, sailing ships, vehicles, devices and fishing tools <sup>3</sup>.

Advanced engineering structures have their shares in composite materials. In aerospace industry, material is carefully selected for the main load bearing member. Hence, CFRP is used to replace Titanium in the base structure as it has a comparable strength and less weight <sup>9</sup>. In aviation, a group of midsize aircrafts manufactured in 2009 and commercialized in 2011 was made of 80% of the entire volume from composite materials. The Boeing 787, which was named “Dreamliner” has around 32000 kg made from CFRP. The load carrying members are treated cautiously by orienting the fibers to enhance stiffness against the maximum load <sup>10</sup>. The bending flexibility is another advantage added to it. The maximum deflection is higher than what can be achieved in metals. Based on Bernoulli principle the higher the speed of the air

below the wing, the higher the lifting force. Speed of air increases when the angle of the wing curvature is adjusted <sup>11</sup>. In automotive industry, the monocoque, which is the external load carrier, is designed as a shell membrane to resist bending stresses while maintaining minimal body forces. In Porsche Carrera GT, both the monocoque and the engine carrier are made from CFRP <sup>12,13</sup>

### 1.2.2 Loading and Joining Types

There are four types of common loads that adhesive joints are subjected to: <sup>14</sup>

Tensile loading: the distributed load is applied normal to the adhesive/substrate line of interface. The stresses generated in both materials and the load is intending to separate them.

Shear loading: the load is applied on the substrate parallel to the interface line. It generates shear stresses in the adhesive. It is the most common types as the adhesive has shown sufficient resistance.

Cleavage loading: a concentrated load is applied at the edge of the joint (which is?) normal to the interface plane. The load is intending to separate the two plates stressing a thick adhesive from the loading edge and creating compression stresses at the other.

Peel loading: a load is applied normal to the interface plane intending to strip the substrate from the joint. A mixture of normal and shear stresses is generated on a thin adhesive.

In designing a mating joint, load resistance is an important factor. Due to the high resistance of the adhesive joint toward shear stresses, the lap joints are the most common type. In the single lap joint, stress distribution takes place concentrating near the edges as the deformation carries out. Another common lap joint is the double lap joint which has the advantage of increasing the bonding area despite the corresponding labor difficulties. For heavy loads, scarf and stepped-lap joints are utilized with thick adhesive. However, the complexity caused by the required size precision made them less favored <sup>1,2</sup>

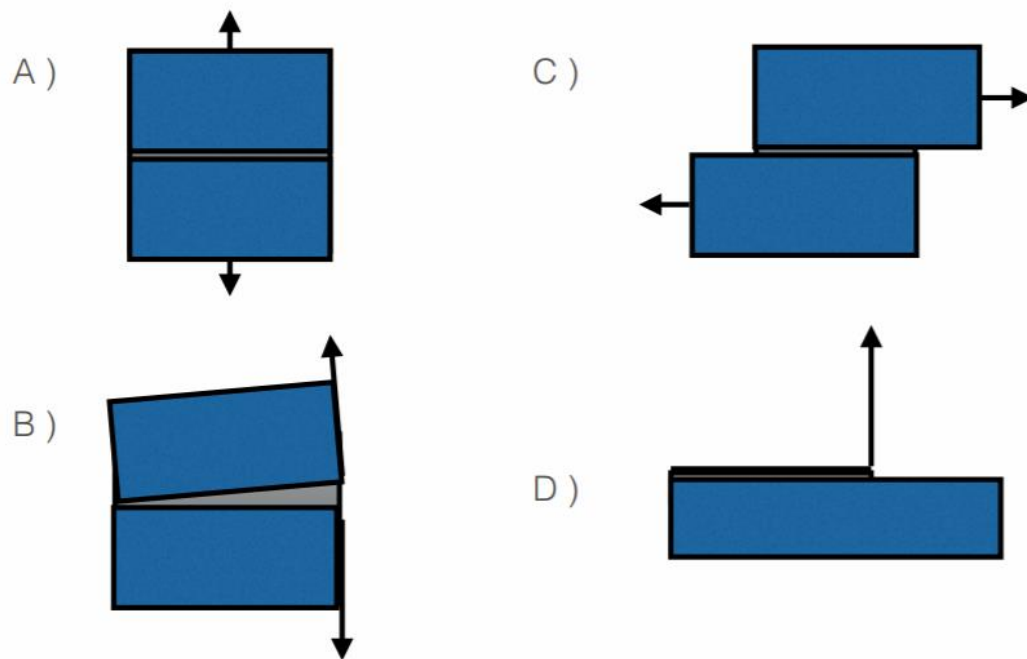


Figure 1.2 adhesive joint type of loadings where a) Tensile loading, b) shear loading, c) Cleavage loading and d) peel loading <sup>14</sup>.

### 1.2.3 Mechanical Damage

Joint members are usually subjected to different types of stresses despite the load direction and the joint type. It is commonly known that defects play a major role in damage initiation and evolution. There are three types of defects in adhesively bonded joints. First, uniform cohesive progressive failure within the adhesive layer. It is usually a result of insufficient curing of the adhesive. Secondly, voids and cavities which are known as the “gross” flaws. They usually form during the adhesive mixing stage. These defects have a major influence on the material properties like the adhesive strength. Lastly, poor surface condition. The strength of the adhesive joint is measured by the bonding energy. Presence of contamination weakens the

bond. In addition, non-uniform surface condition can lead to unexpected failure. Hence, surface pretreatment is utilized to clean the surface and increase the bonding surface. Further discussion on surface pretreatment is presented in the next section <sup>14</sup>.

#### 1.2.4 Surface Pretreatment for Joined Substrates

Surface preparation is essential prior applying an adhesive. By increasing the surface roughness and removing contaminations, an efficient bonding is achieved. Some of the most popular techniques to prepare CFRP are going to be reviewed in the below sections <sup>15</sup>.

##### 1- Sand blasting

Sand blasting is a mechanical pretreatment operation involves blasting an abrasive material using high pressure tool (e.g. air) aiming to enhance surface roughness, remove contamination and increase surface energy and polarity which increase the joint strength and the cohesive fracture toughness <sup>15</sup>. A drawback of such technique is related to the operator skills and the environmental impact resulting from the disposals of the abrasive particles in addition to the ununiform surface cuts that may cause fibers damage.

##### 2- Peel ply

Peel ply is a widely used mechanical surface pretreatment method in aerospace industry and is basically performed by applying fabrics those are laminated on the CFRP surface. While it removes some of the surface layers, the fabrics generates a surface roughness before it is rapidly taken out. In addition, as the peel ply cover remained on, it keeps the surface clean during handling and transportation[1],[2]. However, research has shown considerable surface contamination from the released agents of the peel ply.

### 3- Plasma surface treatment

The surface can be treated by plasma radiation which creates a surface roughness to enhance bonding in order to achieve higher joint toughness. This method has an advantage compared with the mechanical methods in term of surface integrity by removing contamination and activating the CFRP surface energy without damaging the matrix or causing fiber pull out <sup>17</sup>. Although the radiation method has little environmental impact compared to chemical treatment, it causes minor adjustment of surface morphology <sup>1</sup>.

### 4- Laser surface pretreatment

Radiation of laser on CFRP surface causes material removal in a selected pattern beside cleaning the surface from contaminations. There is yet no standardized tool from laser ablation due to the required variation of ablation pulse wavelength which is essential to create different surface energy sites. Various laser tools used including excimer, Nd-YAG and CO2. The last one has much smaller wavelength compared to UV and provides higher speed and larger area. Just like plasma, laser ablation pretreatment has little environmental impact, but it creates deep cutting, therefore, it has to be carefully handled to avoid surface damage. In addition, it requires fewer manual skills than chemical and mechanical techniques due to the preset parameters and in many cases robotic handler. Tao et al (2018) has used two laser treatment methods which are uniform and pattern to compare their influence of fracture toughness with both explain mechanical techniques above <sup>1</sup>.

## 1.3 Failure Modes In CFRP

Distinctively, failure modes are associated with failures in either the matrix or the fibers. To summarize the failures in CFRP, the following list is made <sup>4</sup>:

#### 1) Fibers Failure:

- a) Fibers brakeage due to high stress along the fiber axial direction.

- b) Fiber pull out from the matrix due to the weak cohesive bond.
- 2) Matrix Failure:
  - a) Fiber matrix debonding due to manufacturing defect.
  - b) Matrix cracking due to local stresses.
- 3) Delamination:
  - a) Transfer cracks occurs parallel to the fiber direction within a ply.
  - b) Intralaminar fracture which normal to the ply direction and could involve more than ply<sup>18</sup>.
  - c) Interlaminar fracture which is simply a split between two plies<sup>18</sup>.

## 1.4 Numerical and Analytical Background

Progressive failure due to cyclic loading is becoming a field of interest because large proportion of structural failure is related to fatigue loading. For instant, life estimation in aviation is measured based on periodic inspection of fatigue crack size. Hence, modeling can provide insight of estimation of a component damage tolerant. To estimate a structure life, a model that can comprehend geometric complexity is required. For this reason, numerical modeling is employed. In addition, Once the numerical model is validated by calibrating the results with the experimental observations, it can be employed to predict the crack growth behavior in different geometries and loading conditions that may not be possible to be achieved using analytical methods. In this section, three topics will be discussed. An analytical background related to fatigue crack growth of adhesively bonded substrate is going to be given. Next, modeling techniques for fatigue crack growth will be shown. Finally, the finite element analysis formulation will be illustrated.

### 1.4.1 Fatigue Crack Growth in Fracture Mechanics

Typically, the normal stress due to the applied force normal to a uniform surface is calculate by dividing that force by the surface cross sectional area. In the presence of a geometrical

discontinuity such as hole or notch, the residual stress parallel to the applied load ( $\sigma_y$ ) varies based on the distance from the edge. Far from it, the stress is equal to the simply calculated entity ( $S$ ). As the distance approaches the edge, the residual stress shoots to extreme values. Those values are sensitive to tip radius ( $\rho$ )<sup>19</sup>. Particularly, for a notched member, the stress near the notch edge is expressed as follow

$$\sigma_y = S(1 + \sqrt{\frac{c}{\rho}}) \quad (1.1)$$

Where  $c$  is a constant. If the notch curvature is sharp, the radius will approach zero resulting in a stress singularity. In reality, the stress in cracked members does not reach infinite values because infinitesimally sharp crack tips do not exist. In addition, the plasticity ahead of the crack tip prevents the stress from reaching infinite values. Hence, the need of fracture mechanic parameter to evaluate severity of the loading condition and possibility of crack growth is essential. In linear elastic fracture mechanics, stress intensity factor (SIF) is employed fracture parameter<sup>19</sup>.

To govern the crack growth as results of cyclic loading requires a unique relation that links stress intensity factor to the crack growth rate<sup>19</sup>. The law was established by Paris as

$$\frac{\partial a}{\partial N} = C_1(\Delta K)^\eta \quad (1.2)$$

where  $a$  is the crack length,  $N$  is the number of cycles and  $C_1$  and  $\eta$  are constants.  $\Delta K$  is the range of the SIF. This expression was exploited for other type of fracture parameters like the strain energy release rate (SERR) that is denoted by ( $G$ ) but with difference constants values. The relation is given by

$$\frac{\partial a}{\partial N} = C(\Delta G)^m \quad (1.3)$$

The energy release rate is the amount of energy transformed as fracture progresses. It is the reduction in the potential energy due to the presence of a crack. In the relation expressed earlier,  $\Delta G$  can be approximated by  $G_{max}$ .

Energy release rate became a significant parameter as it can be applied in joined materials with variety of forms like the double cantilever beam (DCB). The modified beam theory is developed to estimate the energy release rate for this form. It found a wide acceptance in the research community and became applicable in countable number of purposes <sup>20</sup>. It was successfully used for adhesively bonded composites under cyclic loading and expressed by

$$G = \frac{3 P D_g}{2 b (a + \Delta)} \quad (1.4)$$

where  $P$  is the load,  $D_g$  is the global displacement,  $b$  is the width and  $\Delta$  is the crack length correction factor as shown in Figure 1. 3. Another form is made based on Timoshenko simple theory of beam analysis. The form is given by <sup>21</sup>

$$G_{max} = \frac{P_{max}^2}{2 b} \frac{\partial C}{\partial a} \quad (1.5)$$

where  $C$  is the compliance.

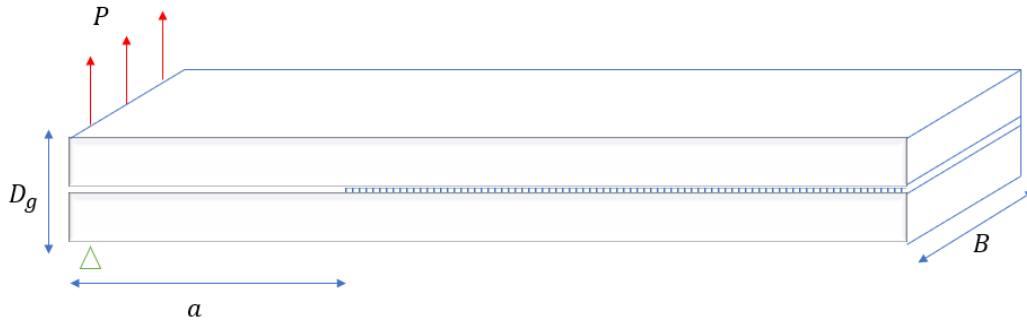


Figure 1. 3 Adhesively bonded substrate formed in DCB.

#### 1.4.2 Crack Growth Modeling Techniques

In this section, the cohesive zone model is going to be introduced. The parameters associated with the bilinear cohesive zone law will be discussed before the fatigue crack growth subsection is presented. Then, the exponential cohesive zone behavior will be explained in both monotonic and fatigue crack growth. Finally, the virtual crack closure technique will be introduced as it can be employed to estimate the maximum stress associated with bilinear cohesive zone model.

### Monotonic crack growth modeling using the bilinear CZM

The cohesive zone model is an interface damage zone ahead of the crack tip that encounter the inelastic influence on the crack growth. The interface physical interactions are estimated by a constitutive law that relate the traction to the crack tip displacement. The traction represents the material resistance to separation. In adhesively bonded substrates, the adhesive is removed and replaced by cohesive elements in finite element modeling which was implemented for delamination failure.

A fundamental form of the cohesive zone behavior is given by the bilinear traction separation law that is shown in Figure 1. 4. This relation presents the material resistance to crack growth. When separation is carried out, the joint resists it until it reaches a critical point which is maximum stress level ( $\sigma_{max}$ ). Afterwards, the joint loses strength and a dramatic propagation continue until complete failure. In principle the cohesive zone is where the joint exist and resist crack penetration as shown in Figure 1. 4. In the stage prior crack initiation, the stiffness relate the load and the displacement using the following expression <sup>22</sup>

$$K_0 = \frac{\sigma_0}{\delta_0} \quad (1.6)$$

where ( $\sigma_{max}$ ) is the maximum stress and ( $\delta_0$ ) is the onset crack tip displacement. Once the crack is initiated, the relation is established based on a damage parameter <sup>23</sup>. This parameter equals to 1 when maximum damage is reached, that is usually associated with maximum separation. In contrast, the damage parameter reaches to zero prior crack initiation <sup>24</sup>. The stress level is reduced as a result of material softening by

$$\sigma = K_0 \delta (1 - D_m) \quad (1.7)$$

The damage parameter  $D_m$  is estimated by evaluating the current onset crack tip displacement and relate it to the final and critical crack tip displacements as follows

$$D_m = \frac{\delta(\delta - \delta_0)}{\delta_f(\delta_f - \delta_0)} \quad (1.8)$$

The energy release rate represents the area under the curve and it is defined by <sup>22</sup>

$$G = 0.5 \sigma_{max} \delta_f \quad (1.9)$$

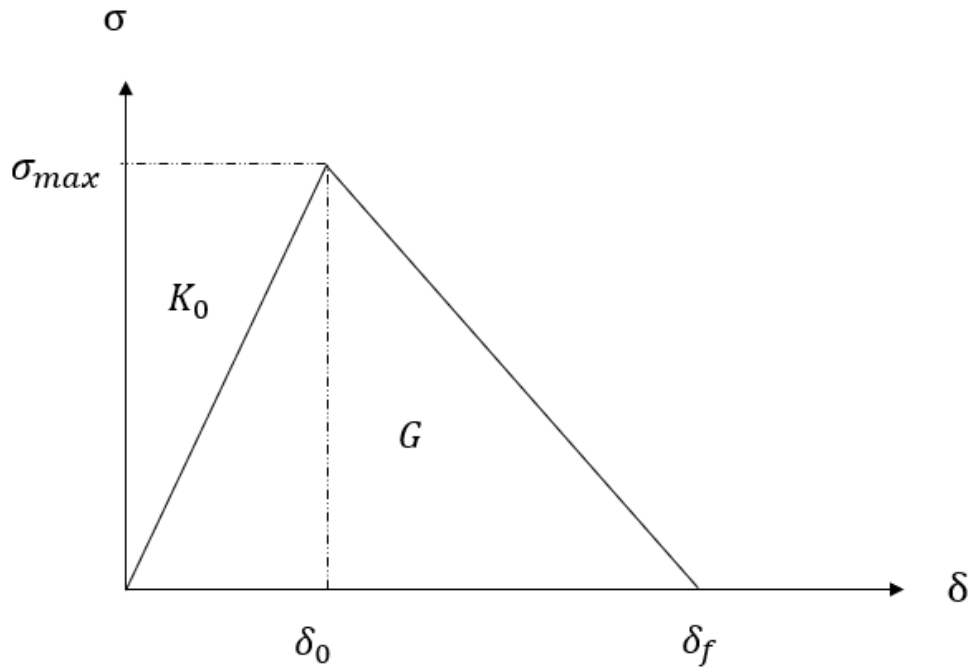


Figure 1. 4 Cohesive zone traction separation law <sup>22</sup>.

Overall, the cohesive zone parameters are defined by the energy release rate  $G$ , the maximum interfacial stress  $\sigma_{max}$ , the maximum stress associated crack tip displacement  $\delta_0$ , the failure

crack tip displacement  $\delta_f$  and the initial stiffness  $K_0$ . Three of the cohesive zone parameters must be obtained as the rest can be derived by simple triangle relations. The energy release rate is the main parameter and can be obtained experimentally. The two other parameters are the maximum stress and the initial stiffness. The stiffness is proposed by Turon<sup>25</sup> using the following form

$$K = \varphi \frac{E}{t} \quad (1.10)$$

where E is the modulus of elasticity and t is the thickness.  $\varphi$  is a number selected by the user depending on convergence severity and damage level. In general, it was recommended to be as high as possible. For instant, Turon used a value of 50<sup>26</sup>.

Obtaining the stress has been done by three methods<sup>27</sup>:

- 1- The direct method: by experimentally measuring the crack tip displacement and differentiate the energy released rate with respect to it.
- 2- The inverse method: it is a finite element model where trial and error process runs until the model's output matches the experimental data.
- 3- The property identification method: Experimentally obtaining all cohesive zone parameters.

## Fatigue crack growth using the bilinear CZM

As the LEFM has proven succession in a wide range of applications, it is not applicable for problems that involve small process zone. In contrast, the CZM was the suitable alternative as it handles large damage zone ahead of the crack tip. The constitutive behavior described in the previous section can be used for both monotonic and fatigue modeling. The monotonic damage depends on the crack tip condition. In contrast, the fatigue damage is related to the history of the progressive damage which is caused by the increment of number of cycles. The progression of damage is taken into account by updating the element stiffness. The damage parameter was derived in number of forms. The relation is selected based on its ability to reflect the actual physical damage progression. In addition, the precision of the estimated cohesive zone

parameters increases the accuracy of the damage increment if it relies on them. A relation implemented by De moura and Gonçalves where the damage is a function of Paris parameters, number of cycles, the cohesive zone model properties and outputs is given by <sup>28</sup>

$$\Delta D = \frac{\delta_f \delta_0 C r_w}{\delta^2 b l_{cz} n_{PFZ}} \Delta N \left( \frac{\Delta G}{G_{IC}} \right)^m \quad (1.11)$$

where  $r_w$  is the relative weight of each integration point in the Newton–Cotes integration scheme used.  $n_{PFZ}$  is the number of the integration points belonging to the process zone and  $l_{cz}$  is the process zone length. This relation is suitable if the cohesive zone parameters are accurately selected and hence can be highly reliable to reflect the physical damage.

Another relation is implemented in describing the damage evolution in fatigue crack growth. A number of the authors used the form that was described as a combination between the fracture mechanics and cohesive zone model. The damage relation is given by Pasco et al <sup>29</sup>. It simply relates the damage to both number of cycles and Paris constant. The form is adopted by Turon et al, Pirondi et al , and Vikas et al <sup>25,30,31</sup>. It is given by

$$\frac{dD}{dN} = \frac{1}{L_{cz}} f(\Delta G) \quad (1.12)$$

where  $dD$  is the damage variation while  $L_{cz}$  is the cohesive zone length that will be discussed later. The term  $f(\Delta G)$  is a function of the increment of the energy release rate and is given by

$$f(\Delta G) = C (\Delta G)^m \quad (1.13)$$

The final damage is equal to the accumulated cyclic damage added to the monotonic damage <sup>31</sup>. This value is used to update the cohesive zone elements and because the update involves a damage value that is different than the monotonic one, a new onset point is defined that is not

following the monotonic line. The element stiffness is suggested to be updated by Morvarid et al , Johar and Pirondi <sup>30,32,33</sup>.

$$K = K_0 (1 - D) \quad (1.14)$$

where  $K$  is the updated element stiffness. The cohesive zone length is given by equation (1.13) where the constant  $n$  is estimated based on the shape of the stress distribution ahead of the crack tip. The shape is estimated by utilizing different experimental techniques. The constant  $n$  is given in Table 1. 1. The symbol  $E$  in equation (1.13) refers to the modulus of elasticity.

$$L_{cz} = n \frac{E G_{max}}{\sigma_{max}^2} \quad (1.15)$$

Table 1. 1 cohesive zone constant length constant  $n$ .

| Source                                         | n                           | Note                   |
|------------------------------------------------|-----------------------------|------------------------|
| Rice <sup>34</sup> , Abdel Wahab <sup>20</sup> | $\frac{\pi}{2 (2 - \nu^2)}$ | $\nu$ is Poisson ratio |
| Irwin <sup>35</sup>                            | $\frac{1}{\pi}$             |                        |
| Barneblatt <sup>36</sup>                       | $\frac{\pi}{8}$             |                        |
| Hillerborg <sup>37</sup>                       | 1                           |                        |
| Pirondi <sup>30</sup>                          | $\frac{9 \pi}{32} b$        | $b$ is the width       |

## Monotonic crack growth modeling using the exponential CZM

The main need to select the appropriate type is by understanding the physics of the mating surfaces where the crack is meant to propagate <sup>38</sup>. The exponential cohesive zone constitutive behavior is another traction-separation law that can be implemented to model crack growth in both monotonic and fatigue loadings. The need for the exponential law rises for crack growth mechanisms those includes certain energy dissipation <sup>38</sup>.

The exponential shape is given in Figure 1. 5 where the area under the curve is the dissipated energy as the crack grows. The maximum value in the vertical axis is the maximum stress while the horizontal axis is the onset displacement. It can be noticed that the same principle of the bilinear traction separation law is applied in the exponential law but with different rate of damage accumulation. In general, the function of the described curve is given by the following relation <sup>39</sup>.

$$T_n = e \sigma_{max} \frac{\delta}{\delta_0} \exp\left(-\frac{\delta_n}{\delta_{ot}}\right) \exp\left(-\frac{\delta_t}{\delta_{ot}}\right) \quad (1.16)$$

The area under the curve represents the maximum energy released during the load step requires to propagate the crack and it is given by <sup>39</sup>

$$\Phi = e \delta_o \sigma_{max} \quad (1.17)$$

The monotonic damage value is obtained by the difference in the crack tip displacement divided by the onset displacement <sup>40</sup>

$$D_m = \frac{\delta_i - \delta_{i-1}}{4 \delta_0} \quad (1.18)$$

The new stress level is updated as follow <sup>40</sup>

$$\sigma = \sigma_{max} (1 - D) \quad (1.19)$$

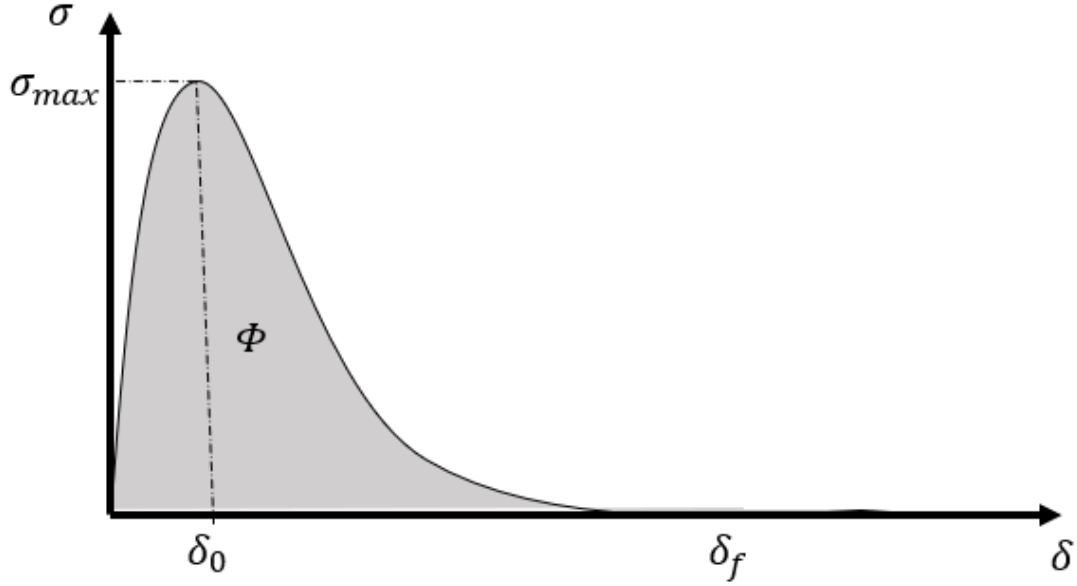


Figure 1. 5 Exponential cohesive zone traction-separation behavior.

