MARMARA UNIVERSITY
FACULTY OF ENGINEERING

COMPOSITE DEFECT MODELLING & DEFECT IDEALIZATION WITH FINITE ELEMENT MODEL

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GRADUATION PROJECT REPORT

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Composite Defect Modelling
& Defect Idealization with Finite Element Model

by

Nurcan AYGUN, Hayrettin Mert TOPAK, Abdulsamed BILGEN

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SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

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AT

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June 2024 **Abdulsamed BİLGEN, Hayrettin Mert TOPAK, Nurcan AYGÜN**

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ABSTRACT

This project investigates the modeling and idealization of defects in Carbon-Fiber-Reinforced Polymers (CFRPs) through experimental analysis. It focuses on understanding the impact behavior, mechanical properties, and the influence of adhesive thickness in composite materials. The primary objective is to compare the performance of CFRP samples with varying adhesive thicknesses, thereby identifying optimal configurations for enhanced material performance. This foundational study offers insights into the defect mechanisms in CFRPs and sets the stage for more detailed future research. The findings aim to contribute to advancements in high-performance applications across industries such as aerospace, automotive, and construction, where material integrity and reliability are critical. Additionally, it would be beneficial to include a Double Cantilever Beam (DCB) test and Finite Element Method (FEM) analysis in the study to make it more comprehensive. The DCB test is important for evaluating the fracture toughness and delamination resistance of CFRPs under controlled conditions, while FEM analysis can model and forecast how changes in adhesive thickness affect the structural integrity and performance of the composite materials. By utilizing these approaches, the research not only fills current knowledge gaps but also aims to improve the design of CFRPs for critical applications, ensuring the creation of safer and more durable structures across various industrial sectors.

SYMBOLS

Π = Potential Energy

ΔA = An incremental increase in the crack surface area

U = The strain energy within the body of the component

W_{ext} = External Work done

A_1 = slope of plot of a/h versus $C^{1/3}$

a = delamination length

a_0 = initial delamination length

B = width of DCB specimen

C = compliance, δ/ P, of DCB specimen

h = Thickness of DCB specimen

n = Slope of plot of Log C versus Log a

P = Applied load

δ = Load point deflection

Δ = Effective delamination extension to correct for rotation of DCB arms at delamination front

G_1 = Mode I strain energy release rate

G_{1c} = Critical Mode I strain energy release rate

G_{IIc} = Critical Mode II strain energy release rate

ABBREVIATIONS

PMC: Polymer Matrix Composites

GFRP: Glass Fiber Reinforced Polymers

CFRP: Carbon-Fiber-Reinforced Polymers

MMC: Metal Matrix Composites

CMC: Ceramic Matrix Composites

NDI: Non-Destructive Inspection

ENF: End-Notched Flexure

DCB: Double Cantilever Beam

CNC: Computer Numerical Control

FEA: Finite Element Analysis

FEM: Finite Element Model

UTS: Ultimate Tensile Strength

VCCT: Virtual Crack Closure Technique

ADH: Adhesive Failure

COH: Cohesive Failure

TCL: Thin-Layer Cohesive Failure

FT: Fiber-Tear Failure

LFT: Light-Tear Failure

SB: Stock-Break Failure

TWL: Thermal Work Limit

LL: Linear Limit

KK: Knee

MCC: Modified Compliance Calibration

EASA: European Union Aviation Safety Agency

FAA: Federal Aviation Administration

ASTM: American Society for Testing and Materials

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1. INTRODUCTION

1.1. Review of Impact Behavior of Composite Materials

Composite materials are materials obtained by combining two or more components that are specifically designed for specific engineering applications and have significantly different physical or chemical properties. Composite materials formed by combining these components exhibit mechanical, thermal or chemical properties that are different and generally superior to those of each component alone.

The basic components of composite materials are the matrix and reinforcement materials. The matrix acts as a continuous phase and surrounds the reinforcement materials and fixes them in position. The matrix materials are usually polymers, metals or ceramics, and these materials determine the properties of the composite, such as deformation and impact resistance. The matrix also maintains the integrity of the composite material and optimizes the load-carrying capacity of the reinforcement materials. Reinforcement materials are components that provide strength and stiffness to the composite material. These materials are usually found in fiber form (such as carbon fibers, glass fibers, aramid fibers), particles or flakes. Fiber-reinforced composites are preferred especially in applications requiring a high strength-to-weight ratio. Reinforcement materials significantly improve the mechanical strength and stiffness of a composite material by increasing its load-carrying capacity. Composite materials have a wide range of applications in a variety of industries, including aerospace, automotive, construction, and sports equipment. These materials allow design engineers to optimize material properties to meet high-performance requirements.