Fatigue crack growth modeling using the exponential CZM

The fatigue crack growth takes place in the exponential constitutive behavior as well. Roe et al have established a relation that is independent of Paris parameters. The time dependent cyclic damage rate relation is obtained by <sup>40</sup>

$$\dot{D}_c = \frac{|\dot{\Delta}|}{\delta_{\Sigma}} \left( \frac{r}{\sigma_{max}} - C_f \right) H(\Delta - \delta_0) \quad (1.20)$$

where  $\dot{\Delta}$  is the difference in the maximum crack tip displacement between the current and previous time step.  $C_f$  is the fatigue limit divided by the maximum stress and  $T$  is instantaneous stress level.  $H$  is the Heaviside function of the difference between the current crack tip displacement  $\Delta$ , and the onset displacement. The symbol  $\delta_\Sigma$  refers to the accumulated crack tip displacement. The damage is finally obtained by integrating the damage rate with time. The integration is simplified by Zhang and Tabiei <sup>41</sup> by summing the damages of each time step

$$D = \sum \dot{D}_c dt \quad (1.21)$$

### Monotonic Crack Growth Modeling Using VCCT

The virtual crack closure technique is another method to obtain fracture parameters and simulate the crack propagation. The technique can be implemented to estimate the maximum traction stress for the cohesive zone model. It was introduced by Irwin et al <sup>42</sup> and has been used in parallel with the other methods. In cases where it is applicable, it has given similar results to the ones obtained from the cohesive zone model <sup>30</sup>. The main fracture criterion is the energy release rate and hence if the maximum value is reached, the crack starts to grow. It is evaluated by the following relation according to Rybicki and Kanninen <sup>43</sup>.

$$G_I = \frac{1}{2 \Delta a} [F_{yi}(u_{yk} - u'_{yk})] \quad (1.22)$$

where  $F_{yi}$  is the crack tip nodal force and the  $(u_{yk} - u'_{yk})$  term is the total crack tip element displacement.

### 1.4.3 Numerical Analysis Formulations

The finite element method is an engineering tool employed to solve problems those are beyond analytical capabilities. For instant, complex geometry requires finding critical points where failures may occur. In addition, nonlinear material behavior and response are analyzed without

the need for complex derivations. The benefit extends to reach simulation of deformation and failure which allow designers to evaluate materials without the need of conducting experiments. The method starts from the simple relation between the nodal displacements and the elemental strains. Also, true stresses are related to the external loads. Finally, by applying the principle of virtual work in continuum mechanics, the kinematic parameters can be related to their conjugate kinetic ones. The relation is simplified to be a stiffness matrix which holds the nodal interpolation operations. As the number of nodes increases, the stiffness matrix become larger. When all nodes are involved, the unknowns from boundary conditions and reaction forces are obtained by applying linear algebraic equations. The dependent variables like the nodal stresses are obtained afterwards.

The logical sequence of solving a crack growth problem using a numerical method is to start with the applied loads. These loads are transferred to the elements and from material to another until all dependent parameters are obtained. Just then, integration around those nodes takes place to calculate the fracture parameters.

In this section the stiffness matrices associated with the model in this work is going to be presented. The stiffness matrix of the adhesive will be explained before the orthotropic stiffness matrix is shown.

#### Elastic Four Nodes Element Stiffness Matrix for Isotropic Material

The formulation of the 2-D 4-nodes plane element is given by Griffiths. Those well-known relations have various forms, but they are all resulted in the same principle. The following details are all performed by him.<sup>44</sup>

The conventional constitutive behavior of linear elastic isotropic material is summarized by matrix of constants relating the stress and strain tensors.

$$\sigma = \mathbf{D} \varepsilon \quad (1.23)$$

This matrix of constants is expressed by

$$\mathbf{D} = \begin{bmatrix} E_1 & E_2 & 0 \\ E_2 & E_1 & 0 \\ 0 & 0 & G \end{bmatrix} \quad (1.24)$$

The shear modulus is expressed by a relation between the poison ratio  $\nu$  and young modulus  $E$ .

$$G = \frac{E}{2(1+\nu)} \quad (1.25)$$

In this model, plane stress assumption gives.

$$E_1 = \frac{E}{1-\nu^2} \quad (1.26)$$

$$E_2 = \nu E_1 \quad (1.27)$$

The stiffness matrix ( $\mathbf{k}$ ) is related to displacement matrix ( $\mathbf{u}$ ) and the load matrix ( $\mathbf{f}$ ).

$$\mathbf{k} \mathbf{u} = \mathbf{f} \quad (1.28)$$

Reformulating this relation using the minimum potential energy approach, the stiffness matrix is given by the volume integral

$$\mathbf{k} = \int_v \mathbf{B}^T \mathbf{D} \mathbf{B} dv \quad (1.29)$$

Where  $\mathbf{B}$  is the strain/displacement matrix related to the shape function by

$$\mathbf{B} = \begin{bmatrix} \frac{\partial N_1}{\partial x} & 0 & \frac{\partial N_2}{\partial x} & 0 & \frac{\partial N_3}{\partial x} & 0 & \frac{\partial N_4}{\partial x} & 0 \\ 0 & \frac{\partial N_1}{\partial y} & 0 & \frac{\partial N_2}{\partial y} & 0 & \frac{\partial N_3}{\partial y} & 0 & \frac{\partial N_4}{\partial y} \\ \frac{\partial N_1}{\partial y} & \frac{\partial N_1}{\partial x} & \frac{\partial N_2}{\partial y} & \frac{\partial N_2}{\partial x} & \frac{\partial N_3}{\partial y} & \frac{\partial N_3}{\partial x} & \frac{\partial N_4}{\partial y} & \frac{\partial N_4}{\partial x} \end{bmatrix} \quad (1.30)$$

The shape function is related to the co-ordinate system by

$$x = \sum_{i=1}^3 N_i x_i \quad (1.31)$$

$$y = \sum_{i=1}^3 N_i y_i \quad (1.32)$$

### Orthotropic 4-nodes Stiffness

Due to the difference of its material properties along the axis of rotational symmetry, the orthotropic material is considered as a subset of anisotropic materials <sup>45</sup>. Classifying it as isotropic material will not result in acceptable results. For this reason, the stiffness matrix is expressed in different stiffness terms ( $Q$ ) in the stress strain relation

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & Q_{13} & 0 & 0 & 0 \\ Q_{12} & Q_{22} & Q_{23} & 0 & 0 & 0 \\ Q_{13} & Q_{23} & Q_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & Q_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & Q_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix} \quad (1.33)$$

Those components are related to the elastic constants by

$$Q_{ii} = \frac{E_i (1 - \nu_{jk} \nu_{kj})}{\Delta} \quad (1.34)$$

$$Q_{ij} = \frac{E_i (\nu_{ji} + \nu_{ki} \nu_{jk})}{\Delta} \quad (1.35)$$

Where  $i, j$  and  $k$  can have the values 1, 2 and 3 but they are not equal in the same relation. The symbol  $\Delta$  is given by

$$\Delta = 1 - \nu_{12} \nu_{21} - \nu_{23} \nu_{32} - \nu_{31} \nu_{13} - 2 \nu_{31} \nu_{21} \nu_{32} \quad (1.36)$$

For the rest of the components

$$Q_{44} = G_{23} \quad (1.37)$$

$$Q_{55} = G_{13} \quad (1.38)$$

$$Q_{66} = G_{12} \quad (1.39)$$

Some of the constants can be simplified by relating them to each other. For instant, the plane stress can be assumed resulting in

$$E_2 = E_3 \quad (1.40)$$

## 1.5 Failure Characterizing Using X-Ray Tomography

### 1.5.1 Principle of x-ray emission

A filament in a vacuum tube is heated by rising the electrical voltage to a level so high that the filament generates a beam of electrons which transfers to a target material where it collides with its atoms. The filament is known as the cathode and the target as the anode where the incident of the x-ray wave generated <sup>46</sup>.

When the beam of electrons collides with the target it can generates two types of X-ray waves<sup>47</sup>.

- Characteristic X-ray. some of the beam electrons knock out an electron in the target and then recovered by a higher-level electron that dissipate amount of its energy in form of x-ray. This type of x-ray has a sharper signal and depending on the electron levels it may generate more than one signals as can be seen in Figure 1.6.
- Continuous X-ray. a continues low intensity wave generated when the beam electron scattered as it approaches the nucleus.

Both X-ray waves can be used based on the type detector and application <sup>48</sup>.

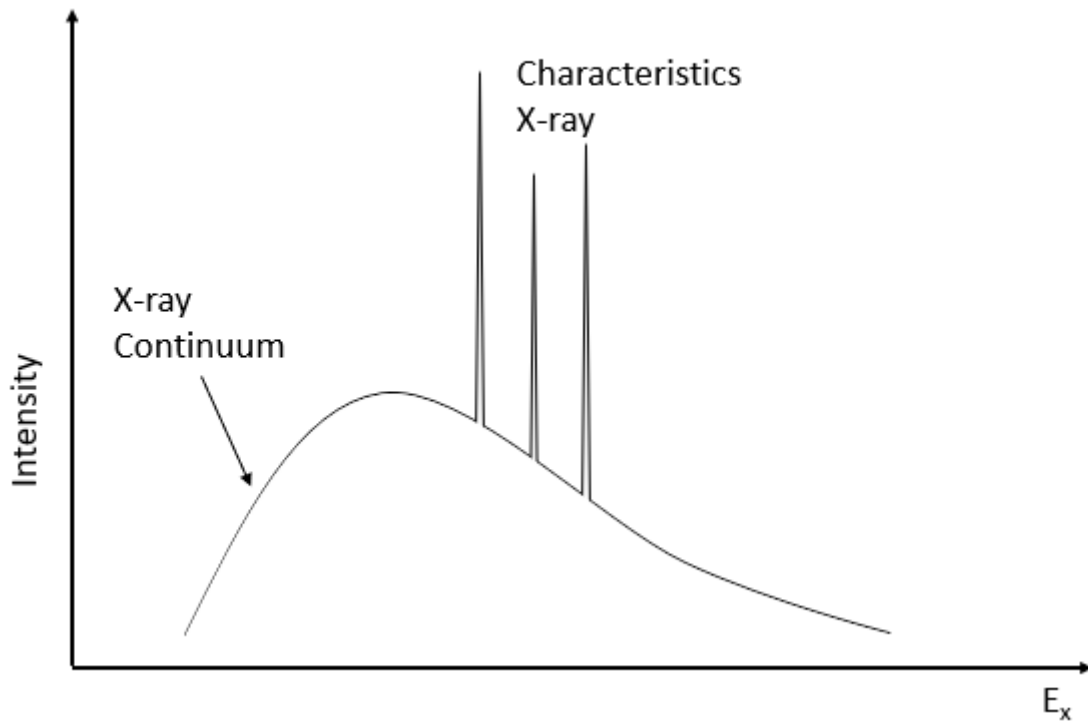


Figure 1.6. The signal of both continuous and characteristics X-ray emissions <sup>48</sup>.

### 1.5.2 X-Ray Tomography

X-ray has been an important source of imaging since their invention days to investigate substrates for various of fields including medicine and material science. Initially the irradiation discovered by Röntgen in 1895 as an electromagnetic imaging technique. Few years later, Radon proposed a method to collect a data of the 2D projections and convert them to a 3D images using linear algebra by solving the multi-projections and construct the final image <sup>49</sup>. The first CT medical device was introduced by Hounsfield in 1970 <sup>50</sup>. Stock has presented the micro X-ray tomography at the end of the last century <sup>51</sup>. The use of the technique spread widely in material scientists specially the in the area of composite materials and material defects since 2012 <sup>52 52</sup>.

The principle is generally same as the conventional X-ray spectroscopy where the emitted wave transfer through a material and has various phase shift when it hit the detector. Every material causes a different wave phase shifting based on its atomic number and density. The rest of the energy of the wave dissipated as wave attenuation and scatter <sup>53</sup>.

X-ray source emits the wave while the sample rotates within  $180^\circ$  and up to  $360^\circ$  to generates multiple 2D spatial projects of the specimen. Each projection provides data with different phase shift that can be either a radiography generated by scintillator screen or collected as data of wavelength and amplitude. The received data then goes through calculations to reconstruct a final 3D image as shown in Figure 1.7. There are available scanning methods where the detector moves as well to create higher resolution.

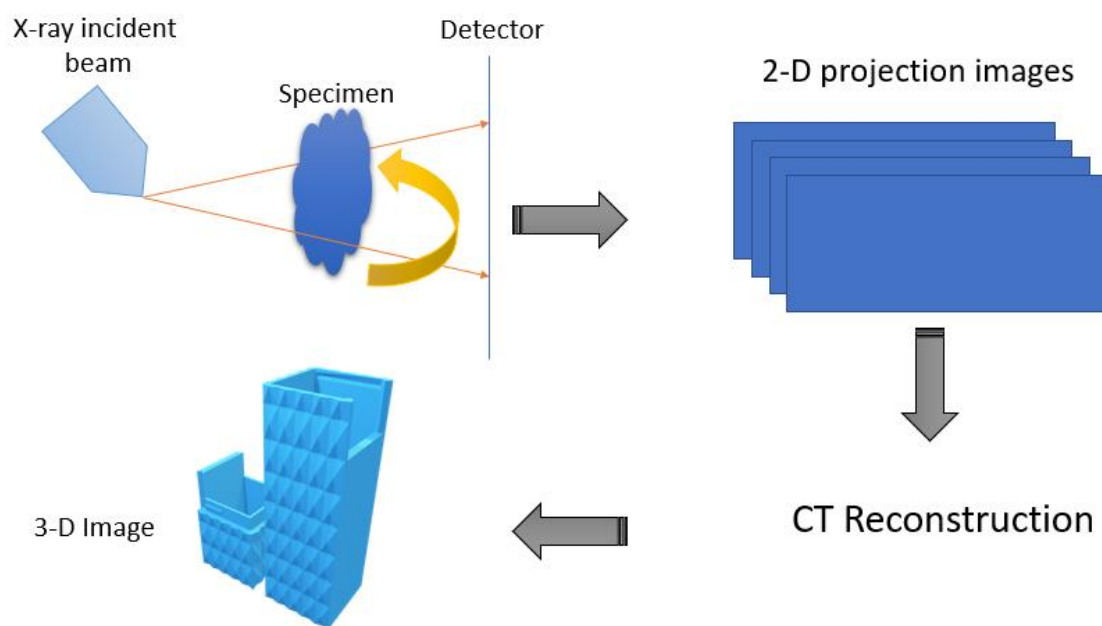


Figure 1.7. Flow chart shows the process of generation and reconstruction x-ray tomography

### 1.5.3 Image Reconstruction

As the X-ray emission passes through objects within the material, each object causes the wave to attenuate with certain measure. This difference indicates first the existence of the object and its material type. Let's assume that there is a platform with column on it like the one in Figure 1.8 and it is required to scan that column with X-ray tomography aiming to generate a high contrast image. First the source generates incidents at different angles creating many 2D shadows of the column. If one incident for instant is made, the object could be wall and if only two projection taken, the object could be a rectangular shape and so as the number of incidents increases, the object shape became clearer like in Figure 1.9. The blurred image is further filtered using Fourier transform which transfer signal from time domain to frequency resulting in sharper signals as in Figure 1.10.<sup>52</sup>

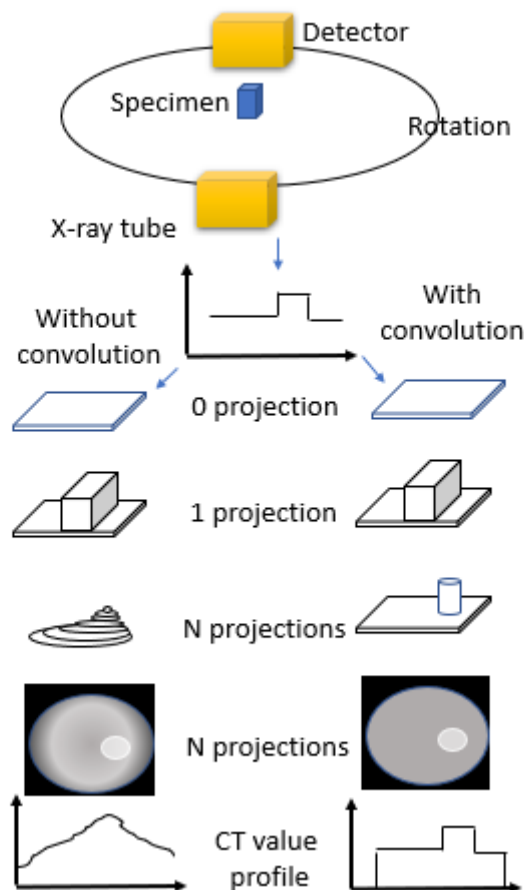


Figure 1.8. Platform with column resulting from multiple incidents and filtration can be seen in the right side <sup>52</sup>.

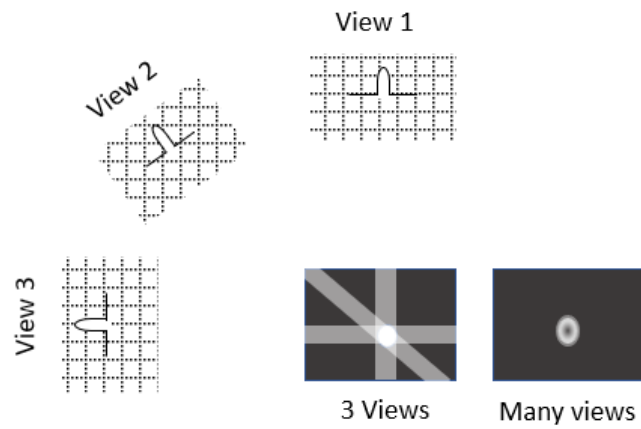


Figure 1.9. Image of a dot resulting from multiple projection with a blurred reconstructed image<sup>52</sup>.

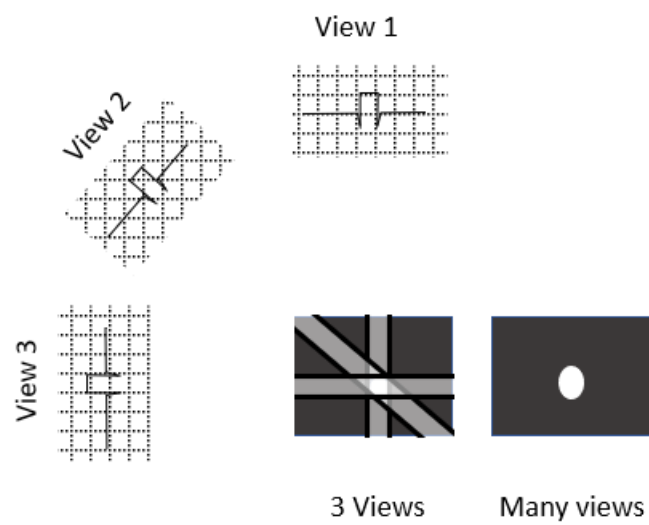


Figure 1.10. The dot image after Fourier transform filtration<sup>52</sup>.

When the measure of intensities is converted to attenuation's Radon method can be used to determine the distribution. If the scanned component divided into set of pixels where each pixel represent and unknow  $\mu$  then each incident is an addition of all the all the pixels it passes through resulting in a matrix form of  $N \times N$  where  $N^2$  is the number of the pixels, as illustrated in Figure 1.11 and hence can be solved using linear algebra <sup>52</sup>.

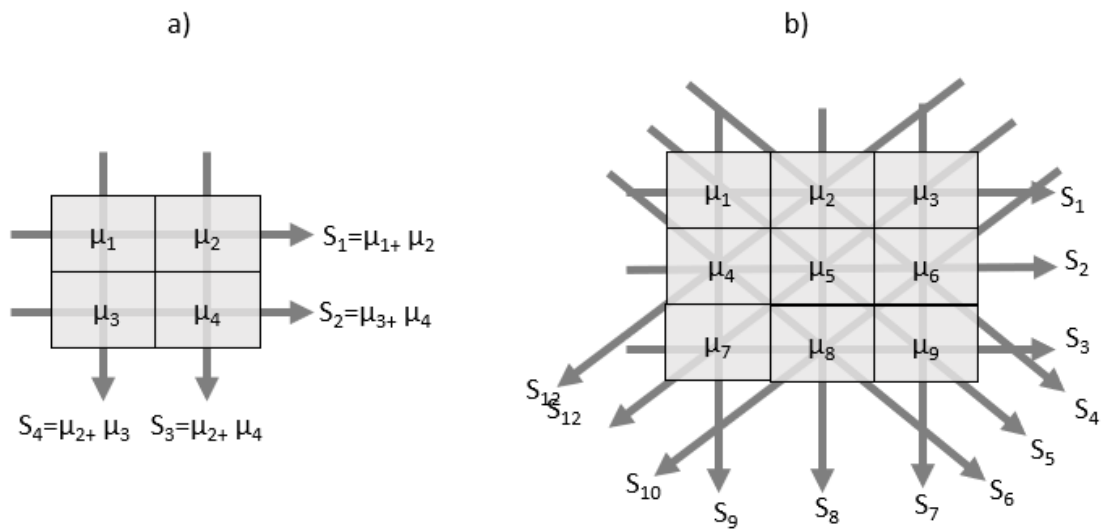


Figure 1.11. Radon method to reconstruct an image for a) four pixels and b) nine pixels <sup>52</sup>.

#### 1.5.4 Contrast and Resolution

The main unite of contrast is the pixel which is directly related to the number of the incident per cycle. The larger number of the incident, the smaller the size and of the pixel and hence the higher the contrast <sup>54</sup>. From another prospect, another element is considered which is the voxel. When an incident complete certain cycle, it proceeds to the next which creates a thickness to the pixel. This jump resulted in a 3D pixel which knowns as voxel. Generally, the crack size is not the smallest which can be detected as it was successfully detected a crack with an opening of a size that is within 5% of the pixel size <sup>55</sup>.

Basically, similar to any other computational method, it is a matter of economy versus accuracy. Maximizing the number of pixels requires more incident and consequently, minimizing the thickness of the voxel leads to dramatic increase of time particularly when dealing with microscale.

## **Chapter 2                      LITTERATURE REVIEW**

In this chapter an overview will take place showing some of the latest works associated to this work. At the beginning, it will spot the light on finite element modeling techniques. Details

related geometry, properties and assumption will be shown to be exploited in the generated model later. Afterwards, tomography images and analysis are presented. They provide insight about damages in composites in their bulk and joint forms.

## 2.1 FEM of Fatigue Crack Growth in Adhesively Bonded Substrate

Conventionally, Paris relation is the common utilized relation for such purpose. It was originally proposed to establish a relation between stress intensity factor and the rate of the fatigue crack growth <sup>56</sup>. Consequently, relation between fracture parameters became a scope of focus to generalize the use of the law which was initially performed by group of authors including Paris himself. Sih et al (1965) were able to relate the SIF to the SERR <sup>57</sup>. To avoid including crack closure effect, maximum energy release rate ( $G_{max}$ ) was preferred over the difference in the energy release rate ( $\Delta G$ ) as proved by Martin and Murri (1990) <sup>58</sup>. Many applications encounter Mode I loading condition which derive authors to prefer double cantilever beam (DCB) setup for sample testing. As explained by Robinson and Das (2004), to track the crack resistance, the modified beam theory is utilized to estimate the strain energy release rate <sup>59</sup>.

ANSYS XFEM provides built-in simulator for fatigue crack propagation where the main calculated fracture parameter is the SIF. It is performed by integrating along the contours those are distributed around the crack tip. To convert it to strain energy release rate, an equation to calculate the SIF for double cantilever beam is required. There are relations available for bulk crack propagation summarized by Oñoro (1996) <sup>60</sup> and for adhesive crack propagation by Wang (1978) <sup>61</sup>.

### 2.1.1 FEM Using Fracture Mechanics Approach

Fracture parameters like SIF calculated based on stresses near the crack tip. In contrast, the ERR is obtained by calculation or conversion of SIF. Pascoe et al (2013) proved that both parameters are equivalent <sup>62</sup>. In this approach, the main applied theory is the linear elastic fracture mechanics. In addition, the extended finite element model (XFEM) is a branch from this section. It basically rely on the enrichment function which is a Heaviside function that gives a positive signal for the nodes above the crack tip plane and negative signal for the nodes below it <sup>62</sup>.

The XFEM features are given by Belytschko and Black (1999) showing that minimal remeshing is required. They have shown that crack region can be defined but not the crack path. Meaning, the crack is free to propagate within the enrichment elements. <sup>63</sup>

Modeling fatigue crack growth in adhesively bonded substrate was successfully done using XFEM by Campilho et al (2011), Fernandes et al (2015) and Stuparu et al (2016) <sup>64-66</sup>. A 2-D, Mode I and DCB geometry has shown acceptance in many cases. The adhesive is kinematically coupled with substrate and an initial crack was introduced <sup>24,66</sup>. Although the plastic zone in front of the crack tip has an influence in dissipating energy, authors has modeled the adhesive as linear elastic material<sup>66,67</sup>. The use of LEFM in adhesively bonded material has shown acceptable accuracy as illustrated by de Moura et al (2008) <sup>21</sup>.

Campilho et al (2011) have provided detailed model of adhesively bonded substrates joined by Araldite. By generating a 2-D geometry, they made the substrates materials in two parallel beams and the adhesive rectangular shape was created between them forming a double cantilever beam (DCB). Orthotropic and isotropic material properties were assigned to a solid element that was used to mesh all areas. Linear elastic isotropic properties were assumed for an Araldite adhesive. Cohesive zone relation was used to obtain associated constants. The results were successfully acceptable <sup>66</sup>.

### 2.1.2 FEM Using Cohesive Zone Model

Recent studies like the one by Camanho and De Moura (2019) on double cantilever beam setup for adhesive joints have shown that it can be modeled by finite element analysis using cohesive zone constitutive behavior which was used originally to simulate interlamination and delamination of CFRP <sup>68</sup>. Simulation of double cantilever beam tests for CFRP is considered complicated due to the contacted surfaces which has different material properties. In addition, bending of orthotropic material along with the isotropic adhesive could results in failure in the composite plies prior to adhesive contact delamination <sup>22</sup>. To resolve such complexity, if the main purpose of the work is to focus only on the mating region the cohesive zone model is used. In addition, it is suitable to generalize the mating behavior despite the bonding details. Many authors like Camanho et al (2019) and Sørensen (2002) preferred using UMAT but there are sufficient built-in models in both ANSYS and ABAQUS to simulate the cohesive zone. Generally, the CZM model has proven succession in modeling fatigue crack growth in adhesively bonded substrate <sup>69,70</sup>.

To track toughness while separation carries out along the contact length, it is convenient to observe the simulation and the experimental results in term of the pulling force and the separating displacement. During the experiment, it is considered difficult to track the crack tip but a strain gauge or DIC detector can record the separation distance which can be compared with the modeling results later. Furthermore, the model can be useful to compare different joint properties in terms of strength and resistance as performed by Lu et al (2019). Despite the tensile strength changes, the variation of the required force to separate the joint is small.

Surface treatment takes a place in the modeling by simulating the joint based on the treated patterns. One of the models suggested by Tao et al (2018) is to have two different cohesive zones in the same surface. Circled regions were modeled on the rectangular untreated surface to simulate the patterned areas, which has both higher cohesive energy and cohesive strength. Consequently, as the crack approaches the circular areas, the joint recovers its toughness and hence more force is required to proceed the separation <sup>71</sup>.

By removing the adhesive layer and replacing it with the cohesive element, the crack is restricted to propagate in 1-D plane. In contrast, the XFEM allows the crack to propagate freely within a defined region determined by the enrichment element <sup>62,72,73</sup>.

Generally, for adhesive joints, the experimental procedure followed is as per standard ASTM D6115-97 where the substrate and the adhesive are formed in DCB. The preferred frequency is up to 10 Hz with displacement control <sup>62,74,75</sup>.

### 2.1.3 Fatigue Crack Grow Using CZM

The fatigue crack propagation in cohesive zone model has been controlled by the damage parameter as explained in the background chapter. Because the monotonic crack grow mechanism is different, the entire constitutive behavior changes as damage carries out. Tabulated constants like Paris parameters were implemented in the models as crack grows in cyclic loading. In the literature, the crack was incremented using a relation between the damage and the Paris law. Pascoe and Abdul Wahab referred to this method as mixing between fracture mechanics and cohesive zone model <sup>20,29</sup>. This implementation was performed by number of authors like Turon et al, Vikas et al and Abdul Wahab et al <sup>20,25,31</sup>. A clear example is given by the flowchart in Figure 2.1 representing a simple form of Abdul Wahab work <sup>20</sup>.

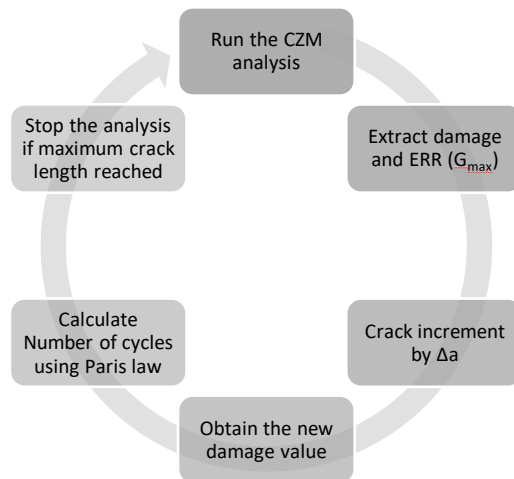


Figure 2.1 Paris law dependent FCG model based on CZM results <sup>20</sup>.

The damage base technique is adopted also by Johar et al, Morvarid et al and Pirondi et al <sup>30,32,33</sup>. They used different forms based on the need. For instant Morvarid et al used a form

based on the applied strain instead of the displacement as it is suitable for variable amplitude<sup>32</sup>. Nevertheless, they used a similar methodology as the one performed by Pirondi et al and Johar et al<sup>30,33</sup>. The flowchart in Figure 2.2 explains the procedure. It simply starts by applying the increment of number of cycles as a number in the damage relation. Then, the analysis is performed and followed by extracting the fracture parameters like the energy release rate. The new damage is calculated based on the new increment of number of cycles along with extracted variables.

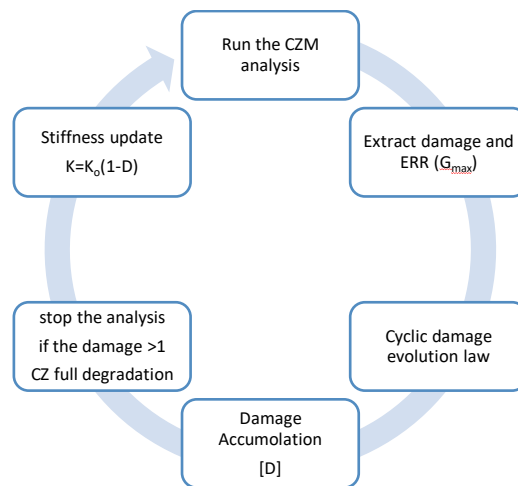


Figure 2.2 procedure similar to Morvarid et al and Pirondi et al published flowcharts<sup>30,32</sup>.

As explained earlier, the constitutive behavior associated with cyclic loading is changing but with different path than the monotonic loading. For displacement control cyclic loading, different behaviors have been reported. Some authors reported a trend higher than the monotonic behavior like Yang et al<sup>76</sup> while other authors like Vikas et al<sup>31</sup> claimed a constant crack tip displacement as the stress drops vertically. Another behavior is reported by Ural et al<sup>77</sup> is showing a curve growing below the monotonic line.

As shown in the previous chapter, the exponential cohesive zone constitutive behavior has a different handling method. Nevertheless, similar to the bilinear behavior, the damage parameter controls the crack propagation and the evolution of the constitutive parameters. The exponential curve formulation was introduced in 1998 by Xu and Needleman<sup>39</sup>. Developing a model for fatigue crack grow was done by Roe<sup>40</sup>. He found a relation for the damage increment

that is independent from Paris law. He described Paris law as mode mixity dependent and it is preferred for data correlation scheme. In general, Roe's model is a widely cited work and has been adopted by Zhang, Yeong-Hun Choi & Hyun-Gyu Kim<sup>41 78</sup>. The model is using the damage which is obtained by integrating the damage rate over time. The estimated value is used to update the constitutive behavior. Zhang suggested that the accumulated damage can be calculated based on the summation of the damage rates multiplied by the time increment of each load step<sup>41</sup>.

The interface delamination physics is the need for formulating different constitutive behaviors. When the delamination is having a unique toughness mechanism, larger energy dissipation is observed despite the low force value. For example, fiber bridging is a physical phenomenon that occurs due to the fiber exposure in the crack region. Naturally, those fibers provide higher toughness by dissipating energy and hence higher energy is required to propagate the crack. The exponential behavior is implemented by Sorensen et al for fiber bridging involvement<sup>38</sup>. Shahverdi and Vassilopoulos used it for delamination with presence of fiber bridging in fatigue crack grow<sup>79</sup>. Unlike Roe, Shahverdi and Vassilopoulos model was based on Paris law. The crack is incremented based on the number of cycles and the extracted energy release rate. The work performed by ANSYS where they used a 2D model with PLANE182 element for the substrate and INTER202 for the cohesive zone. The work provided a reasonable approach and minor results discrepancy<sup>79</sup>.

## 2.2 Tomography Observations in CFRP

To characterize failure in CFRP, it is necessary to observe pores and cracks within the material substrate and within a scale of couple to few tens of micrometers. This can be achieved by conventional microscopy but will require sample preparation, vibration free environment and probably would lead to low accuracy or unreliable results. Nevertheless, tomography offers scanning with variable resolution, relatively reasonable time and effort<sup>80</sup>.

A previous work on tomography took place in multi-scale composite models<sup>81</sup>. Crack arrest has been an interesting topic for many researchers which included pinning, retardation and

bridging<sup>82</sup>, roughness enclosure, crack deflection.<sup>83</sup> Progressive strain delamination failure of carbon fibres was studied on a notch sample<sup>84</sup>. Remarkable work of Scott et al (2012) on in situ transfers ply crack, 0° split and delamination where he proved that matrix cracks occurs in advance of fibre's<sup>85</sup>. Fatigue failure in both ex situ and in situ of Garcea et al (2016) has established remarkable results using computed tomography<sup>86</sup>. In many electronic industries a common x-ray computed tomography studies in laminar scanning.

### 2.2.1 In Situ Computed Tomography Scanning for CFRP Failure

The in-situ test provides information of the scanned specimen while the load is ingoing which allow the researcher to understand the development of the occurring failure and could explain the root and immediate causes.

Scott et al (2012) were successfully able to see the development of the failure modes in a specimen of unidirectional carbon fiber under and axial monotonic load parallel to the fiber direction. The examiner started the test with a load of 20% of the failure load and observed a transfer ply crack in the matrix normal to the load direction. As he increased the load step, a 0° split of the plies starts to generate along the load direction at around 42% of the final load. Delamination including fiber rapture started to take a place at 57% normal to the load direction. As the load stepping carries on, the three failure modes spreads around the specimen causing dramatic failures. The author eventually concluded that It was proven that matrix cracks occurs in advance of fiber cracks<sup>85</sup>.

### 2.2.2 Ex situ computed tomography scanning for CFRP failure

In many cases where the in situ test limitation prevents the tester from performing standardized setup or when the in situ testing device requires limitations of size, loading or time restrictions, it is a better option to use the ex situ test by scanning the specimen after the parametric test exposure. The scan can be performed in a post fully loading stage or between two load steps.

Cyclic loading is the most common test associated with ex situ study that allow scanning of the sample after certain number of cycles or load amplitude. Garcea et al (2016) provided a remarkable example of exploiting computed tomography when he studied the accumulation and distribution of fiber cracking and ply splitting at variety of loads and number of cycles <sup>86</sup>.

Focusing on the 0° ply, as crack grows in the section, fiber rapture during their bridging. All fibers failures are associated with the crack domain from its head to the tail which indicated its influence on the fibers as they are consequences of the ply split. From the work tomography image, fiber cracks in groups (clusters) is an important phenomena related to fatigue failure of CFRP where they have higher tendency to form at peak load of 70% of the ultimate tensile strength. Generally, fibers tend to break due to matrix failure at 50% UTS <sup>86</sup>.

By loading the samples at different load conditions, the effect of stresses generated, and internal tectonics was observed using tomography scanning and imaging for various number of cycles. In the tomography images, it was seen that the fibers are pulling against each other at 700 cycles and they end up breaking at 800 cycles both at 50% UTS. These observations allowed the observer to have a fine counting of the number of breaks due to the matrix cracking and ply splitting at different loading conditions and number of cycles <sup>86</sup>.

### 2.2.3 In situ vs. ex situ

The in situ is clearly a method which can provide information while the loading is ongoing. This allows the tester to observe the damage evolution within the material substrate. But the size limitation of the available devices and the stability that is required make it a less favored method particularly in fatigue testing. In the other hand, ex situ test allows the tester to apply all the required parameters in any enclosed environment he/she might desires before investigating the evolution and possibly the failure using tomography scanning. Although the loads are relaxed in ex situ and some cracks might geometrically enclosed, the previous work shows reliable results due to high resolution of the microscopic x-ray tomography. For fatigue testing, it is recommended to avoid in situ tests due to the modest frequency, the limited available loading and the short number of cycles that can be achieved <sup>86</sup>.

## 2.3 Computed Tomography Observations in Adhesive Joints

Failure in the adhesive joint with a carbon fiber reinforced polymer is related to strength of the adhesive, the orthotropic strength of the connecting components and the strength of the joint, which is related to the surface pretreatment. Different scenarios could occur as an initial failure in the structure which mainly rely on the bonding strength and material properties of the mating components. The failure could be adhesive, cohesive or substrate interlaminar delamination <sup>87</sup>.

A double cantilever beam test was carried out to investigate the tectonic failure within the adhesive/CFRP interface using tomography by Oshima et al (2019). The imaging purpose is to observe cracks nucleation and propagation under mode I and mode II loading layout while the tomography device setup was as follow: “155 kV, the current was 70  $\mu$ A, exposure time was 1 s, and voxel size was 8  $\mu$ m/voxel” <sup>88</sup>. At first, the scan confirmed that crack front has a thumbnail shape. Then, the in situ test showed that crack propagates within the adhesive facing constrains under mode I while a steep crack in the section is following the path under mode II <sup>88</sup>.

Adhesives play an important rule in repairing CFRP detached part wither it occurred by delamination or by cohesive failure. Hannesschläger et al observed that the adhesive dispersed on the raptured surface (the parent laminate) after proper preparation and then the other joining surface (the repair laminate) can be reattached. After the specimen is loaded in z-direction, cracks formed in the y-direction in the three surfaces which are the parent laminate, the repair laminate and the adhesive interface. However, it can be confirmed that the orientation of the adhesive ply has no considerable influence on the failure. Also, the high content region of adhesive has the largest strain concentration which lead to the initial defect <sup>82</sup>.

## 2.4 Objectives

The main objective of this research is to model fatigue crack growth of different surface pretreated CFRP adhesively bonded joints using finite element method. An x-ray tomography scanning is utilized to observe and characterize the failure. The specific objectives are:

1. To perform fatigue experiment on CFRP adhesively bounded joints with different surface pretreatments.
2. To model fatigue crack growth using a finite element analysis by implementing a cohesive zone model.
3. To perform an ex-situ CT scans in order to present a segment of the crack surface.
4. To verify the finite element model using the experimental results.

This work is part of the cooperation with King Abdullah University of Science and Technology (KAUST). Five types of different surface pretreatments samples provided by Prof. Gilles research group were tested under cyclic loading. The fracture behaviors of selected samples were characterize using x-ray tomography.

### 3.1 Material properties and characteristics

#### 3.1.1 Carbon Fiber Reinforced Polymers (CFRP)

The substrates are manufactured in KAUST. Initially, pre-preg process is carried out by pressing layers of toughened epoxy resin with unidirectional carbon fibers before the stack is cured in an oven. Then, the substrates surfaces is pretreated by laser irradiation before the adhesive Araldite 420 A/B applied to join them. The final substrate is classified as an aerospace grade with unidirectional laminates ( $[0^\circ]$ ) and denoted as (HexPly T700/M21) <sup>1</sup>. Properties of the substrates are presented in Table 3.1 while the adhesive properties are shown in Table 3.2.

Table 3.1. CFRP mechanical properties <sup>89</sup>.

| Property                                        | Symbol     | Value  |
|-------------------------------------------------|------------|--------|
| Elastic modulus in longitudinal direction (MPa) | $E_x$      | 67,000 |
| Elastic modulus in transverse direction (MPa)   | $E_y$      | 67,000 |
| Poisson ratio                                   | $\nu_{12}$ | 0.4    |
| Shear Modulus (MPa)                             | $G_{12}$   | 5,000  |
| Volume Density (Kg/m <sup>3</sup> )             | $\rho$     | 1,550  |

### 3.1.2 Adhesive Properties

The joining adhesive is made of two component room-temperature curing epoxy (Araldite 420 A/B). Usually used for structure joints for substrate made of metals and polymers <sup>90</sup>. The properties of the adhesive and the two components are listed in Table 3.2 and Table 3.3.

Table 3.2. Araldite 420 A/B mechanical properties <sup>1</sup>.

| <i>Property</i>                       | <i>Symbol</i>   | <i>Value</i> |
|---------------------------------------|-----------------|--------------|
| <b><i>Elastic Modulus (GPa)</i></b>   | $E$             | 1.5          |
| <b><i>Failure strain</i></b>          | $\varepsilon_f$ | 4.6 %        |
| <b><i>Tensile Strength (MPa )</i></b> | $\sigma_t$      | 29           |

Table 3.3. General properties of the adhesive components <sup>90</sup>.

| <b>Property</b>         | <b>Araldite 420 A</b> |     |          | <b>Araldite 420 B</b> | <b>Mixed Adhesive</b> | <b>Test Method</b> |
|-------------------------|-----------------------|-----|----------|-----------------------|-----------------------|--------------------|
| <b>Color</b>            | Yellow                |     |          | Blue                  | Dark Green            | Visual             |
| <b>Specific Gravity</b> | ca.*                  | 1.2 | Specific | ca.* 1.0              | 1.1-1.2               | ASTM-D-792         |
| <b>Viscosity (pas)</b>  | 100-300               |     |          | 0.6-1.4               | 35-45                 | ASTM-D-2196        |
| <b>Gel time mins</b>    | -                     |     |          | -                     | 60                    | ASTM-D-2471        |

\*ca. Specific gravity

## 3.2 Sample Preparation

The samples are received from KAUST in the shape of double cantilever beams of two adhesively bonded CFRP and they are hold by the two fixtures from both sides as shown in Figure 3.1. The joining adhesive has a thickness of 200  $\mu\text{m}$ . More details about the geometry of the sample are shown in Figure 3.1. The samples were prepared by five different surface pretreatments:

- 1) Laser ablation with 30% of the maximum power
- 2) Laser ablation with 10% of the maximum power
- 3) Baseline Teflon smoothening
- 4) Peelply patterning
- 5) Sandblasting roughening

All samples were covered by a Teflon insert to smoothen the surface of the prepreg prior curing. Hence, it is considered as a reference as it has the least surface bonding energy. To prepare the sample for testing, one side was coated using white paint and equally spaced marking were made for crack measurement.

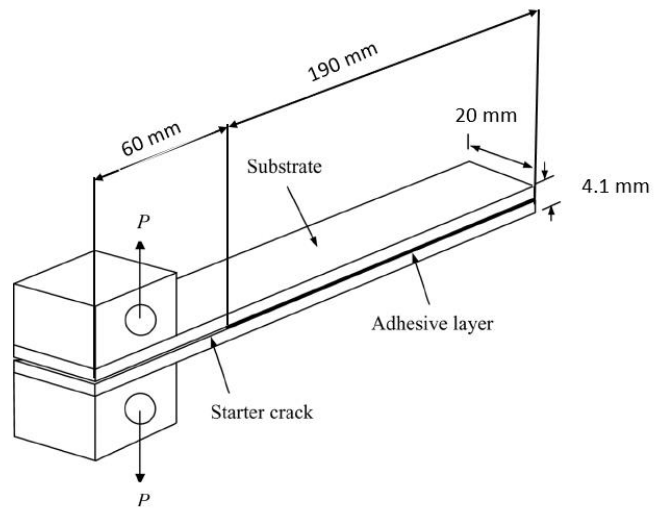


Figure 3.1 Dimensions and geometry of the sample.

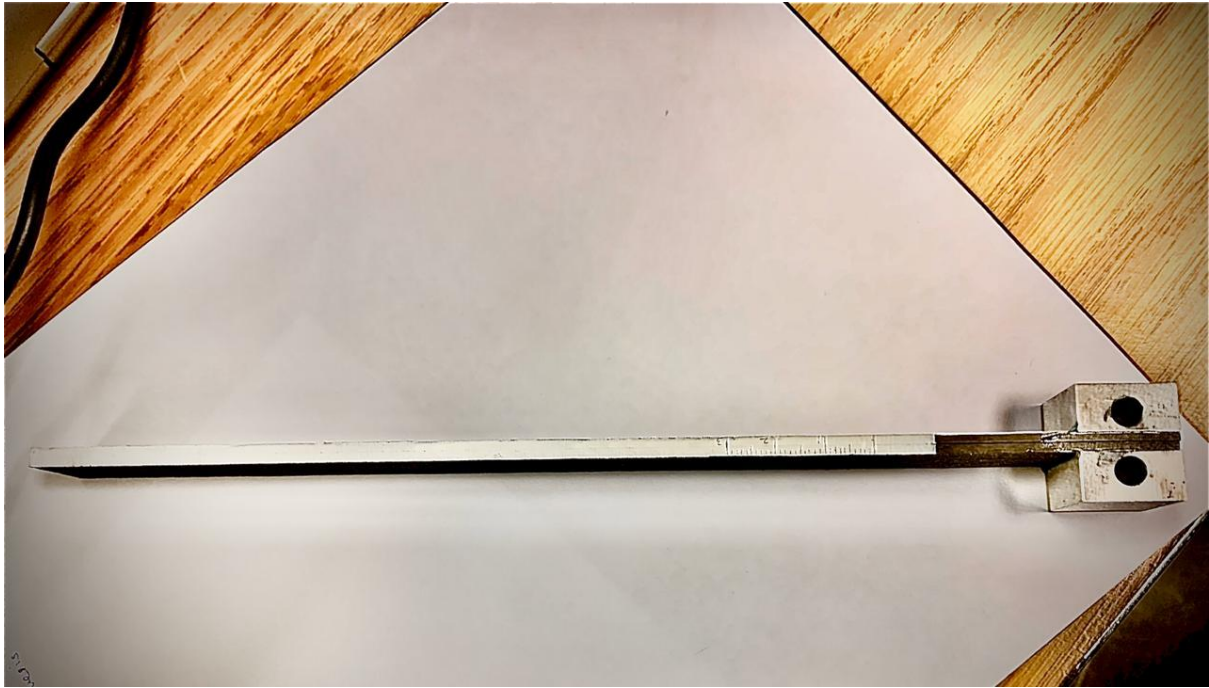


Figure 3.2. prepared samples formed in DCB for an adhesively bonded CFRP beams.

### 3.3 Mechanical Tests

A fixture was used to help mounting the samples on the grips of the testing machine as shown in Figure 3.3. The other end of the sample is fixed in lower corner to prevent vertical oscillation. A detailed drawing of the grips is shown in Figure 3.4. The Bose ElectroForce 3200 is used for testing. The machine has a force capacity of 220 N and features up to 300 Hz frequency.



Figure 3.3. The sample is placed in the cyclic loading machine and ready to be tested.

A static load is first performed at 0.01 mm/s and the crack was observed by D810 Nikon camera equipped with a SP AF 180mm F/3.5 Di lens. To monitor the crack using a computer, a software (DigiCamControl) is connected to the camera. This software has live imaging, capturing capabilities. The level of the displacement is specified to 5 mm along with the rate of opening. When the test is ready, acquisition is started, the button of the level is risen. Once the crack is initiated, the test is terminated. The displacement at the maximum load is recorded for the fatigue test and the crack image was taken.

Another method was performed in some of the samples to ensure the crack will not shoot to undesired length. The monotonic test is performed gradually. For instant, if the maximum expected level is 4.5 mm, the test is performed gradually form 1 mm and increases by 0.5 mm at each step until the pre-crack is occurred. The rate for all the monotonic steps was 0.01 mm/s.

When the sample is ready for fatigue test, The cyclic load related parameters including the next recording number of cycles, the maximum displacement (Level 2), the minimum displacement (Level 1) and the frequency are specified. The test is started by activating the acquisition before running the cyclic load.

The fatigue test carried out at 10 Hz with displacement control based on the recorded value taken from the monotonic test. All data has been recorded at every 1000 cycles except the crack extension which is estimated visually at multiple stages. The crack length is captured and recorded. Fatigue tests were performed for up to 300,000 cycles. Data are taken at the end of the test to be cleaned and analysed in order to obtain the required constant for modelling.