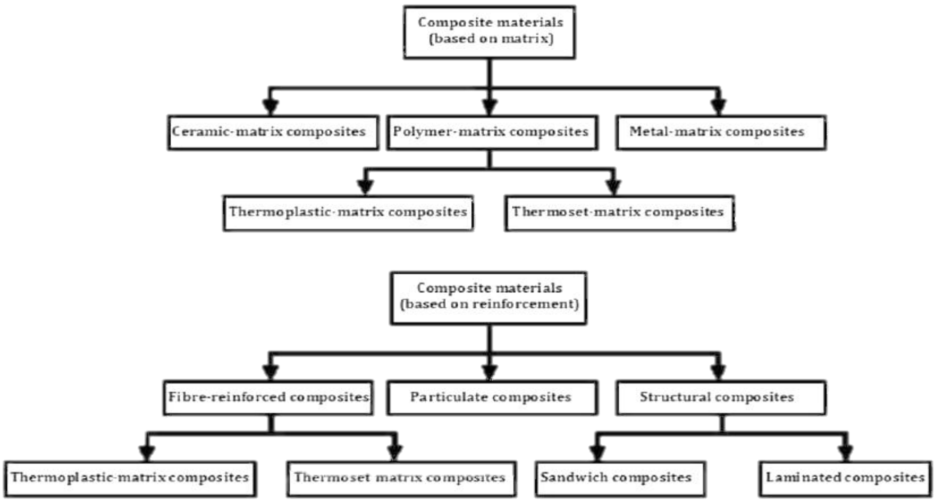


Figure 1.1 Classification of Composite Materials Based Upon Matrix and Reinforcement

There are several types of composite materials, see Figure 1.1 (Huda, 2022), each tailored for specific uses. Polymer Matrix Composites (PMCs) are the most prevalent, with examples including fiberglass, carbon-fiber-reinforced polymers (CFRPs), and Kevlar. Metal Matrix Composites (MMCs) feature a metal matrix, such as aluminum reinforced with silicon carbide particles or fibers. Ceramic Matrix Composites (CMCs) consist of a ceramic matrix, such as silicon carbide reinforced with silicon carbide fibers. Hybrid Composites combine two or more types of fibers or reinforcement materials within a single matrix, such as blending carbon and glass fibers in a polymer matrix.

1.1.1. Carbon Fiber Reinforced Polymer (CFRP)

Carbon Fiber Reinforced Polymer (CFRP) is a composite material with high strength and stiffness values, which stands out with its lightweight and durable structure. CFRP usually consists of carbon fibers embedded in a polymer matrix such as epoxy resin. This unique combination makes CFRP an extremely strong material despite its low weight, making it an ideal choice for applications that require high performance. CFRP's density is generally around 1.6 g/cm^3, and its tensile strength can exceed 4,000 MPa, providing a high strength-to-weight ratio. Its elastic modulus can range from 70 to 300 GPa, providing high stiffness and making it suitable for structures that require minimal deformation under load.

CFRP's excellent fatigue strength makes it ideal for use in applications subject to cyclic loading. In addition, CFRP does not corrode, unlike metals, making it preferred in environments where corrosion is a significant problem. The low coefficient of thermal expansion, a material that does not expand or contract significantly with temperature changes, provides dimensional stability for precision engineering applications. CFRP exhibits anisotropic behavior, meaning that the material’s properties change with the direction of the fibers’ load. This allows engineers to customize the material’s properties by aligning the fibers in the load-carrying directions.

The primary techniques used to manufacture CFRP include additive manufacturing, filament winding, pultrusion, and resin transfer molding. Additive manufacturing involves laying carbon fiber sheets in molds and impregnating them with resin. Filament winding is the process of winding continuous carbon fibers into a rotating mold in a specific pattern. Pultrusion is the process of drawing carbon fibers from a resin bath and passing them through a heated mold to create continuous profiles. Resin transfer molding is the process of injecting resin into a mold containing dry carbon fiber preforms.

The primary advantages of CFRP include light weight, high performance, design flexibility, and long service life. Its lightness provides a great advantage in applications where weight savings are critical for fuel efficiency and performance, especially in the aerospace and automotive industries. High strength and stiffness make it ideal for applications where mechanical performance is critical. Its design flexibility allows CFRP to be molded into complex shapes and fiber orientations, providing innovative and optimized structural designs. Its corrosion resistance and long service life make CFRP suitable for long-lasting structures that require minimal maintenance.