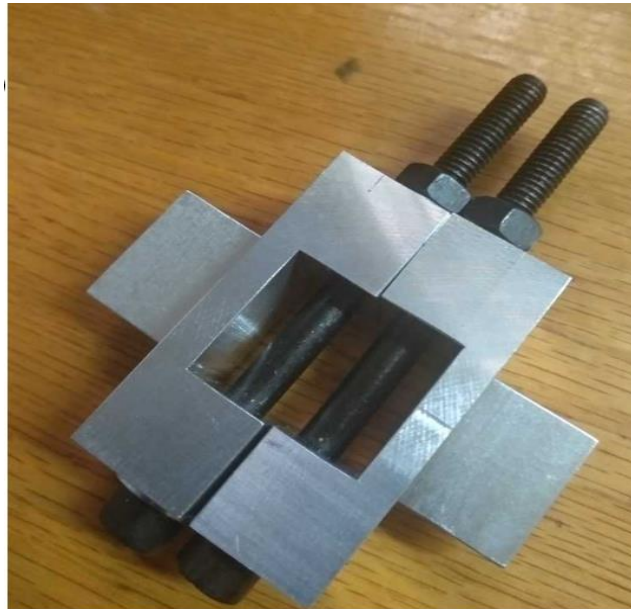


Figure 3.4 Sample gripping fixture that was manufactured and fabricated by KFUPM machine shop.

### 3.4 X-Ray Tomography Test

#### 3.4.1 X-Ray Tomography Scanner

XT H 225 ST Nikon is a high-resolution x-ray computed tomography device that utilize fault detection and failure analysis with up to 225 KV power and minimum spot size of 3.3  $\mu\text{m}$ . The beam falls on a rotating target which yields in faster measurement for high density materials with higher accuracy. It allows tilting of  $\pm 30^\circ$  to observe spatial projections at different angles and hence support the capability to observe substrate failure mode and evolution. The high resolution provides the advantage of imaging small cracks, plies splits, voids and fibers interaction with adhesive contact line.

#### 3.4.2 Sample Loading and Scanning

The main stage where samples are placed is supporting variety of platforms sizes and is designed to keep the sample standing stable. The stage offers rotation in the two axes, but it does not clamp the sample. If tilting is required, a sample fixture must be designed and installed on the stage. In this case, sample fixture was not needed as tilting of the sample was not required. Besides, Rotation speed around the longitudinal axis was 0.5 degree/second which should not cause falling or titling. For precaution, every sample goes through  $360^\circ$  rotation while being observed by the main monitor prior starting the scan.

The sample is placed on the stage on its loading edge (the block side) while the tail is pointing upward as shown in Figure 3.5. A 1 mm wide piece of paper is inserted to open the crack without causing quasi-static deformation.

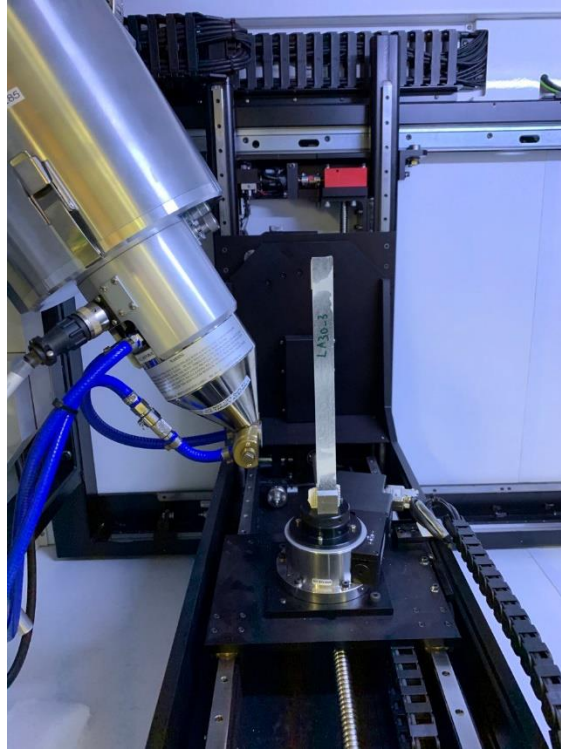


Figure 3.5 Sample is standing on the stage ready for scanning.

The scan was performed for voxel sizes between 10  $\mu\text{m}$  to 33  $\mu\text{m}$  depending on the magnification. The beam energy was roughly 110 KV with a current of 100  $\mu\text{A}$  and the power was around 10 W. The image was taken every 0.5 degree for 360 degrees of the full rotation resulting in 720 images at each section.

### 3.4.3 Reconstruction

When the sample is scanned, the slice reconstruction is performed. The volume size is established by determining the unneeded regions beyond the boundaries. Afterwards, reconstruction is executed and raw data files are generated for analysis and segmentation.

### 3.4.4 Image Segmentation

The aim here is to observe the crack path, surface and tip. The images are available as a raw data file which is added by defining the scanning setting like the voxel size, the scale type and the lattice information. The raw data is used to create a structural image that can be used for the analysis. By finding the intensity range signal, the component can be recognized. To observe a cross section, slice can be seen to understand internally the materials status and interactions.

The air density is the lowest and so it has a low intensity range. Its range can be easily identified but there is always a top hat intensity range that was not involved. There are available techniques to determine the top hat range and include it. This range is observed to be in the crack tip and the small bubbles in the adhesive. When the entire intensity range of air is established, a label is created to segment it in one surface.

More than one surface view can be created simultaneously. Some surfaces can be transparent, and some others are clearly showing. This might require a high level of performance computer. Volume fraction can be performed between the viewing surfaces at the total scanned volume or at each slice. But this is not applicable in this work because the crack can have any degree of opening. In addition, it will not provide a valuable information. Typically, it can be used for geophysics and petroleum engineering researches to estimate for example the porosity in a reservoir core sample.

Size is another important feature that can be performed in this analysis. The crack length can be measured from a reference to any interesting point. The sample dimensions can be verified particularly for important sections like the adhesive thickness.

## Chapter 4    FINITE ELEMENT ANALYSIS USING CZM

In this chapter, the model will be built by obtaining the constitutive behavior parameters required for the cohesive zone. Afterwards, the monotonic model results are calibrated by the experimental ones to ensure the validity of those parameters. The fatigue analysis can be performed by adding the cyclic damage to the damage obtained by the monotonic run. The bilinear traction-separation model for fatigue crack grow is implemented by two types of models.

The exponential cohesive zone model is implemented afterwards. The exponential model is implemented because the 30% laser ablation sample has a unique crack growth mechanism comparing with the rest of the samples. The constitutive behavior parameters are determined by a trial and error technique. These parameters are validated by comparing the load-displacement response of the monotonic model with the experimentally recorded data. Two methods are going to be performed, the first is proposed by Shahverdi and the second is by Roe<sup>40,79</sup>.

### 4.1 Strategy and Methodology

As shown in the literature, the cohesive zone model was successfully used for adhesively bonded substrates. In this work, the model will be used based on the type of the sample. Each surface pre-treatment is causing different critical energy release rate making this parameter the key for simulation. Employing the cohesive zone model requires obtaining specific parameters to represent the constitutive behavior. For the bilinear traction separation law, there are five parameters to describe the triangle shape. The energy release rate ( $G$ ), the interface maximum stress ( $\sigma_{max}$ ), the initial stiffness ( $K_0$ ), the onset crack tip displacement ( $\delta_0$ ) and the final crack tip displacement ( $\delta_f$ ).

The energy release rate is obtained experimentally. The maximum stress is usually obtained by a trial-and-error method. In order to roughly estimate the stress, VCCT is employed. The VCCT model is built with all the CZM inputs like the element's types. The energy release rate is calculated in the model and when it reaches the fracture toughness, the crack is grown. The interface stress is determined from the nodal principle stress contour of the interface nodes. The final stress value is employed in the CZM and compared with randomly higher and lower stress values. It was found that the stress levels obtained from VCCT are bringing the lowest scatter among the trial's values. The stiffness will be calculated by Torun relation while the onset and the final crack tip displacements are going to be derived by simple triangular relations. Finally, those parameters are validated by comparing the model load-displacement response with experimental data. A summary of the methodology is given by Figure 4. 1.

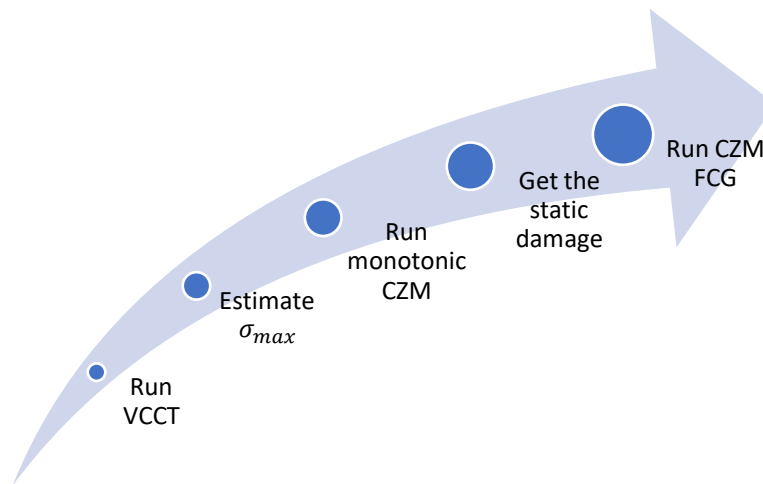


Figure 4. 1 Summary of the strategy implemented to model fatigue crack grow.

The fatigue crack grow method is performed by implementing two techniques. The first is by using Paris law to increment the crack based on the energy release rate resulted from stiffness evolution in the cohesive zone analysis. The stiffness update is controlled by the cyclic damage which is a function of the number of cycles. The second model is similar to the first model, but the crack is incremented based on the damage evolution and the change of the zone properties.

It was observed that the bilinear behavior is not sufficiently applicable in all the types of pre-treatments. Hence, the exponential behavior was examined. The reason behind this

requirement, is the toughening mechanism as was proposed by Sorensen et al <sup>38</sup>. Two exponential models will be presented based on the literature. The first will have a crack grow based on Paris law where the maximum energy release rate is extracted from the cohesive zone model. The second model is entirely independent from Paris law. The model developer claimed that Paris law is not preferred in modeling but rather for data calibration scheme <sup>40</sup>. Hence, this model will be time dependent damage-based fatigue crack grow. Finally, the results will be given and compared with the experimental data.

Before each of those models are presented the common model inputs such as the boundary conditions, the substrate material properties and the loading are going to be presented.

## 4.2 Finite element modeling inputs

In this section the common items between all the model are going to be presented. They are including the substrate material properties, the model geometry, the loading position and the boundary conditions. In addition, the experimentally calculated energy release rate that will be used for data calibration scheme will be discussed.

### 4.2.1 Material Models

The orthotropic material properties are given in

Table 3.4. They are obtained for Hexply T700/M21 unidirectional carbon fiber reinforced polymers. These properties are going to be used for the substrate in the model.

Table 3.4. CFRP mechanical properties <sup>91</sup>

| Property                                        | Symbol | Value   |
|-------------------------------------------------|--------|---------|
| Elastic modulus in longitudinal direction (MPa) | $E_x$  | 132,000 |

|                                               |            |       |
|-----------------------------------------------|------------|-------|
| Elastic modulus in transverse direction (MPa) | $E_y$      | 8,300 |
| Poisson ratio                                 | $\nu_{12}$ | 0.3   |
| Shear Modulus (MPa)                           | $G_{12}$   | 4,800 |
| Volume Density (Kg/m <sup>3</sup> )           | $\rho$     | 1,550 |

---

#### 4.2.2 Geometry

The geometric dimensions for all samples have almost the same values. All the dimensions in the longitudinal and transvers directions are used to generate a 2-D component. The adhesive is replaced by cohesive zone elements. The pre-crack is equal to the initial crack shown in Figure 3. 1 added to monotonic test crack.

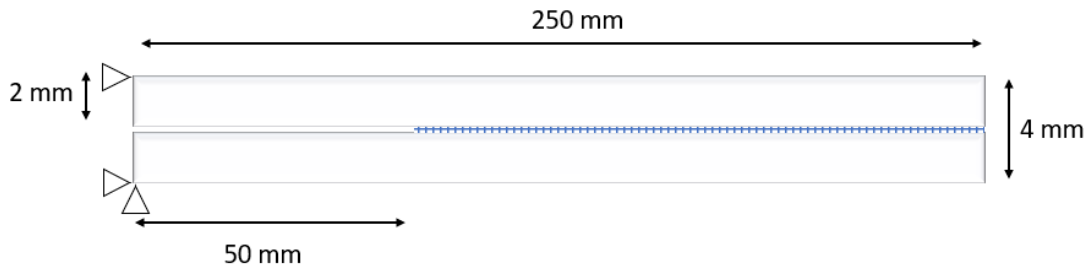


Figure 3. 1 Geometric model of CFRP adhesively bonded substrate formed in DCB.

#### 4.2.3 Loading and Boundary Condition

The load is fully applied on the top corner in the left side of the model. The boundary conditions is made by constraining the model in the longitudinal direction on the loading point. In the bottom corner of the same edge, the model is constrained in all directions as shown in Figure 4. 2.

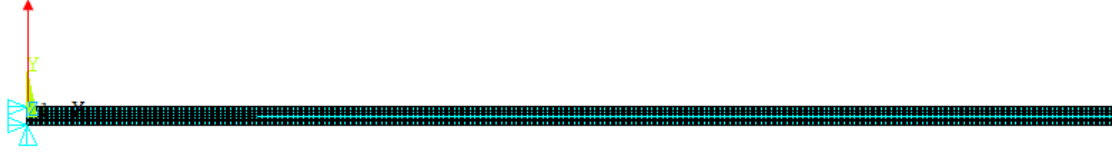


Figure 4. 2 Load and boundary conditions

#### 4.2.4 Energy release rate

The experimentally obtained energy release rate that will be used to calibrate the models results is given by two theories, the modified beam theory (MBT) and the simple beam theory (SBT). By using the modified beam theory, the energy release rate is denoted by ( $G_{max}$ ) and is calculated using the following relation based on standard ASTM D6115-97 <sup>92</sup>

$$G_{max} = \frac{3 P_{max} D_{max}}{2 b a} \quad (4.1)$$

The other form is made based on Timoshenko simple theory of beam analysis. The form is given by

$$G_{max} = \frac{P_{max}^2}{2 b} \frac{\partial C}{\partial a} \quad (4.2)$$

where  $C$  is the compliance and given by a ratio of displacement over the load. The derivative of compliance with respect to the crack length was approximated by different methods. For instant, the compliance is plotted against the experimentally measured crack length  $a$ . The fitted cubic polynomial is differentiated with respect to  $a$  <sup>93</sup>. But this method requires an accurate measurement of the crack length. The method was described by Pereira et al as suitable for microcrack and fiber bridging <sup>94</sup>. The energy released rate was formulated by De Moura et al <sup>95</sup> as follow

$$G_{max} = \frac{6 P_{max}^2}{h b^2} \left( \frac{2 a}{h^2 E_f} + \frac{1}{5 G_{LR}} \right) \quad (4.3)$$

where  $G_{LR}$  is the shear modulus in the XY direction. The equivalent effective modulus of elasticity is given by <sup>95</sup>

$$E_f = \left( C - \frac{12 a}{5 b h G_{LR}} \right)^{-1} \frac{8 a^3}{b h^8} \quad (4.4)$$

It was observed that both the MBT and the SBT were giving extremely close values as shown in Figure 4. 3. For this reason, the experimentally resulted values are going to be presented without specifying the type of the theory used.

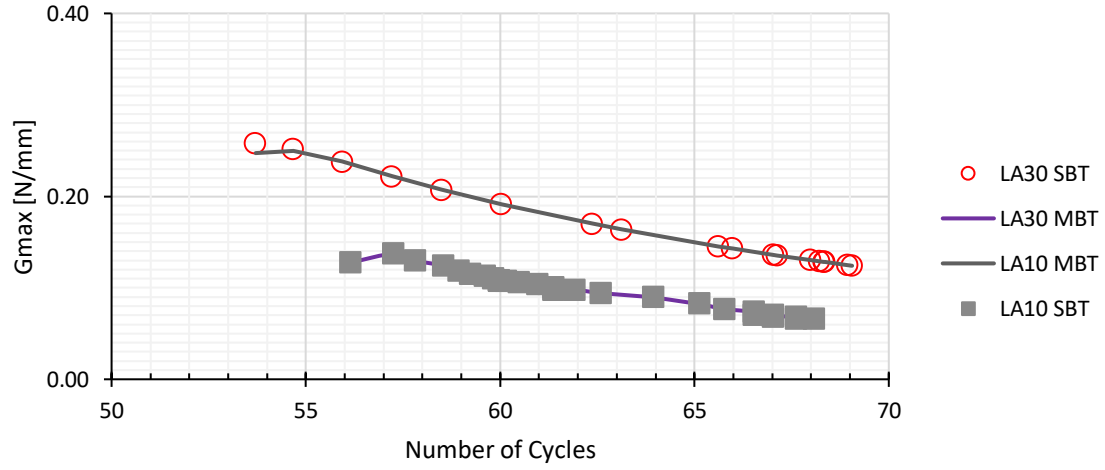


Figure 4. 3 Energy release rate obtained by MBT and SBT.

To estimate the number of cycles for a given crack length, Paris parameters are estimated from the experimental results based on the previously mentioned standard. The relation between the number of cycles ( $N$ ) and the crack extension are estimated by fitting them into a logarithmic function curve. The resulted equation must follow the form

$$a = \mu \text{Log}(N) + \lambda \quad (4.5)$$

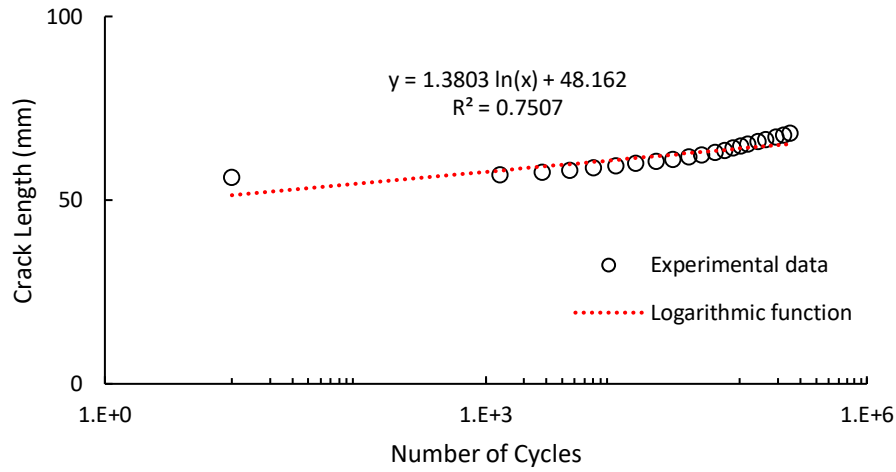


Figure 4. 4 Logarithmic relation constants obtain by fitting the curve to the associate relation for the LA10 sample.

And by taking the derivative of  $da/dN$ , it will yield to following result:

$$\frac{da}{dN} = \frac{\mu}{N} \quad (4.6)$$

This will enhance the accuracy of Paris parameters but increase the sensitivity of the recorded crack increment which will be explained further in the results section. When the constant  $\mu$  is obtained, it can be fitted to the Paris law curve to find the parameters  $C$  and  $M$ .

$$\frac{da}{dN} = \frac{\mu}{N} = C (G_{max})^M \quad (4.7)$$

#### 4.2.5 Substrate Elements Type

The main element type is PLANE182 that is typically used for modelling structural solids. Both elastic and orthotropic materials can be assigned to it. It is a 4-node that allow plain stress, plane strain and axisymmetric behaviours activated by key-options. It is the preferred element

for crack extension and the only option for fatigue crack propagation. Its geometry is presented in Figure 4. 5 <sup>96</sup>. This element is assigned to the substrate in all the models while different interface elements types were given for the cohesive zone.

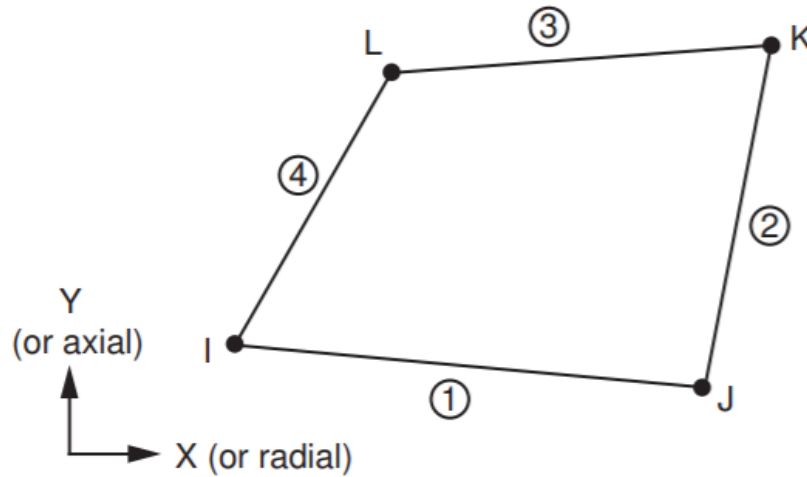


Figure 4. 5 PLANE182 element <sup>96</sup>.

### 4.3 Details of the Finite Element Modeling

#### 4.3.1 Virtual Crack Closure Technique (VCCT)

The model is made so the crack is initiated when the energy reaches the fracture toughness. In this finite element model, the fracture criteria was the energy release rate at the initial crack prior the monotonic test. The model made where the adhesive is replaced by interface elements and hence the crack path is determined by those elements. However, the purpose is only to estimate the maximum interface principle stress to be used in the cohesive zone model.

The element type that was used in this model is the interface element INTER202 that is shown in Figure 4. 6. It is a 2-D, 4 nodes interface element with 2 integration points. Two degree of

freedom are allowed while utilizing fracture mechanics constitutive behaviours that includes cohesive zone model and virtual crack closure techniques.

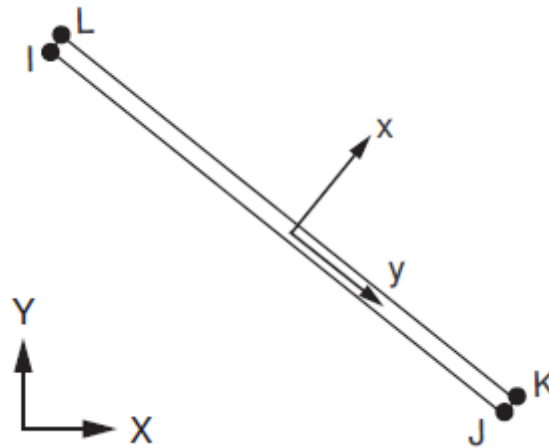


Figure 4. 6 INTER202 element <sup>96</sup>.

The model output values are shown in Table 4. 1. The resulted load-displacement response is plotted against the experimentally obtained values as shown in Figure 4. 7.

Table 4. 1 Virtual crack closure technique results

| Sample | $G_{IC}$ [N/mm] | Principle stress [Mpa] |
|--------|-----------------|------------------------|
| BT     | 0.134           | 32                     |
| LA10   | 0.227           | 42                     |
| PP     | 0.33            | 48.6                   |
| SB     | 0.504           | 53.4                   |

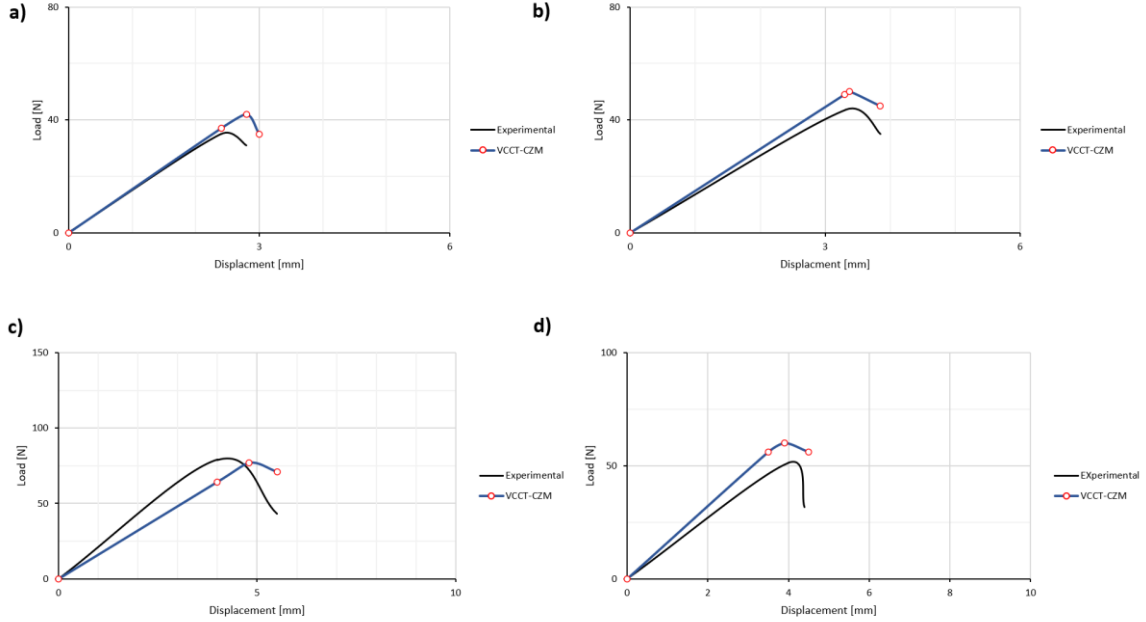


Figure 4. 7 Load-displacement response for a) BT, b) LA10, c) SB and d) PP samples.

#### 4.3.2 Bilinear Cohesive Zone Model

As shown in Figure 4. 8, the triangle shape that describe the constitutive behaviour requires five parameters to be known. Mathematically, only three are enough to define the shape and two can be derived accordingly. In this case, the onset and the final crack tip displacements will be the derived quantities. The area under the curve represent the energy dissipated to propagate the crack and that is the fracture toughness. It is obtained by the theories described in the previous section to find the energy release rate. The stress is equivalent to the principle stress extracted from the VCCT in Figure 4. 8. The stiffness is obtained by Turon<sup>25</sup> relation as follow

$$k = \varphi \frac{E}{t} \quad (4.8)$$

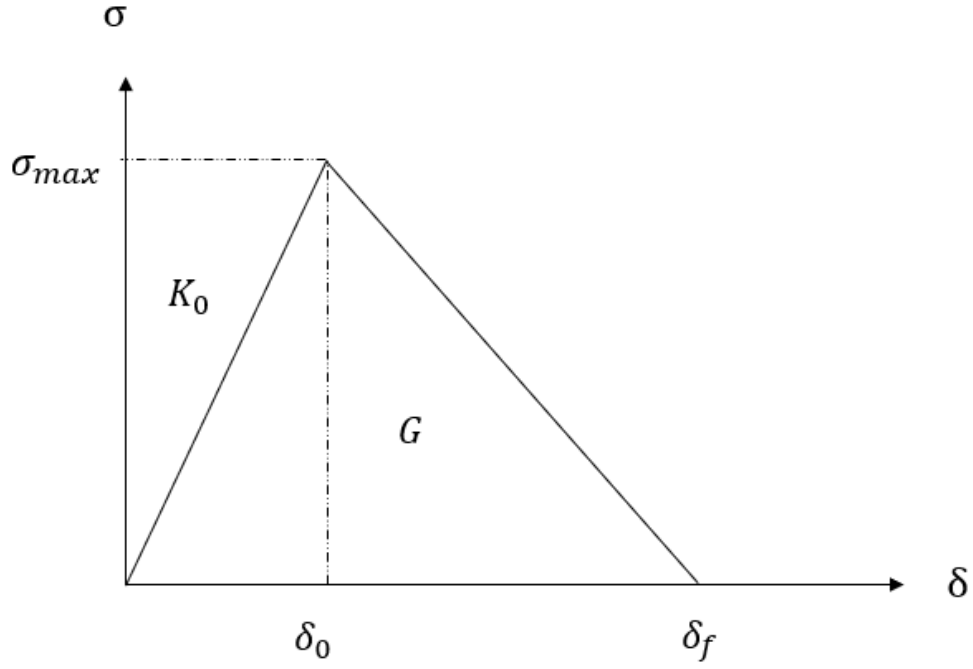


Figure 4. 8 Bilinear traction-separation law

where  $E$  is the substrate transverse modulus of elasticity and  $t$  is the thickness. The constant  $\varphi$  is suggested by Turon et al to be between 1 and 50. However, it is recommended to be much higher than one <sup>27</sup>. After a number of trials, a value of 20 was selected as it was giving acceptable results. The onset and final crack tip displacements are obtained mathematically by

$$\delta_0 = \frac{\sigma_{max}}{K} \quad (4.9)$$

$$\delta_f = \frac{2 G_{IC}}{\sigma_{max}} \quad (4.10)$$

The final material properties given for both the monotonic and fatigue models are listed in Table 4. 2. Because the monotonic results are similar to the VCCT ones, the graphs in Figure 4. 7 are considered as the calibrated results to validate the obtained CZM parameters.

Table 4. 2 The derived bilinear CZM parameters

| Sample | $\delta_0$ [mm] | $\delta_f$ [mm] |
|--------|-----------------|-----------------|
| BT     | 0.00077         | 0.0083          |
| LA10   | 0.00101         | 0.0108          |
| PP     | 0.00115         | 0.0133          |
| SB     | 0.00129         | 0.0189          |

#### 4.3.3 Fatigue Crack Grow Using Bilinear CZM

In this section, the fatigue crack grow that follows the monotonic model will take place. However, the same parameters will be used. The monotonic damage will be used as an initial condition that effect of the fatigue crack grow. This damage level represents the total damage at the beginning and the followed cyclic damage levels will be accumulated on it. The model associated inputs are going to be shown first then the damage modelling methods will be explained afterwards.

The cohesive zone element is selected to be a contact element. The contact pair have the advantage of allowing the user to relate the element stiffness to a define parameter. The contact pair has two elements, the contact and the target. The contact element is the controller and it carries all the properties while the target element responses according to it. The contact element is CONTA172 that is suitable of interface delamination and paired with target element TARGE169. It is a 2D and 2-nodes element that can be assigned for cohesive zone and damping

constitutive behaviours with two degree of freedom. A displacement rate degree of freedom can be activated as upon request. The Figure 4. 9 illustrates the contact elements shape and position.

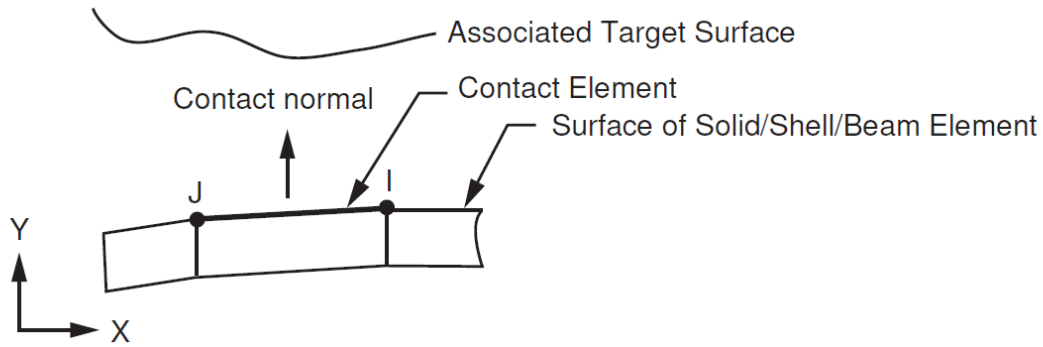


Figure 4. 9 CONTACT171 element <sup>96</sup>.

Two models are going to be given. The first is based on Paris law where the crack is growing by the obtained energy release rate from the cohesive zone model. The fatigue damage parameter is the controller of the material degradation and hence the model outputs <sup>20,25,31</sup>. It was confirmed that the fatigue damage rate is different than the one generated in monotonic loading <sup>31,76,77</sup>. The fatigue damage rate influences the entire constitutive behaviour by adjusting the element stiffness. Similar to equation (1.10), some of the relation used to obtain the damage are a function of the crack tip displacement <sup>28</sup>. Because there is a need for high quality imaging device to accurately capture the crack tip parameters, a relation that is only dependent on the energy release rate was select as there were no such measurements were performed. The term used by Turon et al, Vikas et al and Abdul Wahab et al <sup>20,25,31</sup> is as follow

$$\frac{dD}{dN} = \frac{1}{L_{cz}} C G_{max}^m \quad (4.11)$$

where  $D$  is the cyclic loading damage and  $L_{cz}$  is the cohesive zone length. A convenient relation is given by Pirondi for the cohesive zone length <sup>34</sup>

$$L_{CZ} = n \frac{E G_{max}}{\sigma_{max}^2} \quad (4.12)$$

where  $n$  is given in Table 1. 1. The constitutive behaviour is updated by adjusting the stiffness which is related by the total damage by

$$K = K_0(1 - D_T) \quad (4.13)$$

Where  $D_T$  is the total damage which is the summation of the monotonic  $D_m$  and cyclic accumulated damage as follow

$$D_T = D_m + \sum_i D_c \quad (4.14)$$

The principle of this method is based on the crack increment due to the obtained energy release rate. The finite element model is using substep iteration to obtain the new stress level that converge the solution required for the incremented crack and the updated stiffness. Hence, it establishes a new value of the energy release rate and new constitutive behaviour. The damage accumulation mechanism is illustrated by Figure 4. 10. The increment in number of cycles is influencing the damage parameter and the damage parameter causes a crack increment and new energy release rate which causes a new crack increment. The new energy release rate influences the damage parameter and so on.

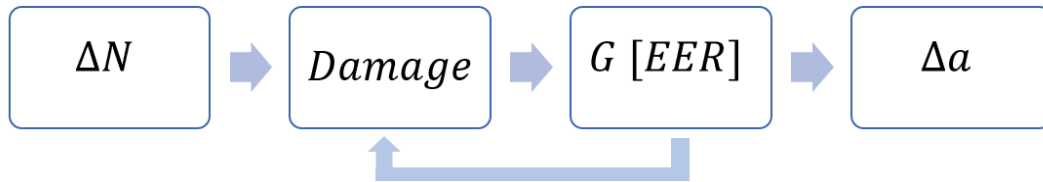


Figure 4. 10 FCG by damage accumulation mechanism

The process is illustrated by the flowchart in Figure 4. 11. It is started by running the analysis at given increments in number of cycles followed by extracting the numerically calculated  $G_{\max}$  which is used to obtain the damage. The crack is incremented by Paris law and new increment of number of cycles is given. A close method is found in the literature <sup>20,25,31</sup>.

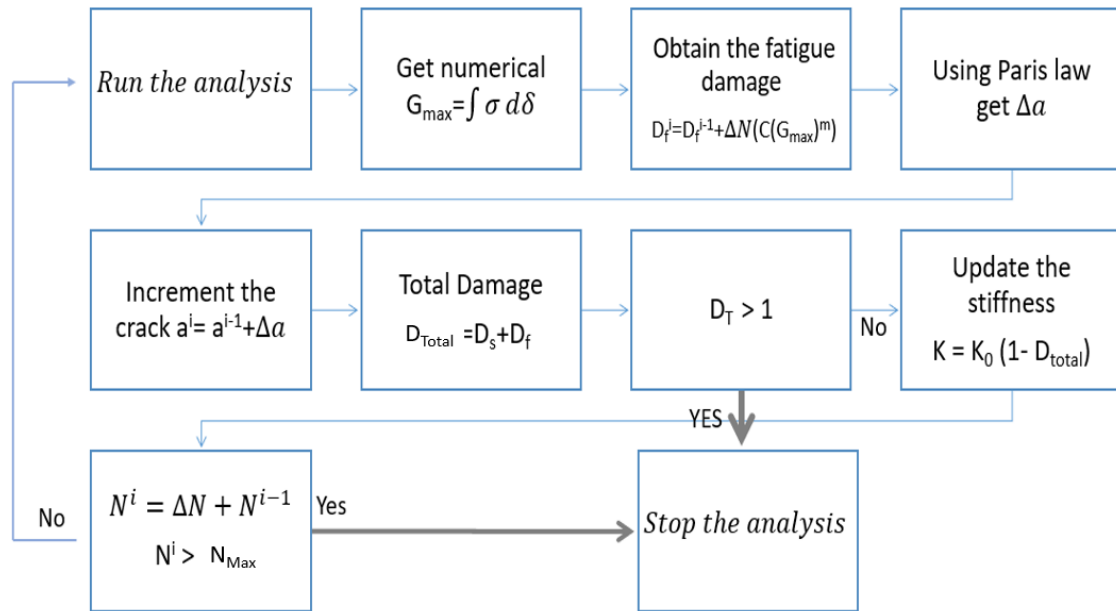


Figure 4. 11 Flowchart of bilinear CZM for fatigue crack grow <sup>20</sup>.

The second model is the same as the first model but without having the crack incremented by Paris law. Instead, the crack is incremented by the damage influence directly. To understand this mechanism, the principle of the damage influence in the cohesive zone has to be explained as it has been misunderstood by some authors as described by Leo Škec et al <sup>97</sup>. By taking the simplest form of the bilinear traction-separation law in Figure 4. 12 and compare it with the well know strain hardening phenomena. As the workpiece is displaced by certain strain, some elements may reach failure while some of them above the yield strength. When the workpiece is unloaded, a new yield strength level is defined and updated in the constitutive behaviour. A similar principle occurs in the cohesive zone model. When the stress reaches the maximum level, some elements fail as they are displaced to the final displacement  $\delta_f$  and so the crack propagates. When the model is unloaded, a new maximum stress level is given based on the damage level and the crack length.

In fatigue crack grow model, if the model is loaded while using the original material behaviour, the crack won't propagate because the load level is too low to cause crack grow unless the material become weaker. Hence, a material degradation is required which is done by the influence of number of cycles. This is taken care by the damage value as it is the main influential parameter in the element stiffness. For this reason, the model can propagate the crack between two level of material weaknesses caused by two different increments of number of cycles. The flowchart of this model is similar to the ones found in both Pirondi <sup>30</sup> and Morvarid <sup>32</sup> works and given by figure.

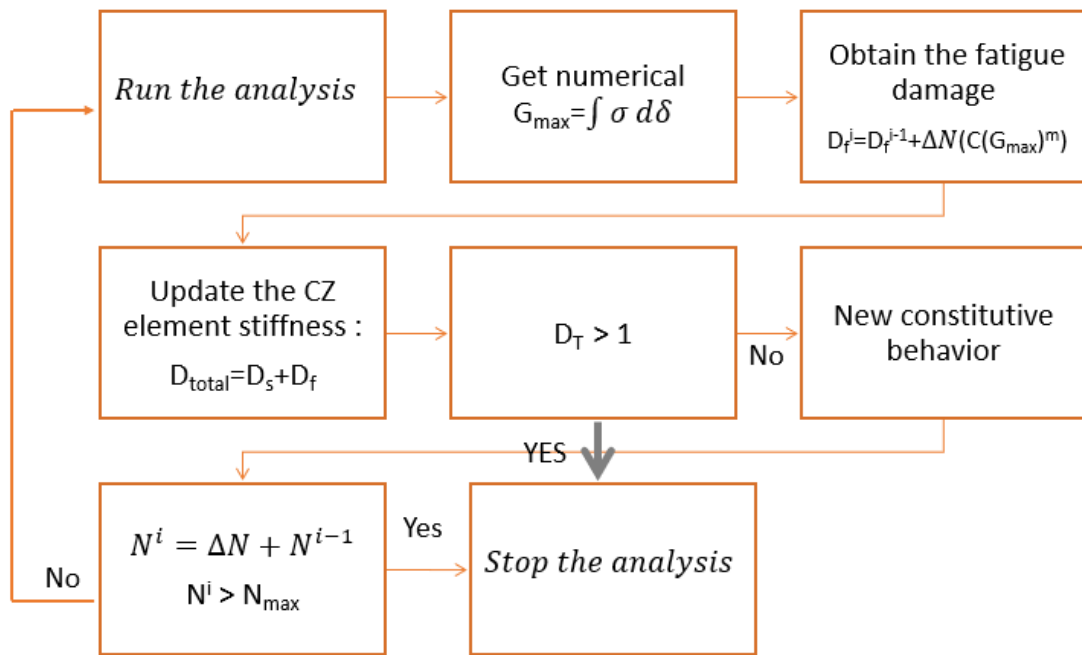


Figure 4. 12 Flowchart of the damage-based model <sup>30,32</sup>

The formulation used in this model is similar to the previous one except that the cohesive zone length is taken from the same source <sup>30</sup> the flowchart is following and it is given by

$$L_{CZ} = n \frac{E G_{max}}{\sigma_{max}^2} \quad (4.15)$$

#### 4.3.4 Exponential Cohesive Zone Model

When the VCCT and the CZM monotonic results were obtained for all the types of pre-treatments, all of them have a load-displacement response that is close to experimental outputs except one. It was observed that the laser ablation 30% have a large discrepancy as shown in Figure 4. 13. The reason is due to the fully exposed fibre those are interacting with adhesive and creating a crack arrest mechanism which lead to higher toughness. Such physics is reported but with slightly different setup. For instant, the fibre bridging in the crack surface was modelled using the exponential cohesive zone constitutive behaviour. This was implemented by Sorensen et al <sup>38</sup> in a monotonic test modelling and by Shahverdi and Vassilopoulos <sup>79</sup> in fatigue test modelling. The exponential behaviour was performed using the monotonic model and by comparing it with the results, a good matching was found.

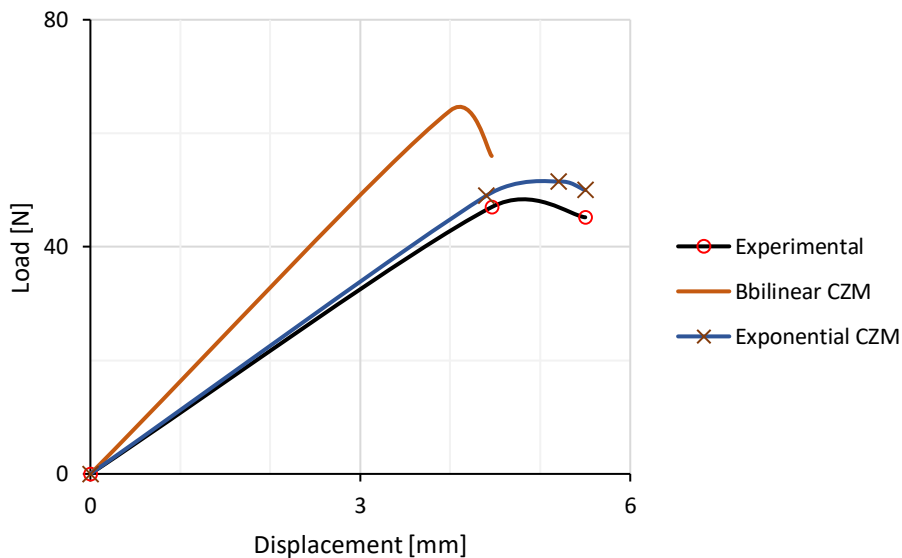


Figure 4. 13 Load-displacement response for the LA30 sample

The exponential constitutive behaviour is presented in Figure 4. 14. By applying trial-and-error, the maximum stress is estimated while adjusting the onset of displacement using the

energy release rate which is the area under the curve. The area is given by the following relation

39 .

$$\Phi = \sigma_{max} \delta_0 e \quad (4.16)$$

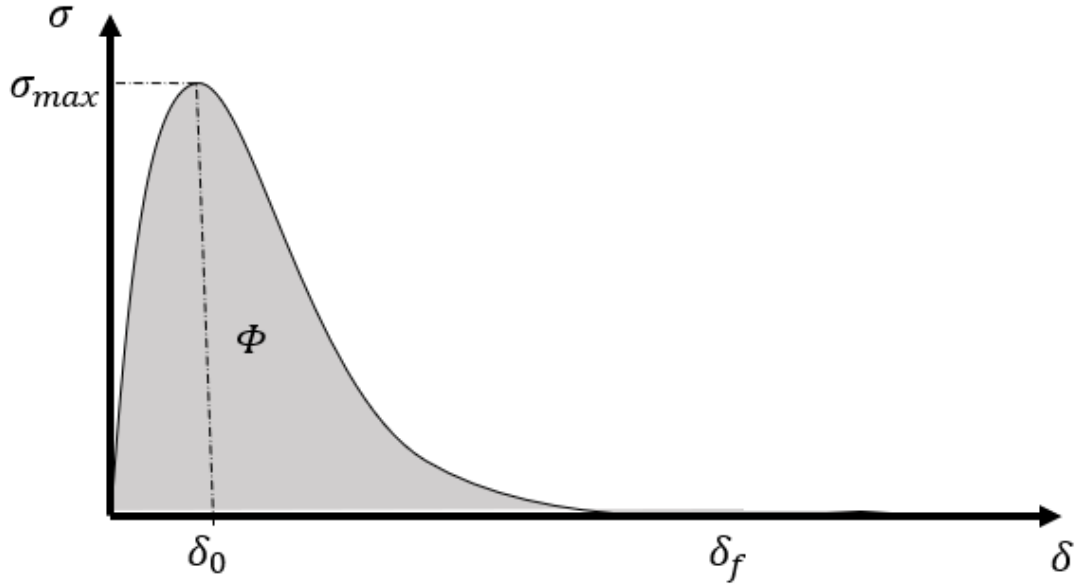


Figure 4. 14 Exponential traction-separation law.

The final crack tip displacement is obtained by plotting the traction-separation curve using the following relation <sup>39</sup>

$$T = e \sigma \Delta_n e^{-\Delta_n} e^{-\Delta_t^2} \quad (4.17)$$

where  $\Delta_t = \frac{\delta_i}{\delta_{i0}}$  and hence the mode II onset crack tip displacement  $\delta_{t0}$  is given by an arbitrary high value to suppress the mode. The behaviour is given by the plot in Figure 4. 15 and the parameters are listed in Table 4. 3.

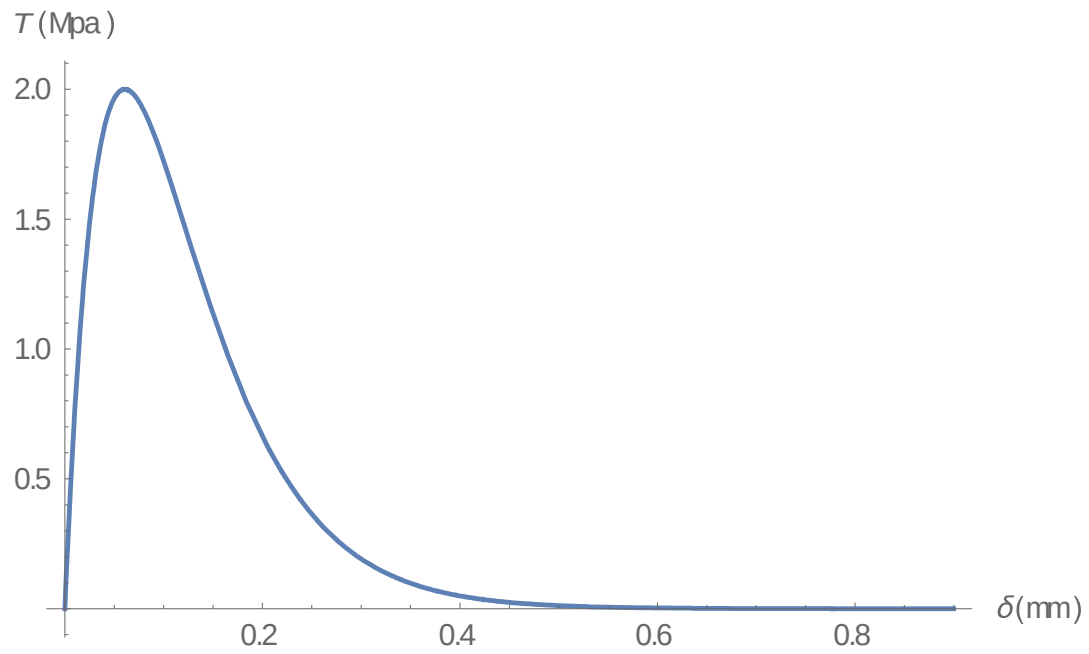


Figure 4. 15 The exponential traction-separation law for the LA30 sample.

Table 4. 3 The exponential CZM parameters for the LA30 sample.

| Parameter            | Value  |
|----------------------|--------|
| $\sigma_{max}$ (MPa) | 2      |
| $\delta_i$ (mm)      | 0.0607 |
| $G_{IC}$ (N/mm)      | 0.31   |
| $\delta_f$ (mm)      | 0.9    |

The substrate element is PLANE182 that was described in the common model items. The cohesive zone element is INTER202 that is shown in Figure 4. 16. It is a 2-D, 4 nodes interface element with 2 integration points. Two degree of freedom are allowed while utilizing fracture mechanics constitutive behaviours which includes cohesive zone model.

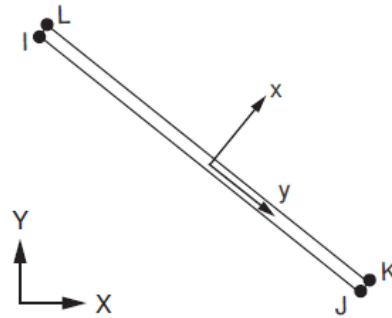


Figure 4. 16 INTER202 element <sup>96</sup>.

#### 4.3.5 Fatigue Crack Grow Using Exponential CZM

Modeling fatigue crack grow using the exponential cohesive zone model is performed by two methods. The first model is a Paris law dependent where the crack is incremented based on the energy release rate the incremented number of cycles. This model is suggested by Shahverdi and Vassilopoulos where they used Paris law to increment the crack <sup>79</sup>. This model is made to follow their exact procedure including the element types and assumptions. The procedure is given by the flowchart in Figure 4. 17.