CFRP has a wide range of applications in various industries such as aerospace, automotive, sports equipment, construction and marine. In the aviation sector, it is used in aircraft structures that reduce fuel consumption and increase load capacity with its lightweight structure. In the automotive sector, it is used in body panels, chassis components and internal structures to increase vehicle performance and efficiency. In high-performance sports equipment, it provides superior strength and responsiveness with its lightweight and durable structure. In the construction sector, it is used as long-lasting and corrosion-resistant structural elements in bridges, buildings and other infrastructure projects. In the marine industry, it is preferred in the production of lightweight and high-strength bodies and poles. Detailed material image under optical microscope can be seen in the Figure 1.2 (Lukyanov, 2010).

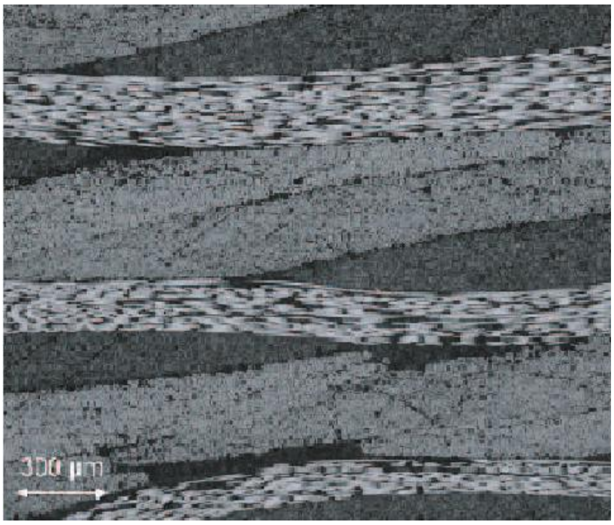


Figure 1.2 CFRP under optical microscope

1.1.2. Ceramic matrix composite (CMC)

Ceramic Matrix Composites (CMCs) are advanced engineering materials that combine the high-temperature strength and corrosion resistance of ceramics with the toughness and formability advantages of metal matrices. These materials offer excellent thermal and chemical stability even at high temperatures. CMCs are designed to operate in harsh conditions such as gas turbines, rocket engines and spacecraft as high-temperature and pressure-resistant components. Their resistance to mechanical and thermal impacts at high temperatures makes them indispensable in sectors such as energy production and aviation. With these properties, Ceramic Matrix Composites offer an ideal solution for engineering applications requiring high performance. Detailed material image under optical microscope can be seen in the Figure 1.3(Ultramet Advanced Materials Solutions, 2024)

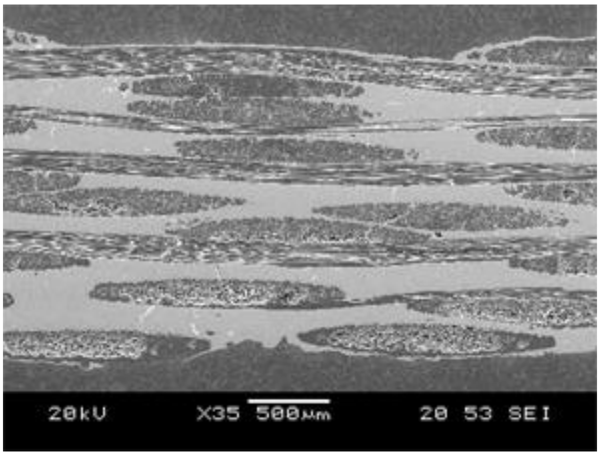


Figure 1.3 CMC under optical microscope

1.1.3. Glass fiber reinforced polymer (GFRP)

Glass Fiber Reinforced Polymer (GFRP) is a cheaper and lighter material compared to Carbon Fiber Reinforced Polymer (CFRP). GFRP offers high strength and durability while offering a cost advantage. This material has a wide range of applications such as insulation, pipelines and construction materials thanks to its low density and excellent corrosion resistance. The lightness of GFRP saves labor and costs, especially in transportation and assembly processes. At the same time, this material is widely used in the construction sector as durable and long-lasting structural elements. Glass Fiber Reinforced Polymer plays an important role in engineering projects by providing economical and effective solutions. Detailed material image under optical microscope can be seen in the Figure 1.4 (Bieniaś et al., 2013).