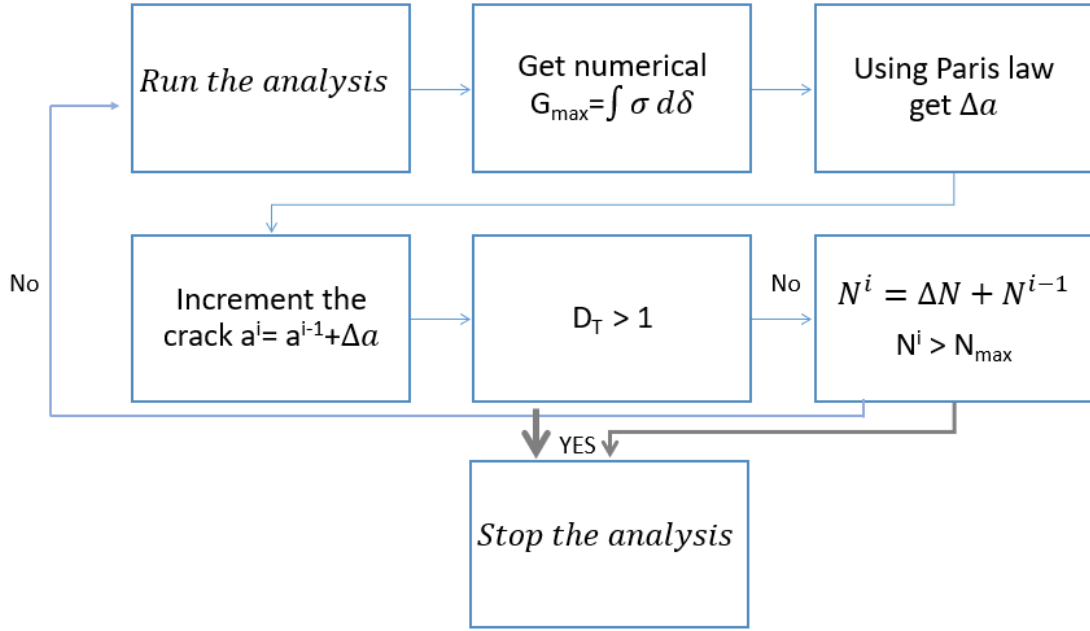


Figure 4. 17 Flowchart for Paris law dependent model for FCG exponential CZM <sup>79</sup>.

The second exponential cohesive zone fatigue crack grow model is given by Roe. It is a widely cited model that was successfully implemented by Zhang et al and Yeong-Hun et al <sup>41,78</sup>. Roe considered Paris law as suitable only for data calibration and not sufficient for modelling <sup>40</sup>. For this reason, Roe proposed a time dependent model. As described in the bilinear model, the damage is the controller of the material degradation that causes crack propagation. The same principle is applied in this case. The damage rate is given by the following relation

$$\dot{D}_c = \frac{|\dot{\Delta}|}{\delta_{\Sigma}} \left( \frac{T}{\sigma_{max}} - C_f \right) H(\Delta - \delta_0) \quad (4.18)$$

where  $\dot{\Delta}$  is the difference in the maximum crack tip displacement in the current and previous time load step.  $C_f$  is the endurance limit divided by the maximum stress while  $T$  is instantaneous stress level. This work assumes that the endurance limit is zero and hence  $C_f$  is equal to zero.  $H$  is the Heaviside function of the difference between the current crack tip displacement  $\Delta$  and the original onset displacement. The symbol  $\delta_{\Sigma}$  is the accumulated crack tip displacement. The damage is finally obtained by integrating the damage rate with time. The

term is simplified by Zhang and Tabiei <sup>41</sup> and hence this form will be adopted as this model is performed by load stepping.

$$D = \sum \dot{D}_c dt \quad (4.19)$$

The procedure follows the flowchart in Figure 4. 18. It was noticed that the smaller the time stepping, the better the result. The model was first built by using a course time stepping but rough results were given. Hence, a smaller time of 1 minute is given for each load step. The time is related to the number of cycles by the frequency that was applied during the experiment as follow

$$\Delta t = \frac{\Delta N}{f'} \quad (4.20)$$

where  $f'$  is frequency and equal to 10 Hz.

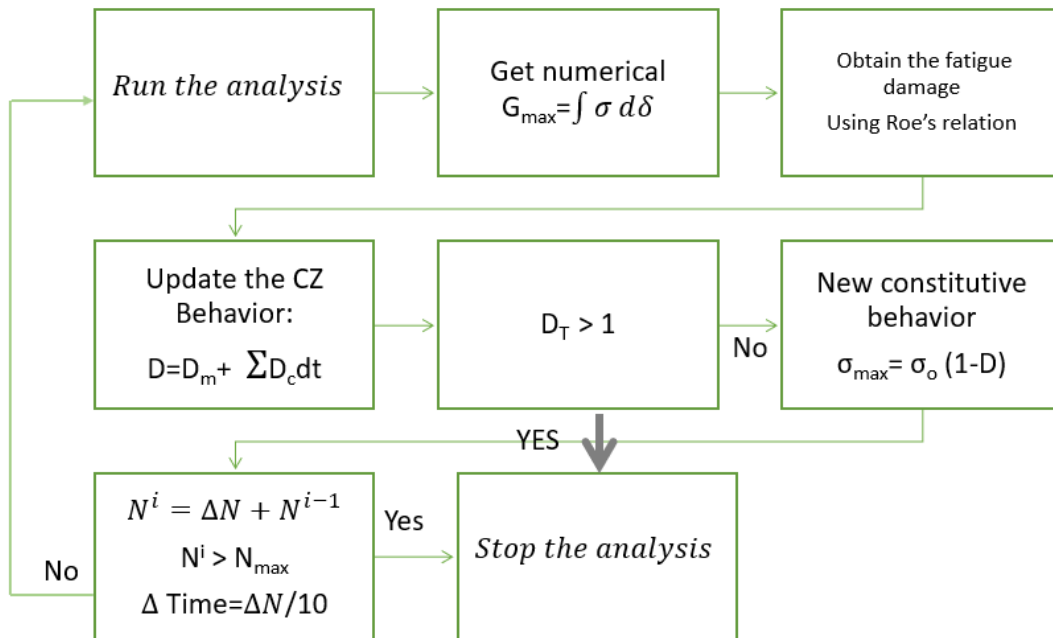


Figure 4. 18 Flowchart based on Roe's model for FCG exponential CZM <sup>40,41</sup>.

## Chapter 5      RESULTS AND DISSCUSSION

In this chapter, the results are given to compare the model outputs with the experimental values. The comparing entities are the maximum energy release rate ( $G_{\max}$ ) and the crack length ( $a$ ). A discussion is made to explain the sensitivity of the model including the time increment and the mesh size. The delamination physics is another important subject that raised the importance of having different types of models. The data calibration scatter will be explained as well. In the CZM section, four models' results are going to be shown. The models were made based on the flowcharts in previous chapter.

### 5.1 Bilinear CZM Results

The first model is the one presented by the flowchart in Figure 4. 11. It was made based on the damage rate that was given by Turon et al, Vikas et al and Abdel Wahab <sup>20,25,31</sup>. The graphs in Figure 5. 1 represents the energy released rates for each surface pretreatment. The FEM results show small scatter compared with the experimental results.

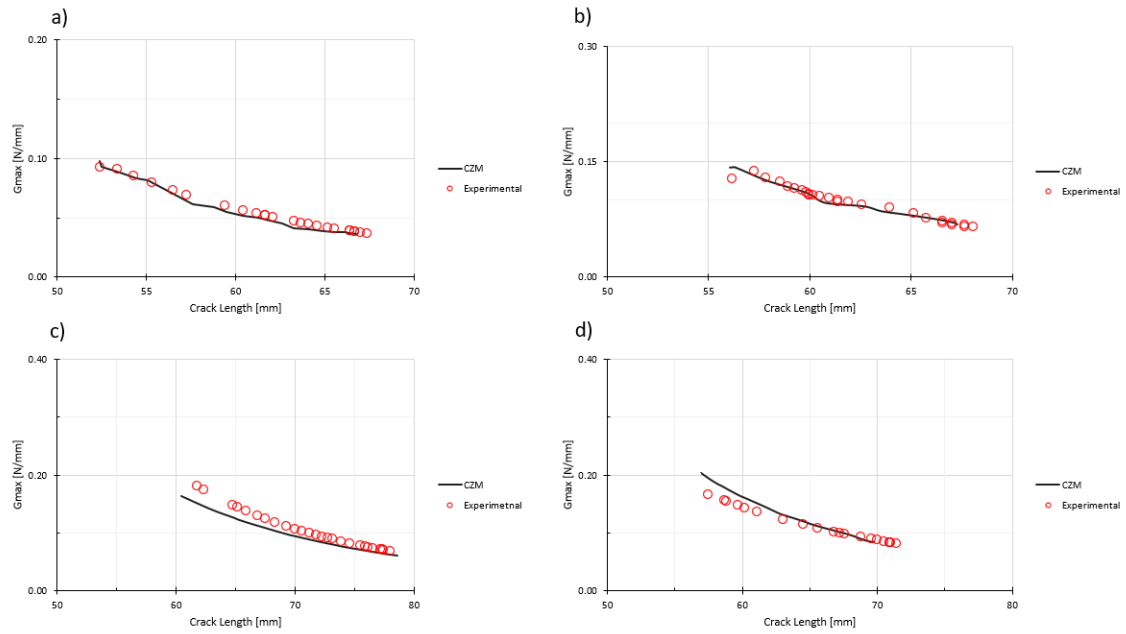


Figure 5. 1 Strain energy release rate resulted from the FEM compared with the experimentally computed values for the a) Baseline Teflon, b) laser ablation 10%, c) sandblasting and c) peel ply samples.

The crack increment due to the cyclic energy release rate is plotted against the number of cycles for each type of pretreatment are presented in Figure 5. 2.

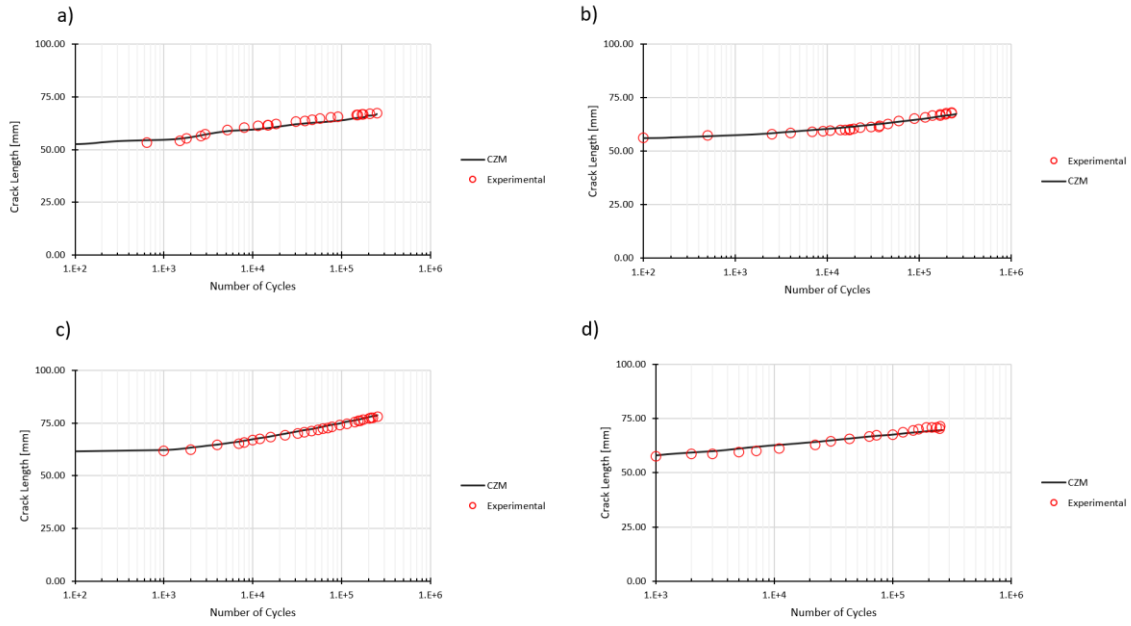


Figure 5. 2 Fatigue crack grow resulted from the FEM compared with the experimentally computed values for the a) Baseline Teflon, b) laser ablation 10%, c) sandblasting and c) peel ply samples.

The second model is the damage base model. It is made based on the flowchart in Figure 4. 12 which is based on Morvarid et al <sup>32</sup> and Pironi <sup>30</sup> flowcharts in the literature shown in Figure 2.2. The cohesive length model used is suggest by Pironi as shown in the model formulation <sup>30</sup>. The resulted energy release rate ( $G_{max}$ ) is shown in Figure 5. 3 plotted against the crack length.

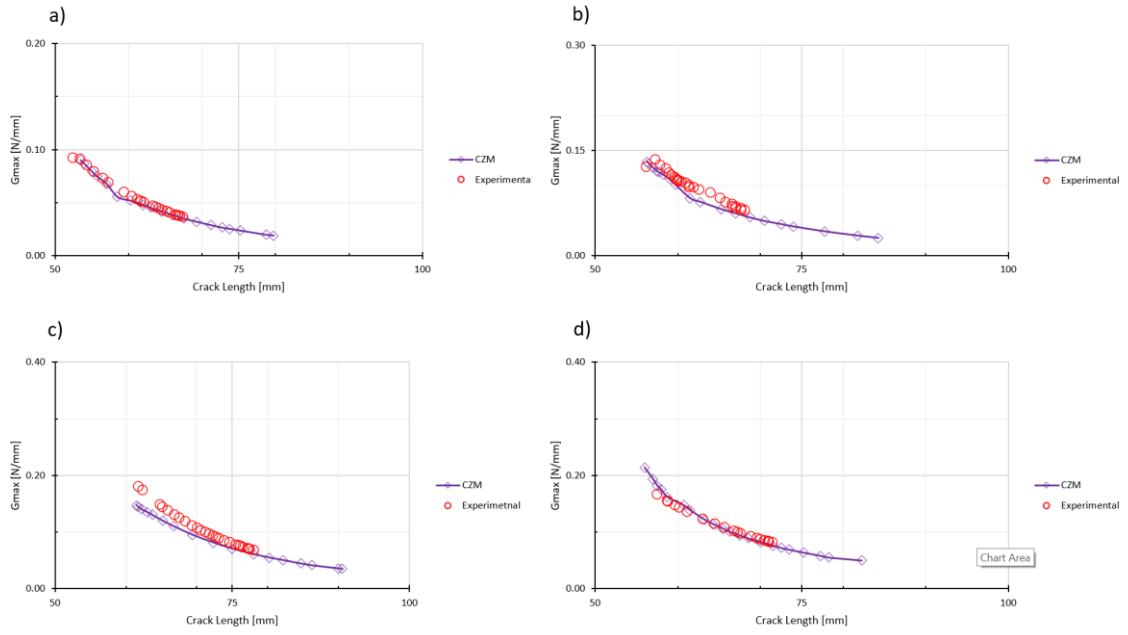


Figure 5. 3 Strain energy release rate resulted from the FEM compared with the experimentally computed values for the a) Baseline Teflon, b) laser ablation 10%, c) sandblasting and c) peel ply samples.

The crack increment due to the cyclic energy release rate is plotted against the number of cycles for each type of pretreatment are presented in Figure 5. 4.

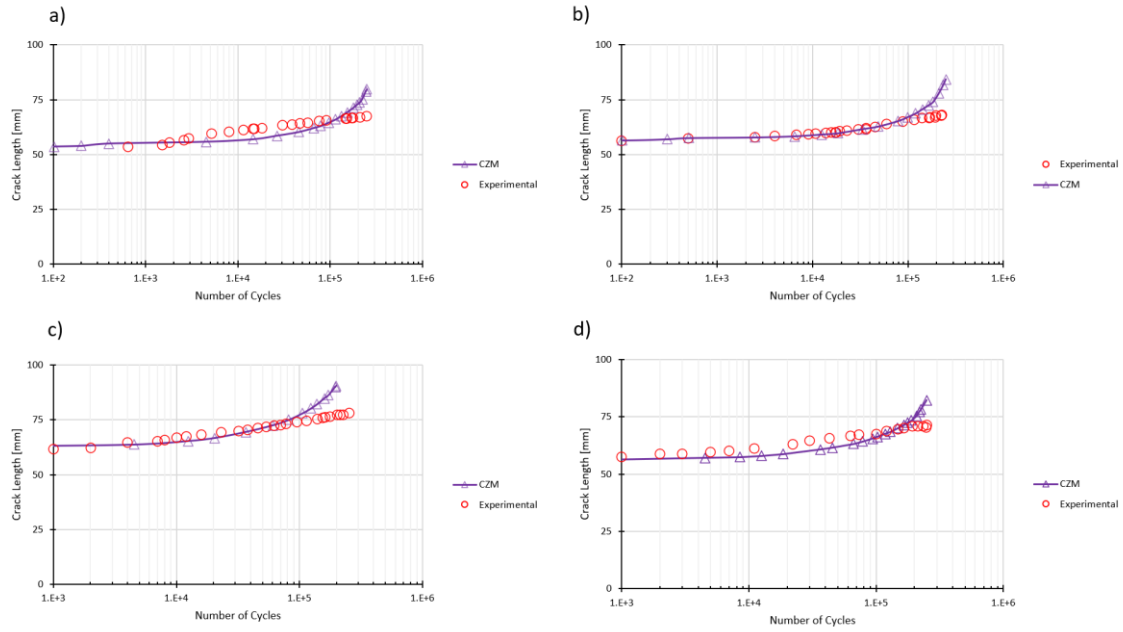


Figure 5. 4 Fatigue crack grow resulted from the FEM compared with the experimentally computed values for the a) Baseline Teflon, b) laser ablation 10%, c) sandblasting and c) peel ply samples.

It can be seen that the first model has stable and more accurate results. This is associated with number of factors. In general, CZM tends to be unstable at high number of cycles due to the high accumulation of damage as can be seen in De Moura and Gonçalves results <sup>98</sup>. For this reason, Abdel Wahab preferred using Paris law to increment the crack <sup>20</sup>. Naturally, if the test is load control, the damage rate will grow faster, and instability will be observed earlier. As the second model is damage dependent, the monotonic damage accuracy is essential to determine the starting point of the fatigue damage accumulation. Turon et al have shown that the monotonic damage plays an important role in the accuracy of the fatigue crack grow results <sup>25</sup>.

In general, to achieve the best results using cohesive zone model, the constitutive parameters should be accurate according to the load-displacement response. As per Campilho <sup>99</sup>, this can be achieved by experimental measurements of the crack tip displacement. Although, Yangjian Xu et al used trial-and-error algorithm, the resulted response had a level of discrepancy <sup>100</sup>.

Comparing with Hyejin et al results, the monotonic model load-displacement response is considered acceptable <sup>101</sup>.

In this work, the stress was obtained from the VCCT. As per Leo Škec <sup>97</sup> the technique is valid when the damage zone is small. At the first crack increment, based on the zone length relation, the damage zone is small because the stress is high making it valid for this period. By applying the stress values, a reasonable result is given in the monotonic model with a level of scatter compared with many other tested values. Pirondi et al described the techniques as it gives similar results as the cohesive zone model <sup>30</sup>.

Using small increment in number of cycles can be sufficient and bring higher accuracy but raise the cost. Just like the mesh size, there are regions where the increment in number of cycles need to be refined. Pirondi et al <sup>30</sup> used a method to calculate the increment in number of cycles that can minimize the crack grow rate oscillation while Turon et al <sup>25</sup> used a relation to calculate the skipped number of cycles. In this work, the increment in number of cycles is first given by 2000. But a sharp increment in the crack grow at the beginning has occurred making the followed outcomes not accurate. To solve this issue, the increment started by 100 cycles until the total cycles are 1000. Then, the increment is increased to 1000 until the total is 6000 where the increment became 2000 to the end of the analysis.

The mesh has shown a considerable level of influence in Pirondi et al work where three mesh sizes between 0.1 and 0.5 mm results were examined <sup>30</sup>. In this work, it was observed that this much difference in the mesh size can cause a discrepancy. The current model is made with 0.125 mm element size. In Figure 5. 5, two mesh sizes are presented for a 10,000 cycles run. It can be seen that the finer mesh provides higher accuracy in both the energy release rate and the crack length.

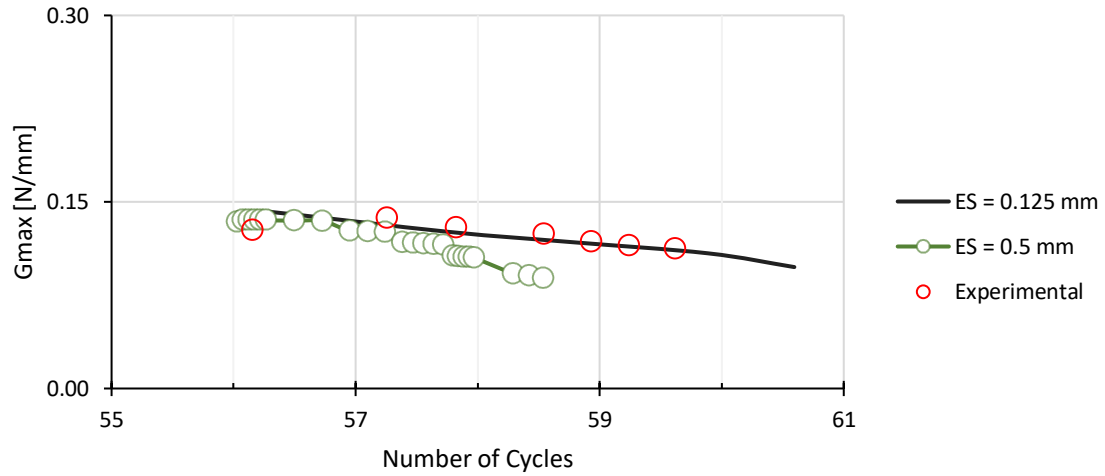


Figure 5. 5 A comparison between different element size for the LA10 results.

## 5.2 Exponential CZM Results

The exponential model is made for the 30% laser ablation pre-treatment as the bilinear traction-separation law couldn't represent its physical behavior at any strength level. The most matching load-displacement response was given by the exponential constitutive behavior. Two exponential models were performed as shown in the previous chapter. The first is similar to the one performed by Shahverdi and Vassilopoulos<sup>79</sup> and presented in Figure 4. 17. It is a Paris law dependent model. The model outputs are presented by the energy release rate in Figure 5. 6.

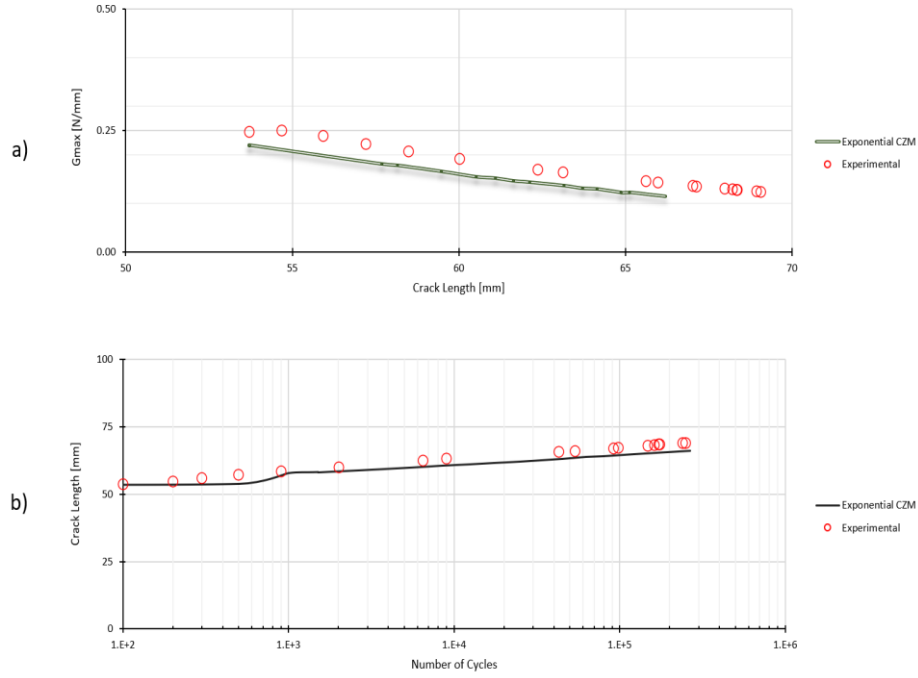


Figure 5. 6 a) Strain energy release rate and b) fatigue crack grow resulted from the exponential CZM compared with the experimentally obtained values for the LA30 sample.

The second model made by Roe <sup>40</sup>. The reference preferred using the cohesive zone model without any influence from Paris law. It claimed that the law parameters are entirely dependent on the mode mixity. However, a proposed damage relation that is completely dependent on the cohesive zone damage accumulation and material degradation was given. First, the cohesive zone initial crack grow criteria is shown in Figure 4. 15. Second, the damage rate that causes evolution of the crack grow criteria based on time increment is estimated. The instantaneous damage is obtained by integrating the damage rate with respect to time. Zhang et al used a numerical form of which the integration is replaced by a summation of the damage rate multiplied by the time increment <sup>41</sup>. Hence, the smaller the time increment the higher the accuracy based on the integration definition. Finally, the constitutive behavior is updated using the damage parameter. This procedure is an elaboration of the model described in Figure 4. 18. The resulted energy release rate is plotted against the time estimated in minutes in Figure 5. 7. In this case, the time is related to the number of cycles by the frequency.