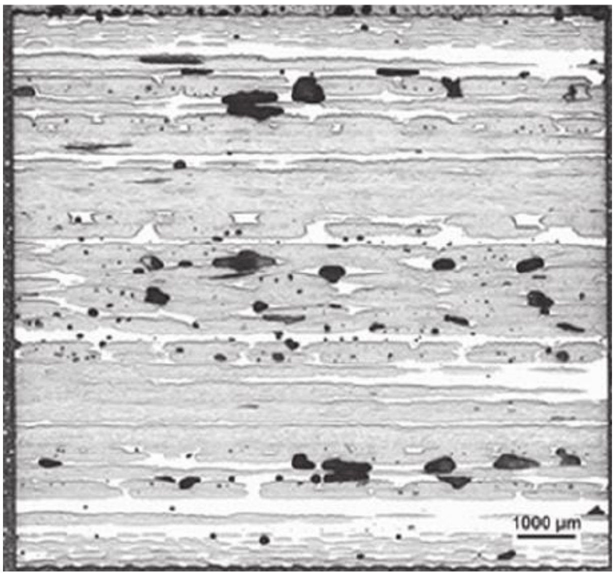


Figure 1.4 GFRP under optical microscope

1.1.4. Metal matrix composite (MMC)

Metal Matrix Composites (MMCs) are advanced materials that combine the toughness and formability of metal matrices with the high strength and hardness of reinforcement materials. Due to their superior mechanical properties, MMCs are widely used in high-performance applications such as aircraft, automobiles and military equipment. These materials combine the flexibility of the metal matrix with the durability of the reinforcement material, allowing to produce lighter and stronger structures. Metal Matrix Composites play an important role in engineering applications that require high load-carrying capacity and durability by improving performance. Detailed material image under optical microscope can be seen in the Figure 1.5 (İrem Belge, 2024).

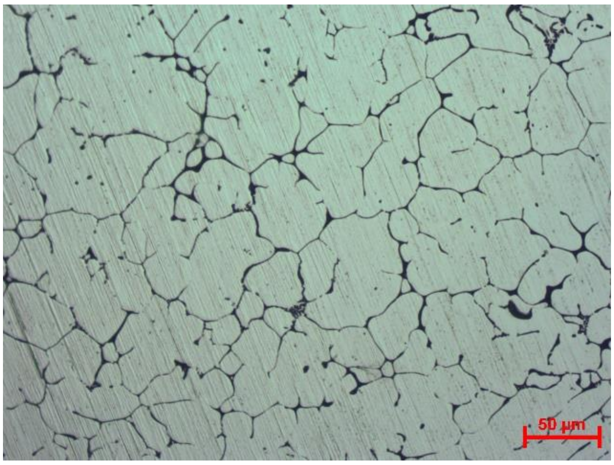


Figure 1.5 MMC under optical microscope

1.1.5. Polymer matrix composite (PMC)

Polymer Matrix Composites (PMCs) are advanced engineering composites that use reinforcement materials such as fibers, particles or textile materials within a polymer matrix. PMCs stand out with their high strength, hardness and lightness. For example, their densities are generally in the range of 1.5-2.0 g/cm³ and their tensile strength can range from 2,000-3,500 MPa. In addition, these materials can contain 30-60% fiber reinforcement and their elastic modulus can reach 70-120 GPa.

PMCs have a wide range of applications in different industries. In the aviation sector, they are used in aircraft fuselages and wings thanks to their low weight, which increases fuel efficiency and increases carrying capacity. In the automotive industry, PMCs used in vehicle parts reduce vehicle weight, providing lower fuel consumption and higher performance. In the construction sector, these materials are used as durable structural elements in bridges and buildings, standing out with their high durability and corrosion resistance. In the production of sports equipment, they are preferred in bicycles, tennis rackets and ski equipment due to their lightness and high strength.

PMCs play an important role in engineering projects that require high performance with their superior mechanical properties. Their low weight and high strength make these materials indispensable in areas such as aerospace, automotive, construction and sports equipment. The flexibility and processability provided by polymer matrices and the strength and hardness properties of the reinforcement materials allow PMCs to be used in such a wide range of applications. For example, the thermal expansion coefficient of

PMCs is between 30-60 x 10^{-6}/°C and offers dimensional stability over a wide temperature range.

These properties allow Polymer Matrix Composites to perform better than traditional materials in engineering applications. Properties such as high strength-to-weight ratio, corrosion resistance and durability make PMCs one of the indispensable components of modern engineering solutions. Detailed material image under optical microscope can be seen in the Figure 1.6 (Guo et al., 2017).