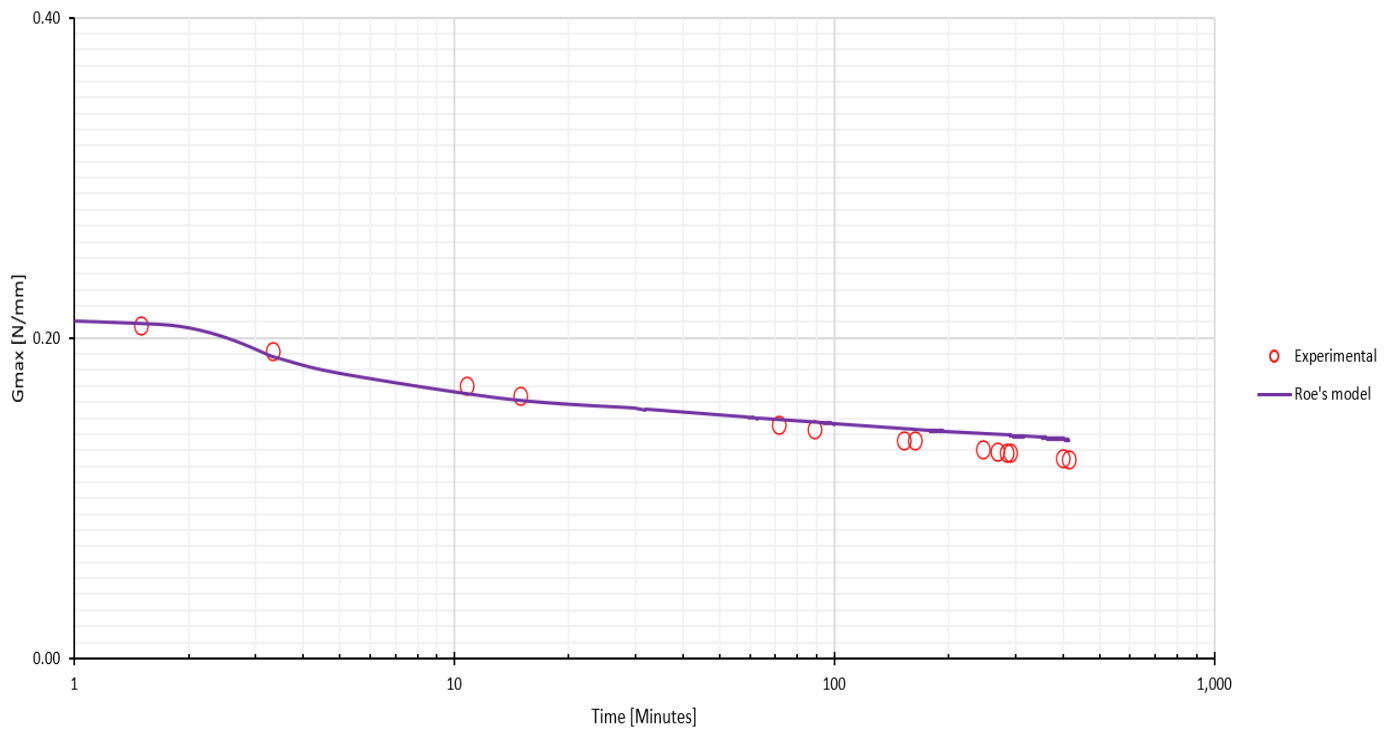


Figure 5. 7 Strain energy release rate resulted from Roe's model compared with the experimentally computed values for the LA30 sample.

The crack increment is plotted against the number of cycles in Figure 5. 8 for both the experimental and numerical results.

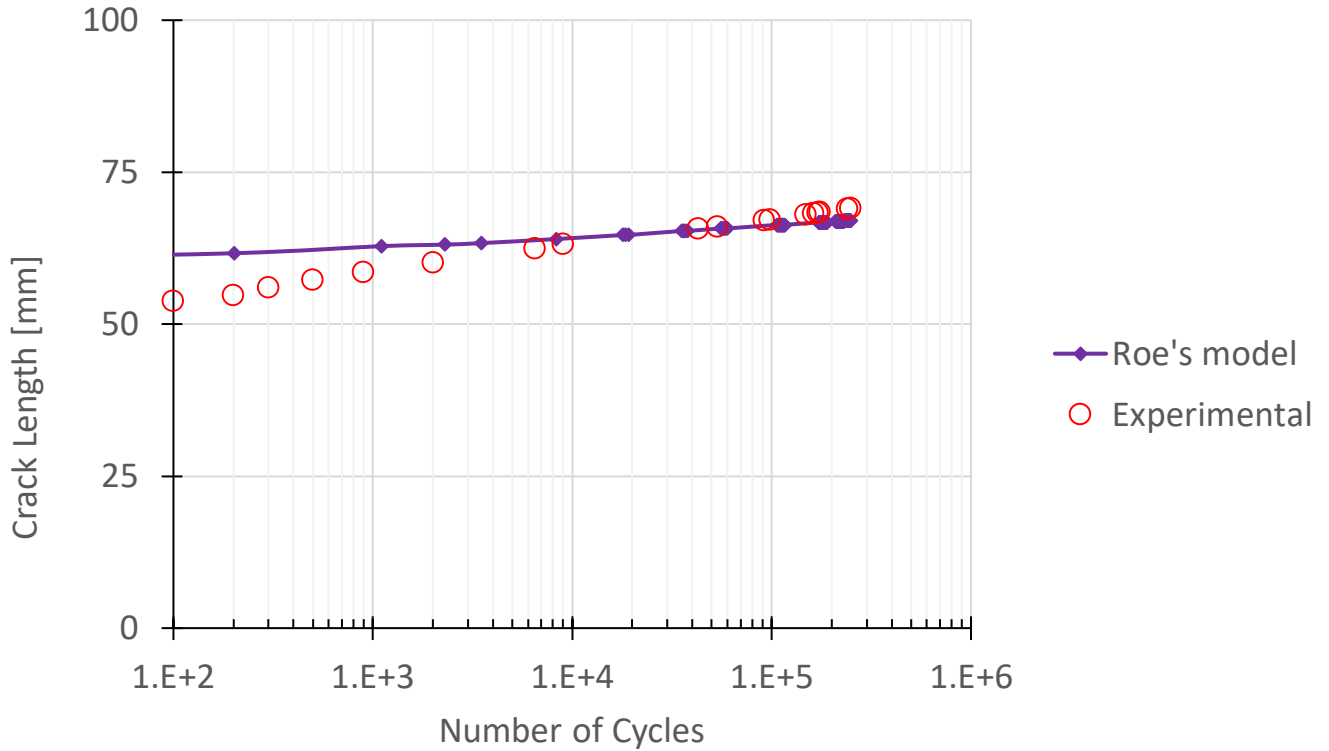


Figure 5. 8 The resulted fatigue crack growth calibrated by the experimental values based on Roe's model for the LA30 sample.

In both models, a small scatter is observed and hence an acceptable level of accuracy can be considered. Although, a small number of works has been done and few authors were calibrating their results, this model supports the successful work of the constitutive behavior suitability and validity for such cases <sup>38,40,41,79</sup>.

As described earlier, the exponential behavior were the suitable constitutive behavior for fiber bridging in both monotonic as performed by Sorensen <sup>38</sup> and cyclic loading as implemented by Shahvedi and Vassilopoulos <sup>79</sup>. The toughening mechanism given by fiber bridging is resulted from the fiber exposure. The exposure occurs when the laser ablation is applied and the surface matrix is dispersed. The fiber bridging caused by laser ablation is confirmed by Ran Tao et al as part of failure characteristics for number of surface pre-treatments <sup>1</sup>. Although, the sandblasting surface pre-treatment causes a fiber exposure, the toughening mechanism is not

found. The reason is due to the fiber damage that is made by the high impact of the sand particles <sup>1</sup>.

Similar to the bilinear traction separation law, the element size is an important factor in the accuracy. The element is set to be 0.08 mm and the minimum crack increment was 0.083 mm. Time is another important factor and its sensitivity appears particularly in Roe's model as it entirely depends on it <sup>40</sup>. At the beginning, this model was made by a rough time increment of 5 minutes. Then, it was reduced to 1 minute where the final results are given. A comparison between the two different time increment models are shown in Figure 5. 9.

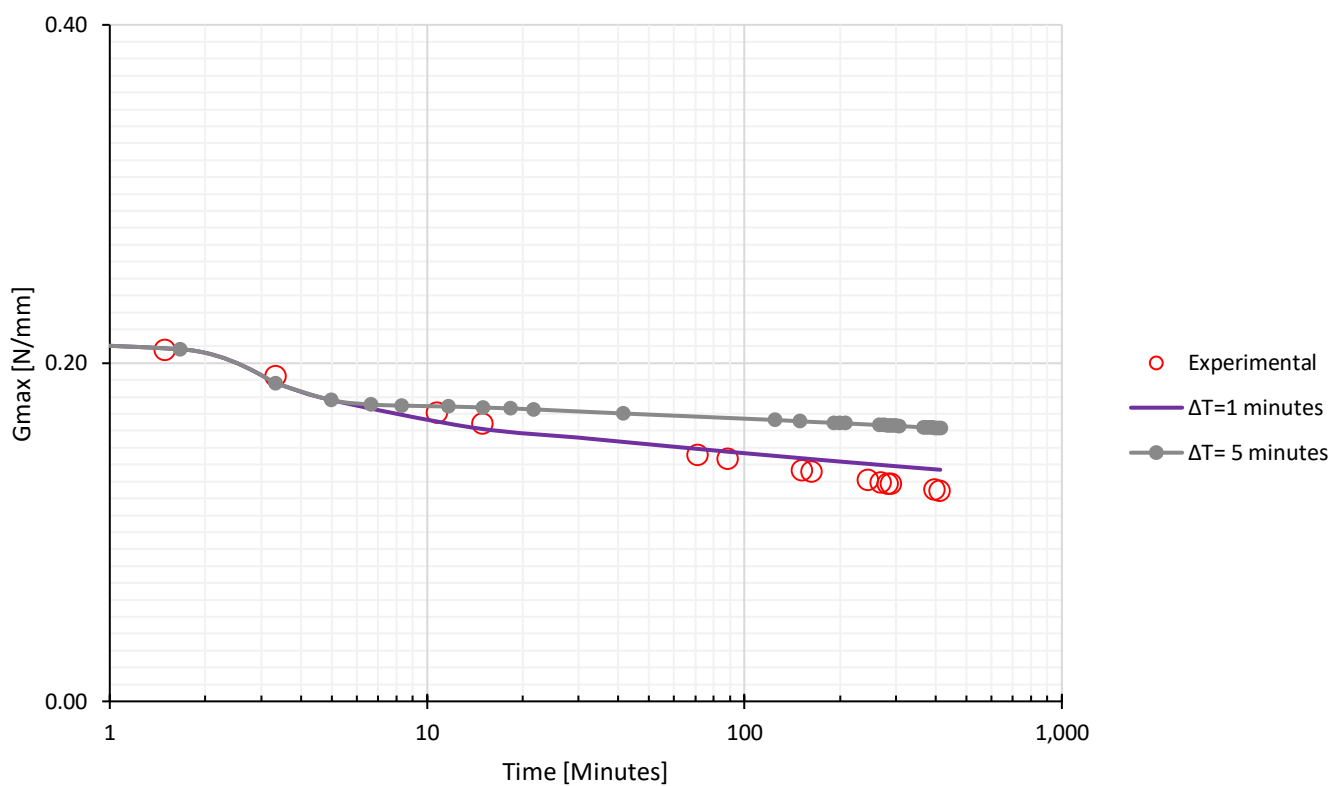


Figure 5. 9 A comparison between two different time increments based on Roe's model.

Reducing the time to cycle-by-cycle is costly as it requires high performance solving device and consumes large amount of time as explained by De Moura et al Abdel wahab and Pirondi et al <sup>20,30,98</sup>. Turon described it as “computationally interactable”. Roe model produced accurate results as he performed the analysis literally cycle-by-cycle and not incrementally accounted

<sup>40</sup>. The maximum number of cycles that was made in his work is less than 100 cycles. If this was performed in this model, it will require months to finish it. Beside the time consumption, the accumulation of data and errors might be other technical difficulties. The Table 5. 1 is showing a comparison of different time increments.

Table 5. 1 Influence on time increment on the total actual time.

| <b>Case</b>                    | <b>Method</b>                   | <b>Time<br/>increment</b> | <b>Total<br/>modeling time</b> | <b>Total actual<br/>time</b> |
|--------------------------------|---------------------------------|---------------------------|--------------------------------|------------------------------|
| <b>Exponential<br/>Roe CZM</b> | Cycle by cycle                  | 0.1 s                     | 41,600                         | 29 days                      |
| <b>Exponential<br/>Roe CZM</b> | Incremental<br>number of cycles | 1 s                       | 4,160                          | 3 days                       |
| <b>Exponential<br/>Roe CZM</b> | Incremental<br>number of cycles | 1 Minute                  | 416                            | 7 hours                      |
| <b>Bilinear CZM</b>            | Incremental<br>number of cycles | 100 Cycles                | 2,500                          | 40 hours                     |
| <b>Bilinear CZM</b>            | Incremental<br>number of cycles | 1,000 Cycles              | 250                            | 4 hours                      |

In order to understand the importance and influence of the type of pretreatment on the results and on the resistance of fatigue crack propagation, a previous work has shown that the strain

energy release rate and Paris parameters are the main determinant of the bonding strength <sup>102</sup>. Stress ratio ( $R$ ) is another aspect of concern. The stress ratio used in the experiment was 0.1. It has been shown in the in a previous work <sup>102</sup> that for low  $R$ ,  $\Delta G = G_{max}$ , which what this model is assuming.

There are many other forms of Paris law where other parameters like the fracture toughness were involved <sup>102</sup>. They can be implemented to obtain Paris parameters from the experimental data and then used in the model as well. However, adding the fracture toughness to the denominator will lower Paris law exponent and hence it will be less sensitive to change in the strain energy release rate. In fact, there are other forms to reduce scatter and sensitivity to the applied conditions. For instant, the form that was introduced by Jones et al (2015) <sup>103</sup> is implemented using a threshold value. Generally, Paris parameters for adhesive joints are found to have large values <sup>104</sup>.

### 5.3 Computed Tomography Images

In this section, segmented crack is presented to observe failure evolution and crack path. Segmenting the substrate and the adhesive was not performed because they did not have significant deformation. However, the adhesive voids and cavitation are included in the crack segment. Besides, there were technical difficulties caused eliminating them from the viewing surfaces.

For instant, epoxy is a common material used for both the adhesive and CFRP making the density of both very close. It was difficult to select one of them without the other. They have common intensity range and presenting the adhesive without it will create distorted image. Separating them can be achieved by number of techniques but this will not be essential since the focus of this work is on the crack surface. In the presented crack segment, the intensity signal is limited to air to present crack, bubbles and cavitation.

A CT scans was performed on two samples, the baseline Teflon and the laser ablation 10%. Segmentation of the cracks allowed presenting it separately from the materials. Tracking

through the orthotropic slices provides detailed information of which side of the adhesive the crack is growing.

Firstly, the LA10% sample is showing a straight crack growing in the interface during the static test region. The upper crack surface shown in Figure 5.10 is the crack/adhesive interface. The circular shape is an air bubble identified by the lower side of the crack that revealed a solid spherical shape. During the fatigue test, crack was visually monitored, and it was following the path of the static test. However, the crack segment is showing that the crack was bridging through the adhesive in a region where the naked eye cannot observe. Some bubbles within the adhesive are showing too in both the crack segment and the orthotropic slice in Figure 5.10 can be considered as sort of fatigue failure. Some authors considered them as voids and cavitation<sup>105</sup>. Crack shifting from the substrate to the adhesive was a fatigue failure mechanism occurs due to nucleation of microcracks ahead of the main crack. As soon as they meet, they emerge resulting in new path<sup>105</sup>.

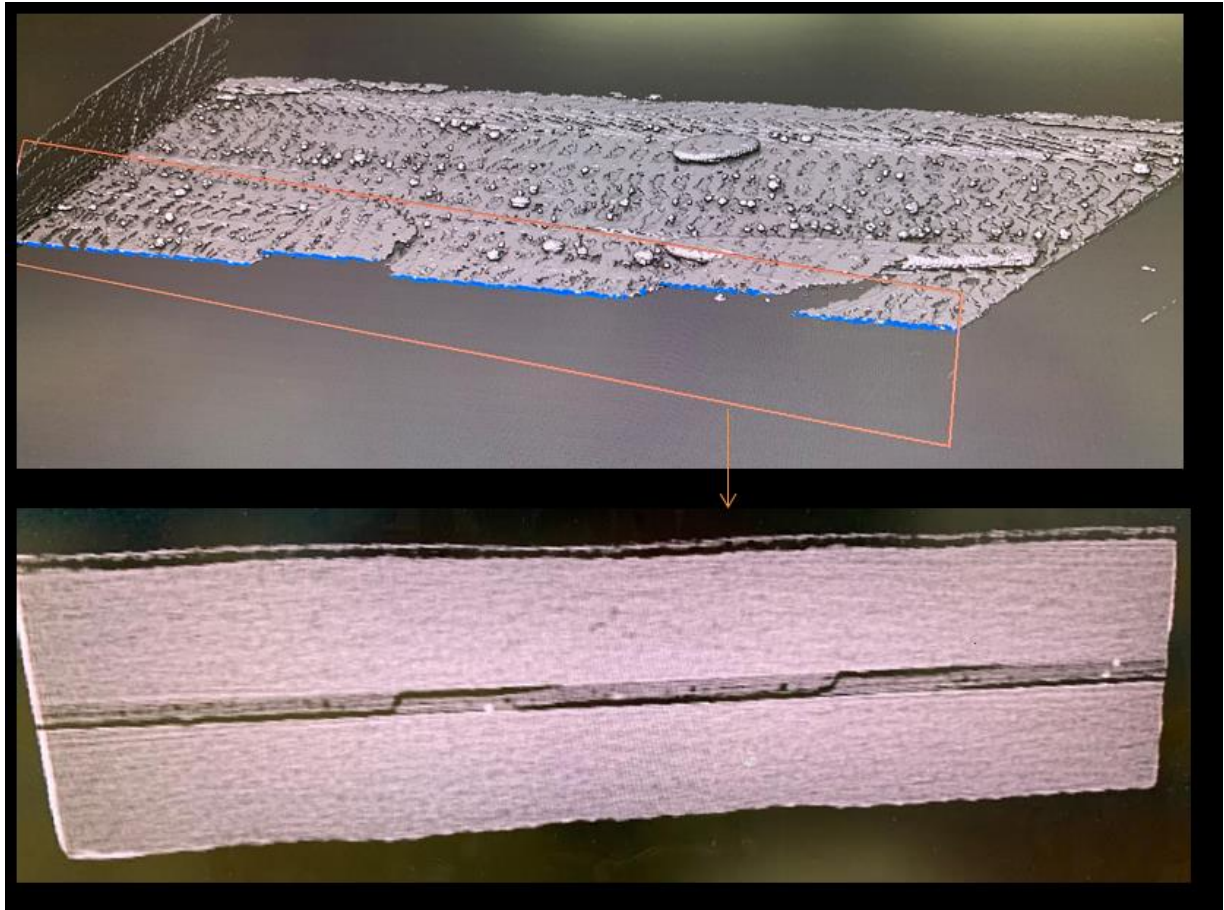


Figure 5.10 CT image of the LA10%% showing a crack segment in the top and an orthotropic slice is in the bottom.

Secondly, A baseline Teflon sample is presented for failure analysis. The crack segment underwent measurements to estimate the crack stages. The first stage is the static region followed by the fatigue stage presented by the number of cycles precisely counted at each location of the crack as shown in Figure 5.11. The last part of the crack that was not marked is an extra 4 mm that was not observed by the naked eye. It is not clear if this part is a crack tip or bubbles and voids.

The static test surface is relatively smooth with minor number of cavitation. The large bulge in this region is a manufacturing defect as a result of sagging in the adhesive. The fatigue region

has rough surface starting with crack in the interface. The crack was growing in high rate at the beginning before it starts bridging through the adhesive. It is true that the load was decreasing but there is another reason why the crack increment is slowing down as illustrated by the increment of the slope of the curve. In general, crack movement from the substrate to the adhesive causing cohesive separation plays an important role on its velocity <sup>105</sup>.

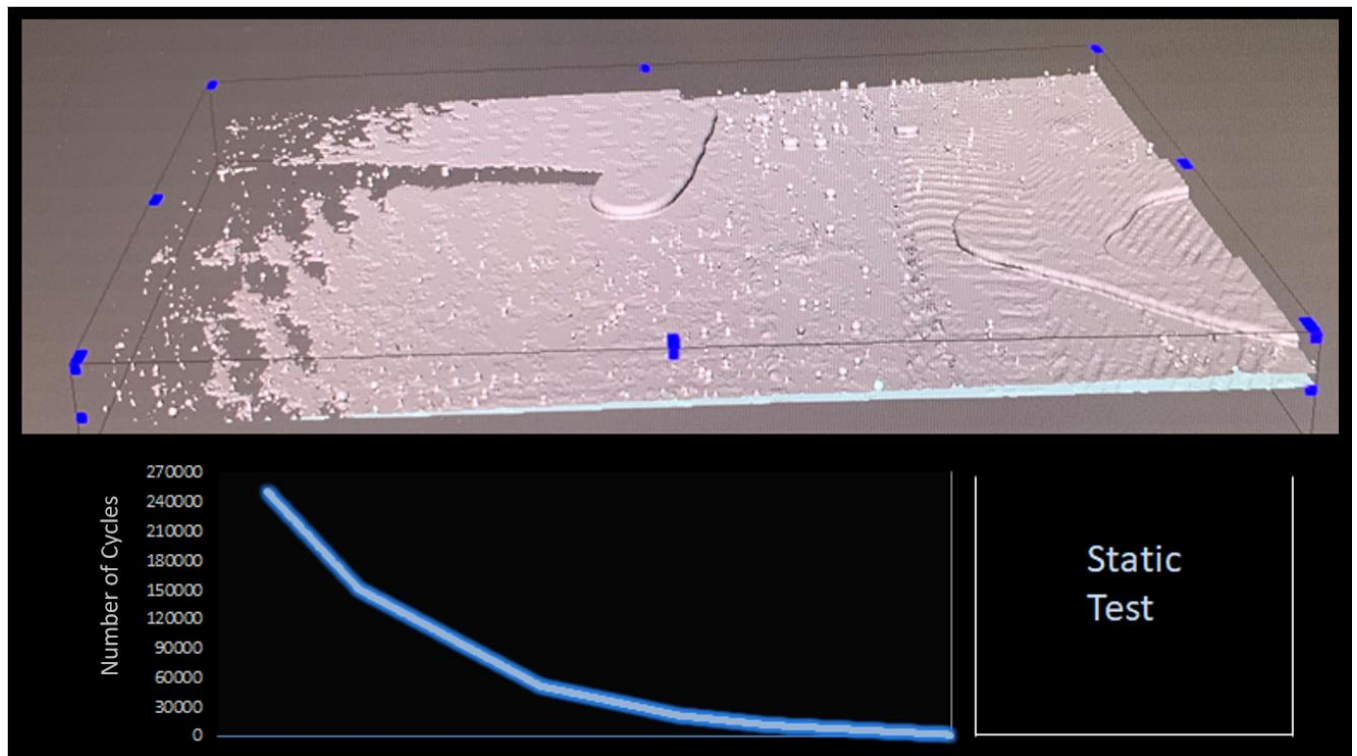


Figure 5.11 CT image of the BT sample showing the crack segment. The static region is determined followed by the fatigue region.

In Figure 5. 12, the crack is viewing its lower side. This image is the CFRP/Crack interface. As predicted, the static region bubble has no trace from this side. During sample manufacturing and preparation, samples were cut by high pressure water jet along the longitudinal axis. This pressure can displace the adhesive producing an empty space. There was doubt about the bridging region whither it is a crack path, or an air bubble generated during the waterjet cutting. If it was an air bubble, it will be shown as a solid body in the segment from all sides. Hence,

this view is utilized to answer this question. There are traces of pattern made by surface treatment and the line is a separator between the static and the fatigue regions.