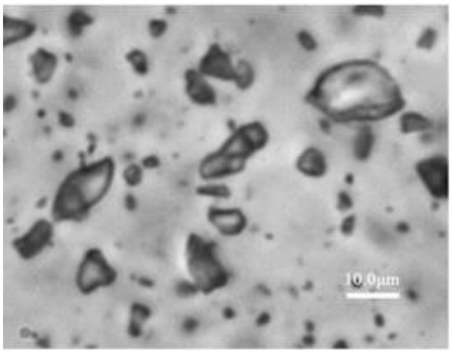


Figure 1.6 PMC under optical microscope

Table 1.1 Comparison of Properties of Types of Composites

PROPERTIES	CFRP	GFRP	MMC	PMC
Density (G/Cm³)	1.5 - 1.8	1.5 - 2.0	2.5 - 5.0	1.5 - 2.0
Tensile Strength (MPa)	3,000 - 6,000	800 - 1,500	500 - 2,000	2,000 - 3,500
Elastic Modulus (GPa)	150 - 300	30 - 50	70 - 200	70 - 120
Toughness	Low	Medium	High	Medium
Corrosion Resistance	Very High	High	Medium (Dependent on matrix)	High
Heat Resistance (°C)	200 - 300	150 - 200	400 - 1,000+	150 - 250
Thermal Expansion (10^{-6}/°C)	0.5 - 1.0	5 - 10	5 - 20	30 - 60
Applications	Aerospace, Automotive, Sports Equipment	Construction, Pipelines, Insulation	Aircraft engines, Armor, Automotive	Aerospace, Automotive, Construction, Sports Equipment
Cost	High	Low	Medium - High	Medium

Table 1.1 sheds light on the material selection process for engineering applications by comparing the numerical and mechanical properties of different composite materials.

CFRP stands out with its high strength and low-density advantage, while MMC are generally preferred in environments requiring high temperature resistance. PMC provide elastic properties and workability, while GFRP offers lower cost and moderate mechanical properties.

Composite materials offer numerous benefits, making them highly valuable across various industries. They possess a high strength-to-weight ratio, allowing them to be stronger and lighter than traditional materials like steel and aluminium. Many composites also exhibit excellent corrosion resistance, making them durable in harsh environments. Furthermore, the properties of composites can be customized to meet specific performance requirements, and they offer design flexibility, enabling them to be molded into complex shapes more easily than metals.

These advantageous properties make composite materials crucial in modern engineering. In the aerospace industry, carbon fiber composites are utilized in aircraft structures for their lightweight and high-strength properties. In the automotive sector, lightweight composite components contribute to improved fuel efficiency. In the construction industry, composites are used to reinforce concrete, bridges, and building facades. High-performance sports equipment, such as tennis rackets, golf clubs, and bicycles, benefit from the unique characteristics of composites. In the marine industry, composites are employed in boat hulls and other components due to their resistance to water and corrosion. The versatility and superior performance of composite materials make them indispensable in a wide array of demanding applications.

1.2. Mechanical Properties of Woven and Unidirectional Composites and Fiber Bridging Effect

Composite materials have an important place in modern engineering applications due to their high strength and low weight properties. In particular, woven and unidirectional composites offer different mechanical properties and application advantages due to their fiber orientation and arrangement. Both types of composites are specially designed to meet different requirements in various engineering projects.

1.2.1. Woven composites

Woven composites are obtained by weaving fibers over each other at right angles. This structure provides strength to the material in two directions and ensures that the loads are distributed homogeneously. In terms of mechanical properties, the tensile strength of woven composites varies between approximately 350-450 MPa. These values indicate that the fibers have the capacity to carry loads in both directions. The flexural strength is in the range of 200-250 MPa, which increases the material's resistance to bending and breaking under load. In terms of impact resistance, woven composites offer a high value of 50-70 kJ/m², making them highly resistant to impact forces.

1.2.2. Unidirectional composites

Unidirectional composites are formed by aligning the fibers in a single direction, and this alignment provides the material with very high strength in a given direction. For example, the tensile strength of unidirectional composites can reach up to 1500-1800 MPa in the fiber direction, making them ideal for applications requiring high tensile strength. The flexural strength is around 350-450 MPa in the fiber direction and 50-100 MPa in the other directions. While the impact resistance is high in the fiber direction (30-50 kJ/m²), it is lower in the other directions (5-15 kJ/m²).