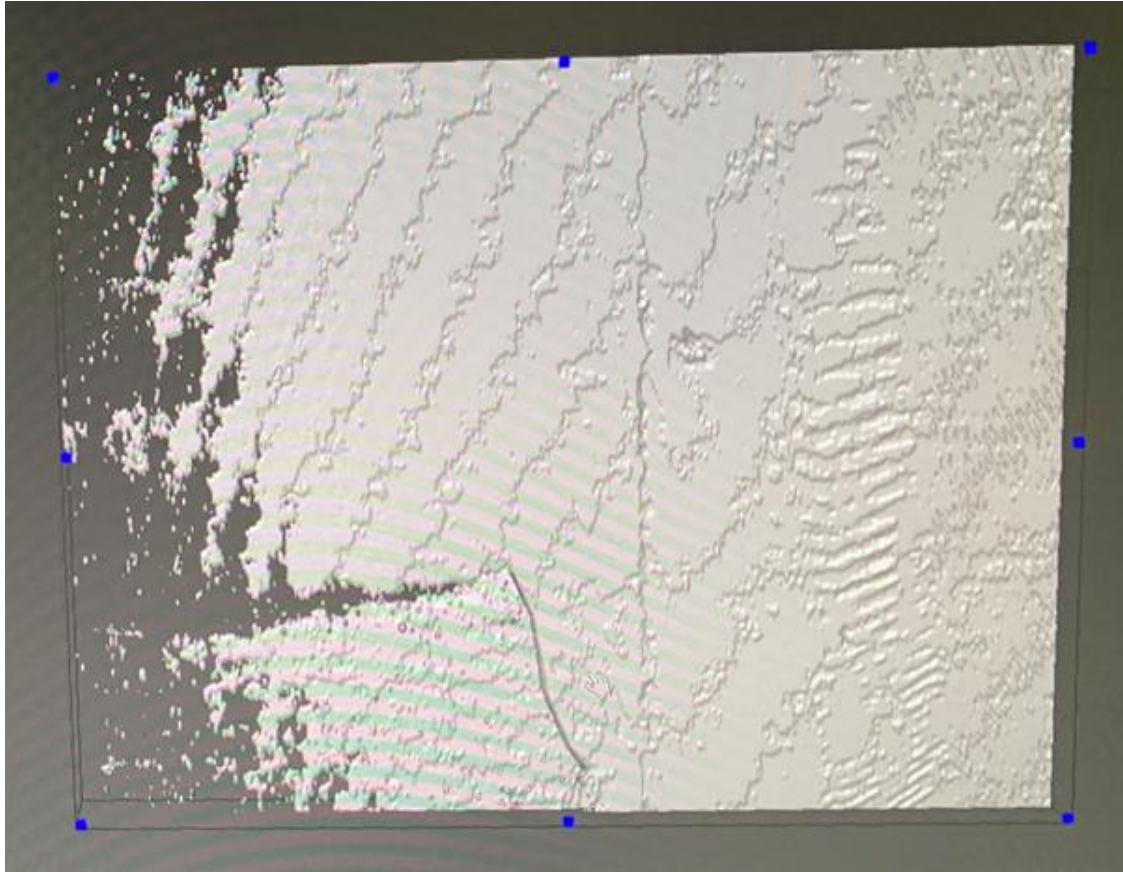


Figure 5. 12 CT image for the BT sample showing the lower side of the crack segment.

In general, material defects are associated to its damage. Separation between crack growth mechanism and existence of voids in the adhesive is not tolerable. Microcracks starts from those voids as result of strain concentration around them. The voids grow and form microcracks which are later emerge with the main crack <sup>14,88</sup>.

Deformation in CFRP may requires higher load. It was shown that a normal load of 20% of the failure load started to cause uniform clear delamination <sup>85</sup>. In fatigue, 50% of the maximum tensile strength started to reveal failure after 700 cycles. In this work, no trace of failure pattern

in the substrate <sup>86</sup>. The maximum applied load was less than 10% of the tensile strength applied on it <sup>1</sup>. In figure, at the orthotropic slice, the dark lines in the substrate indicates normal manufacturing imperfections those extend beyond the crack region.

It was shown that the crack is not always growing in the interface but also bridges and continues within the adhesive. In the FEM, it was assumed that it grows in the adhesive and then a correction from the cohesive zone relation is used. The images confirmed that plane strain is not a correct assumption due to the uneven deformation along the width. Naturally, plane-stress is assumed because the load is applied through the width.

## Chapter 6 CONCLUSION AND RECOMMENDATIONS

### 6.1 Conclusion

The cohesive zone model used to simulate the fatigue crack grow for different surface pre-treatments. By using the bilinear-traction separation law, all the samples have given reasonable results in the monotonic load-displacement response except one. This has been used to validate the input constitutive parameters. The cohesive zone maximum stress was obtained by the VCCT which is a technique that has given similar results as the cohesive zone in the literature. It appeared that there are various methods for the damage increment in the literature. Two models were used and compared. They both lead to acceptable results. The scatter is due to accuracy of the cohesive zone parameters which influenced the monotonic damage level. This level was the starting point of fatigue damage accumulation. For instant, if it is too high, the damage at high number of cycles be will large and can cause instability to the model. The mesh influence has been discussed in this matter as well.

The delamination mechanism of the 30% laser ablation surface pre-treatment raised the need for another cohesive zone constitutive behavior. It was shown that the exponential behavior is used in literature for fiber bridging phenomena in both monotonic and fatigue analyses. The toughening mechanism was simulated using the cohesive zone element. Two models were given, the Paris law dependent model and Roe's model. The second model is a time dependent model that implement a damage relation that controls the material degradation. A small scatter observed in the two models. The second model is sensitive to time increment as the original work has been performed based on cycle-by-cycle analysis which is expensive and can cause technical difficulties. Hence, a time increment of 1 minute was selected and compared with higher time increment.

It was observed that convergence is another issue in the monotonic model. By changing the solving root-finding algorithm from Newton-Raphson to Arc-length method, the issue has been solved. However, this technique requires spending a time higher than the fatigue analysis.

The modeling associated items like geometry, loading, boundary conditions and the element types were explained. The exhibited experiment was conducted to verify the validity of the model. The results were shown in term of strain energy release rate ( $G_{max}$ ) and fatigue crack grow ( $a$ ).

Generally, the inputs of the model can be summarized by the following items:

- 1) Geometric dimensions
- 2) Material properties
- 3) Cohesive zone constitutive parameters
- 4) The applied load
- 5) The increment in number of cycles
- 6) Paris Parameters

To verify the method and the inputs for the cohesive zone model, results from a reference was selected and a model was made based on it. The model details and results are found in Appendix A.

Tomography scan was performed on two types of samples, the LA10% and the BT. There was no deformation in the substrate observed. Crack is clearly bridging through the adhesive in the fatigue region. Its mechanism is referred to nucleation of microcracks precedes the lead crack. In addition, cavitation and voids appears as failure progresses. Evidence of cohesive crack influence on the crack velocity was given. Deformation along the width refuted the plane strain assumption.

## 6.2 Recommendations

Although the finite element model has shown acceptable results, there were level of sensitivity resulted from the large value of Paris parameters. This can be resolved by using other forms of Paris law in both the experimental and modeling procedures. For instant, by obtaining the fracture toughness from the monotonic test and implementing it in Wang et al (1985)<sup>106</sup>. This is mostly effective in large load ratio ( $R > 0.1$ ).

$$\frac{da}{dN} = C \left( \frac{G_{max}}{G_{IC}} \right)^M \quad (6.1)$$

Another recommended form is implemented with a threshold value proposed by Jones et al (2015) to reduce scatter <sup>103</sup>.

As shown in the results chapter, the experimental methods to obtain the cohesive zone parameters are the most effective methods to capture the constitutive behavior and the hence the initial damage. Consequently, the crack grow estimation will be accurate as well. With super performance device, a mesh smaller than 0.01 mm can be performed with smaller increment in reasonable time.

In order to have a comprehensive understanding of the role of pretreatment on fatigue crack growth two steps can be taken. They will bring significant explanations of the mechanism of fatigue crack growth in adhesively bonded substrates. First, perform tomography scan on all the sample types. By segmenting their crack surfaces, the crack behavior will explain the verity of their features including the uniformity of surface pattern and the level of contamination.

Unfortunately, this will not be enough because there are some questions those are not yet answered. For instant, why the fully exposed fibers in the 30% laser ablation sample has much higher crack growth resistance than the partially exposed fibers in the 10% laser ablation sample?. In order to answer this question, a microtomography should be utilized to observe fibers interaction and bridging.

What limited the resolution in this work is the width of the specimen. It was too large to keep the specimen within the X-Ray frame. If a laser cutter is used to slice the specimen in the longitudinal direction, then the target resolution can be achieved.

The current work images have shown significant influence of the adhesive voids and cavitation on certain types of pretreatments. Although they generated strain concentration cites those evolved to microcracks, they positively influenced the crack growth rate. Finally, reducing them by controlling mixing will may force the crack to grow in the interface.

## **Appendix A**

### **CZM model for a numerical simulation using finite element analysis**

A numerical analysis using finite element method will be used to simulate the adhesive failure using the built-in CZM fracture mechanics for fatigue crack propagation. Although the test which will be performed is cyclic, a verifying analysis of quasi static loading is established in this section. Verification of the model will take place by comparing the result with a reference.

## Simulation of cohesive zone in ANSYS APDL

ANSYS provides cohesive zone material model in form of traction separation law and has been used to simulate adhesive joint in DCB. The material model command start as [[TB,CZM](#)] and followed by the zone properties.

CFRP are modeled as orthotropic material by the following commands:

MP,EX,1,

MP,EY,1,

MP,EZ,1,

MP,GXY,1,

MP,PRXY,1,

MP,PRXZ,1,

MP,PRYZ,1,

An estimation of the mesh will be in the form of two rectangular shapes like the ones in Figure A. 1 are meshed with the layer supporting element and has orthotropic materials properties. A line division between them represents the cohesive zone will be meshed by the mating elements. The cohesive properties are assigned to the two mating lines which are meshed by either contact pair elements or one single cohesive element.

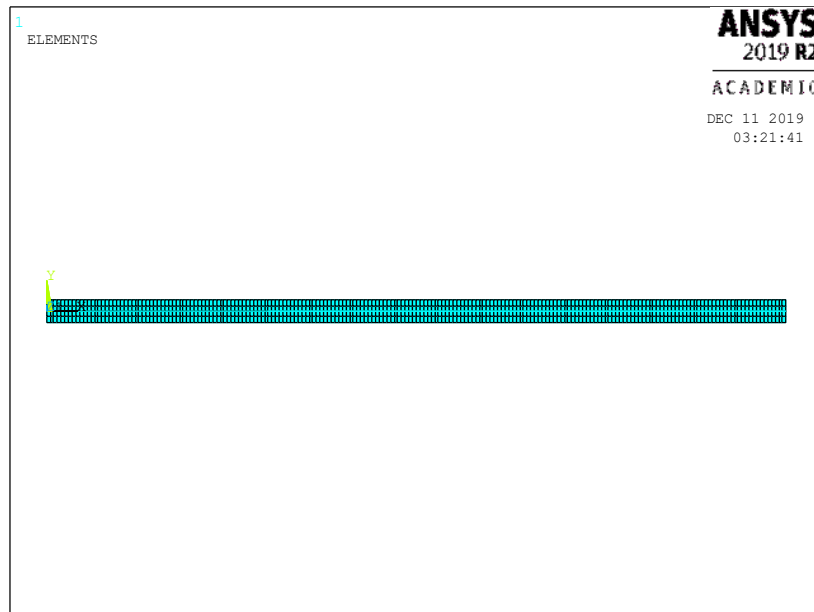


Figure A. 1 Mesh estimation of DCB.

List of elements used to simulate the DCB as the middle line represent the cohesive zone:

Orthotropic layered substrate:

- Solid. PLANE182
- Or SELL181

Cohesive zone:

- 2-D Surface to surface contact element (CONTA172)
- 2-D Target segment element (TARGET169)
- Or 2-D (4-Node) Cohesive zone element (INTER202)

As discussed in literature, resistance force by the adhesive joint varies as crack delamination proceeds. The value of force required to cause crack propagation, increases until it reaches a

critical value where the component starts to lose its toughness and end up separating in a fracture failure. In the following model, a reference was selected to verify the methodology.

## Material Properties

The orthotropic properties can be summarized in Table A. 1 while the cohesive zone properties are shown in Table A. 2.

Table A. 1 orthotropic properties used assign to the substrate material.

| $E_{11}$ | $E_{22}$ | $E_{33}$ | $\nu_{12}$ | $\nu_{13}$ | $G_{12}/ G_{13}$ |
|----------|----------|----------|------------|------------|------------------|
| (GPa)    | (GPa)    | (GPa)    |            |            | (GPa)            |
| 135      | 1.9      | 1.9      | 0.24       | 0.24       | 5.2              |

Table A. 2 Cohesive properties assign to the mating line.

| $K_p$                | $G_{Ic}$ | $\sigma^c$ |
|----------------------|----------|------------|
| (N/mm <sup>3</sup> ) | (N/mm)   | (MPa)      |
| $10^6$               | 1.9      | 1.9        |

## Analysis Assumptions and Modeling Notes

In this model a static rate independent analysis we be done on a double cantilever beam where the cohesive zone will be in the mating regions between the two rectangular shapes. The following assumptions are implemented:

Plane strain. no deformation in the z-axis.

Bilinear Cohesive constitutive model [**TB,CZM,2, $\sigma^c$ , $G_{Ic}$ ,CBDE**]

Crack propagates in a straight path.

Elastic behaviour of the substrate despite the developed stresses.

Plastic deformation occurs only in the cohesive zone.

## Geometric model

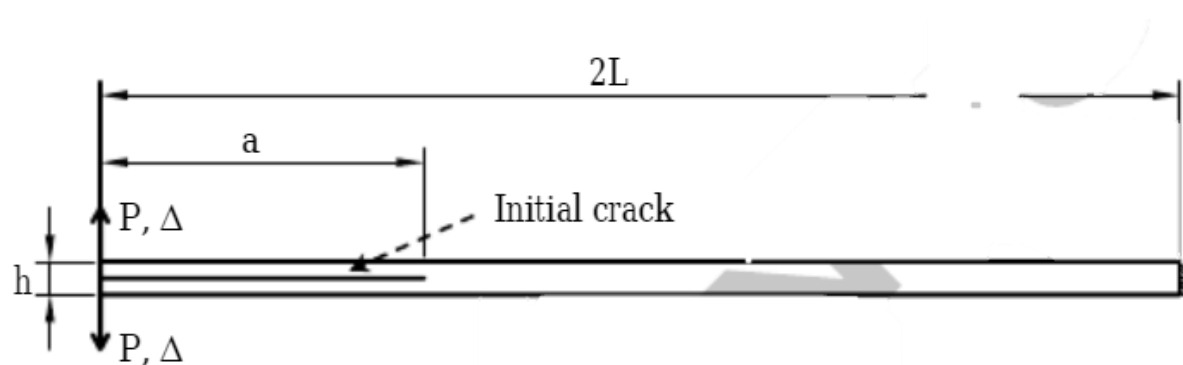


Figure A. 2 Setups for double cantilever beam (DCB) <sup>68</sup>.

Table A. 3 Geometric data for the model <sup>68</sup>.

| Dimension | Value  |
|-----------|--------|
| 2L        | 100 mm |
| h         | 3 mm   |
| width     | 30 mm  |
| a         | 30 mm  |

Basic Model (including mesh generation)

Element Types

- Plane 182: 2-D Layered section of unidirectional fibres.
- Target 169: target element associated with the cohesive material model.
- Conta171: contact element associated with the cohesive material model.

Table A. 4 Mesh details.

| Number of Elements | Number of nodes |
|--------------------|-----------------|
| 1140               | 1206            |

#### Boundary Conditions and applied loads

Constrain the two unloaded corners at (x=60).

Displacement load ( $\pm 10$  mm) on the two edges where the mode-I opening proceeds (at  $\pm 1.5$  mm)

#### Model outputs

In Figure A. 4 effective stress of von miss criterion is presented. Clearly, the region of the mating line has the highest stress value which reached up to 287 MPa and many cases, CFRP develops a plastic deformation. But in this model, we assume that the substrate only experiences elastic deformation. Furthermore, The force Vs displacement graph is plotted in Figure A. 4 where a tensile strength of 1 MPa is used to verify the model convergence.

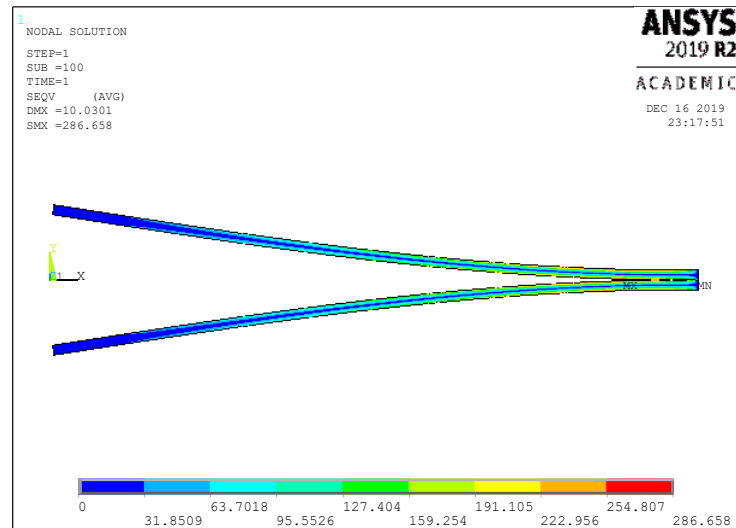


Figure A. 3 Von miss stress in DCB.

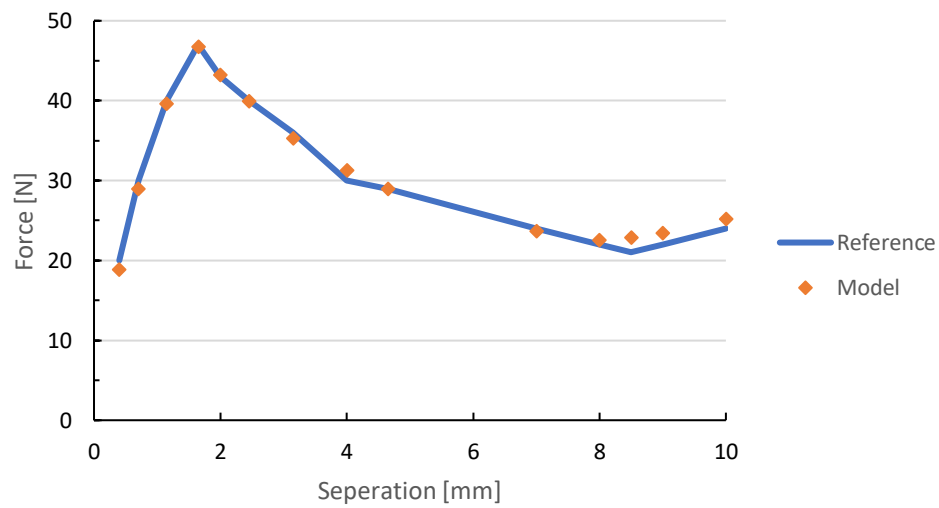


Figure A. 4 Load Vs y-axis displacement for the model and reference. <sup>68</sup>

## **Appendix B**

### **EXPERIMENTAL WORK SOFTWARES**

#### Mechanical Test

The software “Bose WinTest” is run to control the testing device. There are two types of acquisition tools, the cyclic and the static. In both of them, the destination of the saved data, the test parameters and the test settings are inputted. Acquisition starts before the beginning of every type of test. On the right side of the window, there are two levels for high and low displacements. Each of them is a displacement level in (mm) and executed when this level is required with the specified rate. Those levels are used only during the static test or to open the sample for crack capturing.

#### Tomography Test

#### Scanning

The software that controls the device is “Inspect-X”. It has five main taps:

- 1) Start
- 2) Position and optimization
- 3) Corrections
- 4) Reconstruction
- 5) Acquire data base

The “start” tap allows the user to select the setting. If the sample follows another sample with similar geometry, the position and calibration procedure will be automatically performed. Otherwise, a “New sample” button is selected. The second tap is “Position and optimization”. The x-ray can be turn on and the sample can be seen in the monitor. The sample is observed in all its orientation during the scan. If the sample is tilted or not centered, the door can be opened to reposition and support it. It is important to ensure that at maximum magnification will not cause the sample to go out of the frame. Therefore, it should be checked at the larger dimension. The restriction in magnification due geometry plays an important role in limiting the resolution. The finally showing body in the frame is the region of interest that will be scanned. In this tap, the pixel size, the beam current, the beam energy and the power are determined. The third tap is “correction”. Here, the title of the work is given. In addition, calibration is done by taking the sample out of the frame and execute the command button. The Software will return the sample to its original position and start the scan. This step is performed automatically when “use parameters of the last scan” option at the “Start” tap is chosen.

## Reconstruction

“CT Pro 3D” is another software utilized for image reconstruction. First, the scanning file is added. Then at the “center of rotation” tap, the Slice reconstruction is performed by clicking “start” button after checking all the above options. The “setup” tap is entered to set up the reconstruction by clicking on “start” button after checking the above options. The volume is determined by cropping the image which will cause reduction of the file size illustrated in the “volume” tap. Finally, reconstruction of the image will start for some time until all data files are built. Those files consist of all the scanned images and a raw data volume file that will be used for rendering and segmentation.

## Segmentation

The software utilized for this purpose is “AVISO Fire”. It implements a labeling technique which results in segmenting every material alone based on their density.

Once the data file uploaded completely, a volume rendering is added from the main panel. This panel allows the user to add and link all the visual features. Navigation through the Colormaping bar can help tracking the signal. Once it is captured, the sample scanned image will appear in gray color where the degree of brightness indicates a range of certain intensity. In order to take a slice to see inside the sample, an orthotropic slice is added from the main volume. It allows choosing the axis and the slice number.

To eliminate insignificant proportions at the edges like the external air, a sub-volume can be created. The size can be controlled by the blue dotted edges. If the orientation is not compatible with the subvolume shape, it can be adjusted from the “volume rendering” branch. The subvolume can be linked to any added visual feature.

In order to present the crack separately from the rest of the components, a labeling method is implemented. It is performed by selecting the “Edit new label field” option. The label field consists of various material types. The user can add random number of materials and edit their names. Every material will have range of intensity selected or given by the user. The segmentation starts from this point and will follow the points below.

- In the threshold retracker, the intensity range is assessed by recognizing the marked material. Once the required material is estimated, this intensity range is added to the associated material type. This process is repeated for all the added materials while avoiding intensity overlapping.
- The watershed tool is used to create a gradient by applying a new gradient image and creating a new label field.
- Sometimes, there are some proportions those are left without being added to any materials. For instant, a sharp crack tip is not involved in the “air” material type. The

top hat tool is used to add it by clicking on “compute top hat image” button after carefully specifying the intensity.

- Each of the materials in the main label should have its own label so it can be presented in the main panel. In the main label, each material is selected and added to its label type.
- In the main panel, by selecting a material label, surface is created and applied.
- The created surface can be shown by creating a “surface view”. At this point, the material segment is presented alone.

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## Author Vitae

# HUSSAIN AL-DAKHEEL

KSA Eastern province · 966-541455493

[h.k.dakheel@gmail.com](mailto:h.k.dakheel@gmail.com)

Zip Code: 36341

## Experience

### Engineer trainee, SCHLUMBERGER

Internship

### Engineer trainee, SCHLUMBERGER

Coil Tubing Segment

### Field engineer I, SCHLUMBERGER

Schlumberger operational school [CTO]

CT acid stimulation

CT junk milling

CT multi-lateral intervention

CT extended reach intervention

CT tool fishing

CT well cleanout

CT nitrogen kickoff

### Field engineer II, SCHLUMBERGER

Schlumberger technical school [CTT]

Engineer in chart [Khobar]

Field service manager [Bahrain]

Unconventional gas well intervention [UDH]

Post-frac CT copper head plug milling

CT/WL perforation

CT jet plasters

CT active tools

### Research Engineer, SCHLUMBERGER

## Education

2013

**bachelor's degree in mechanical engineering**, KFUPM

GPA: 3.2

2020

**MASTER's Degree in mechanical engineering**, KFUPM

GPA: 3.8

Thesis Title: Fatigue Analysis of Surface Pretreated Adhesively Bonded CFRP using FEM and X-Ray Tomography [in collaboration with KAUST]

## **Skills**

An ability to learn quickly and independently through white papers, patents, and technical textbooks is highly desired

Strong written and verbal communication skills

IELTS Academic test score: 6.5

Performing fracture mechanics simulation using finite element techniques including [VCCT, XFEM and CZM]

Performing tomography scanning and reconstruction

Implementing tomography Image segmentation and measurements

Engineering software: Wellbore simulator, StimCAD, CoilCADE, CoilCAT, AVISO, ANSYS, ABAQUS, AutoCAD, SolidWORKS, Mathematica, MATLAB, COMSOL Multiphysics, BOSE WinTEST, CT pro 3D.

## **Activities**

KFUPM volunteer day in 2008

KFUPM scientific trip to Singapore

Equipment modification: CT drop-in-drum

Schlumberger Olympic games in 2015

IMECE 2020 conference [IMECE2020-23537]

K.A. CARE collaboration program 2020

Skilled free style swimmer and good football striker

## **AREA of PERUSAL**

Mechanical Engineering + Oil and gas Operations+ Unconventional Gas intervention+ Material Science +Fatigue and fracture mechanics+ Fluid mechanics Upstream process and Drill bits +Non-Metals +Material Behavior +Fatigue +Failure and Damages. +Nonlinear Finite Element Analysis +Plates and shells +Mechanical System Integrity +CFRP +Composites Materials +wear analysis +downhole tools +Corrosion and corrosion loops +Oil and gas plant process +Ultrasonic (NDT)