1.2.3. Fiber bridging and mechanical performance

Fiber bridging is the situation where fibers act as bridges between crack surfaces in composite materials to prevent crack propagation and absorb energy during crack formation. This phenomenon plays an important role especially in woven composites, because the interlocking structure of the fibers effectively prevents the propagation of cracks and increases the fracture toughness of the material. In woven composites, fiber bridging increases the durability of the material by slowing down crack propagation and absorbing more energy. This allows the material to carry more load before breaking during crack formation and propagation.

In unidirectional composites, fiber bridging shows different effects depending on the alignment direction of the fibers. Cracks that occur in the fiber direction can show limited progress with the fiber bridging effect and the growth of the crack can be prevented. However, cracks that occur perpendicular to the fiber direction can progress faster due to the alignment direction of the fibers and can negatively affect the durability of the material. Below, Figure 1.7 (Fotouhi & Ahmadi Najafabadi, 2014), the difference in fiber bridging between unidiretional and woven arrangements can be clearly observed. While the fibers are separated more cleanly in the woven material, fringed separation is observed in the unidirectional.

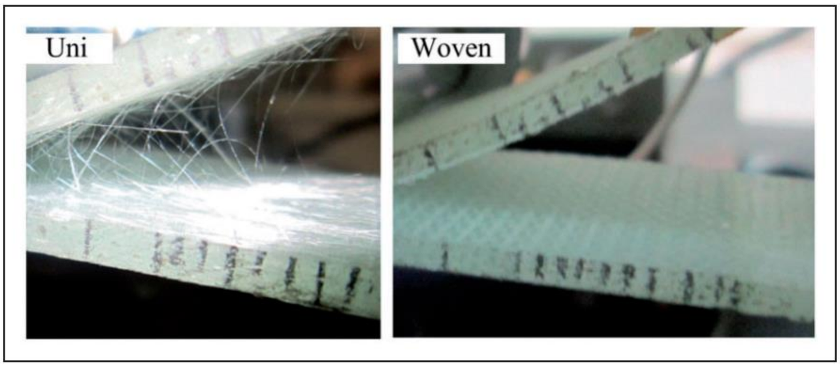


Figure 1.7 Fiber bridging in unidirectional and woven composites

1.2.4. Numerical data and application areas

Woven composites offer high impact resistance and bidirectional strength properties thanks to the fiber bridging effect, which makes them ideal for structural components exposed to impact and load changes such as the aviation and automotive industries. For example, woven composites used in an aircraft wing provide high safety and durability by distributing the loads from various directions evenly. Unidirectional composites are suitable for applications requiring high tensile strength. Unidirectional composites used in wind turbine blades increase energy production efficiency by providing high strength against forces in the fiber direction of the blade.

1.3. A Brief Review of Manufacturing Composites

Composite materials are engineered to combine two or more different materials to achieve desired properties that are not available individually. These materials are widely used in a variety of industries, including aerospace, automotive, construction, and sports. The manufacturing methods for composite parts are diverse, and each has its own advantages and suitable applications. For example, carbon fiber reinforced polymer (CFRP) parts are often used in the aerospace industry, where high strength and low weight are required, while glass fiber reinforced polymer (GFRP) parts are preferred in lower-cost applications such as construction and sports equipment. However, each composite part manufacturing process is determined by a number of factors, including the properties of the material components, structural requirements, and economic factors.

1.3.1. Wet lay-up/wet woven method for composite manufacturing

The Wet Lay-Up, also known as the Wet Woven method, is a fundamental technique in composite manufacturing. This method involves manually applying fiber reinforcements and resin to create composite structures. Its simplicity, cost-effectiveness, and flexibility make it suitable for a wide range of applications, especially where complex shapes and large sizes are involved.

The process begins with preparing a mold that defines the shape of the final composite part. The mold surface is treated with a release agent to ensure the easy removal of the cured part. Molds can be made from various materials, including metals, plastics, or composites, depending on the required surface finish and part complexity. Dry fiber reinforcements, such as fiberglass, carbon fiber, or aramid fibers, are manually placed into or onto the mold. The fibers can be in the form of woven fabrics, unidirectional tapes, or chopped strand mats. Careful arrangement and orientation of fibers are crucial to achieve the desired strength and mechanical properties in the final part.

Liquid resin, typically polyester, epoxy, or vinyl ester, is applied to the laid fibers using brushes, rollers, or spray equipment. The resin serves to impregnate the fibers, acting as the matrix that binds them together. The resin must be worked into the fibers thoroughly to eliminate air pockets and ensure complete wet-out of the reinforcement material. Additional layers of fibers and resin can be added as needed, with each layer being thoroughly consolidated to remove trapped air and ensure proper resin distribution. This step may involve using hand tools to roll out air bubbles and ensure good contact between layers.The resin-impregnated fibers are left to cure, which can occur at room temperature or with the application of additional heat to speed up the process and achieve better mechanical properties. Curing times and temperatures depend on the type of resin used and the part thickness. Once fully cured, the composite part is removed from the mold. The use of a release agent aids in this step, ensuring the part does not stick to the mold. Post-processing steps may include trimming excess material, sanding, and finishing to achieve the desired surface quality and dimensions.

The Wet Lay-Up/Wet Woven method is commonly employed for manufacturing large, simple structures where high production volumes and precision are not critical. Typical applications include boat hulls, decks, and panels in the marine industry due to the method's suitability for large and contoured surfaces. In construction, it is used for custom architectural elements such as decorative panels, domes, and columns. The automotive industry uses it for prototyping and low-volume production of car body panels, interior components, and custom parts. In the recreation sector, it is used for manufacturing sports equipment like surfboards, canoes, and playground structures.

This method offers several advantages. It has minimal equipment and tooling costs, making it accessible and affordable, especially for small to medium-sized operations. It can accommodate a wide range of shapes and sizes, allowing for significant design flexibility. The process is straightforward, making it suitable for manual operations and small-scale production. However, it is labor-intensive, which can limit scalability and consistency. Compared to advanced methods like autoclave molding or RTM, Wet Lay-Up parts often have lower fiber volume fractions and mechanical properties. Achieving consistent quality and avoiding defects like air bubbles and uneven resin distribution can also be challenging.

The Wet Lay-Up/Wet Woven method remains crucial in composite manufacturing due to its cost-effectiveness and versatility. Although it lacks the performance and precision of advanced methods, it offers an accessible way to produce composite parts, especially for large and complex structures. Understanding its process, applications, and limitations helps manufacturers effectively use this method, promoting the widespread adoption and advancement of composite materials across various industries. Wet layup manufacturing parts can be seen below Figure 1.8 (Flake C. Campbell, 2004).

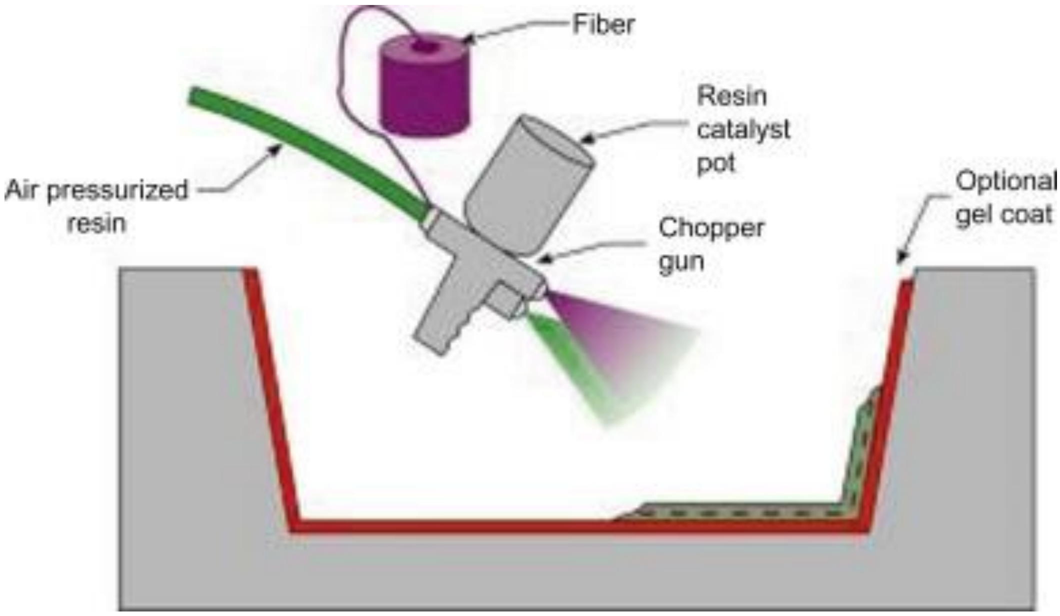


Figure 1.8 Wet-Woven method with autoclave

The Wet Lay-Up process can be summarized as follow, see Figure 1.9 (Sonat, 2021):

1. Adhesive need to be prepared and weighted.
2. Dry fabrics will be wet with adhesive
3. Composite plies and lay-up need to be prepared

4. Specimen will be bagged.
5. Cure process will be implemented with heat blanket.

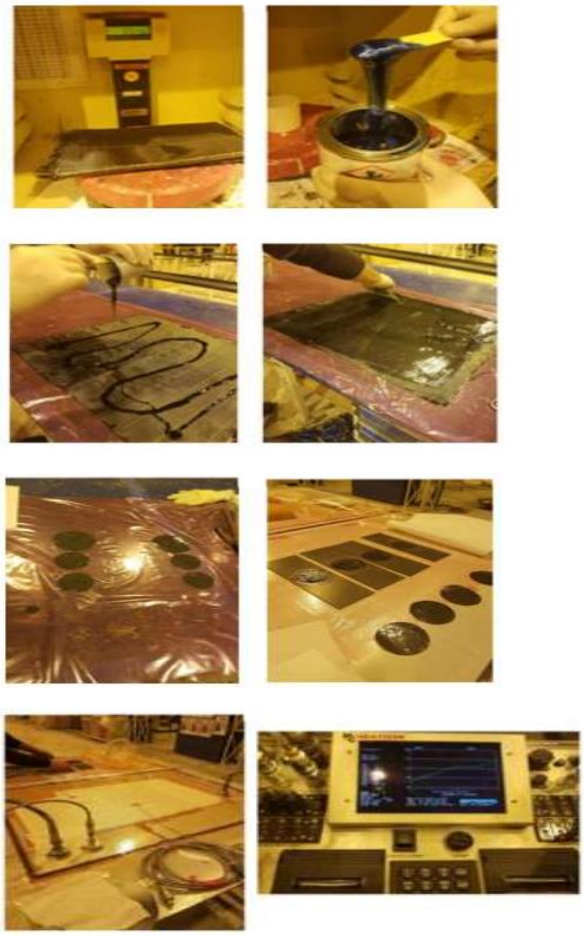


Figure 1.9 Steps of wet-woven repair & manufacturing method

1.3.2. Prepreg method for composite manufacturing

The Prepreg method is an advanced technique in composite manufacturing that involves using fiber reinforcements pre-impregnated with partially cured resin. This method is renowned for its precision, exceptional mechanical properties, and extensive use in high-performance sectors like aerospace and motorsports. The process begins with the preparation of prepreg materials, which involves impregnating fibers such as carbon fiber, fiberglass, or aramid with a resin system, typically epoxy, that is partially cured to create a tacky material that can be manipulated and cut to shape. These materials are stored at low temperatures to prevent further curing before they are used.

In the lay-up stage, the prepreg sheets are cut into specific shapes and sizes using templates or CNC machines and then laid onto a mold in particular orientations and stacking sequences to achieve the desired laminate properties. Ensuring proper alignment and fiber orientation is crucial for optimal mechanical properties. Once the lay-up is complete, the assembly is covered with a release film and breather fabric, then sealed inside a vacuum bag to remove air and compress the layers, ensuring good consolidation and eliminating air voids within the laminate.

The vacuum-bagged assembly is then placed in an autoclave or oven, where heat and pressure are applied to enhance laminate quality by increasing resin flow and reducing void content. The curing cycle involves controlled heating to specific temperatures, followed by a dwell period and gradual cooling, with exact parameters depending on the resin system used. After curing, the composite part is removed from the mold, and post-processing steps such as trimming, machining, sanding, and surface finishing are carried out to meet precise specifications.

The Prepreg method is widely employed in industries requiring high performance and precision. In aerospace, it is used for structural components, control surfaces, and fairings due to its ability to produce lightweight, high-strength parts with excellent fatigue resistance. In motorsports, it is used for chassis components, body panels, and aerodynamic parts, leveraging the superior strength-to-weight ratio and precision. Sporting goods such as high-end bicycles, tennis rackets, and golf clubs benefit from the performance and consistency of prepreg composites, while medical devices like prosthetics and imaging equipment components require high precision and biocompatibility.

The advantages of the Prepreg method include high mechanical properties, consistency, and quality due to controlled fiber orientation and resin content, as well as design flexibility, allowing materials to be tailored for specific applications. However, the method also has limitations, such as high initial costs for prepreg materials and specialized storage and processing equipment, handling requirements to prevent premature curing and contamination, and the time-consuming nature of the curing process, which requires precise temperature and pressure control. Prepreg manufacturing parts can be seen below Figure 1.10 (Orthogonal Engineering Ltd, 2024).

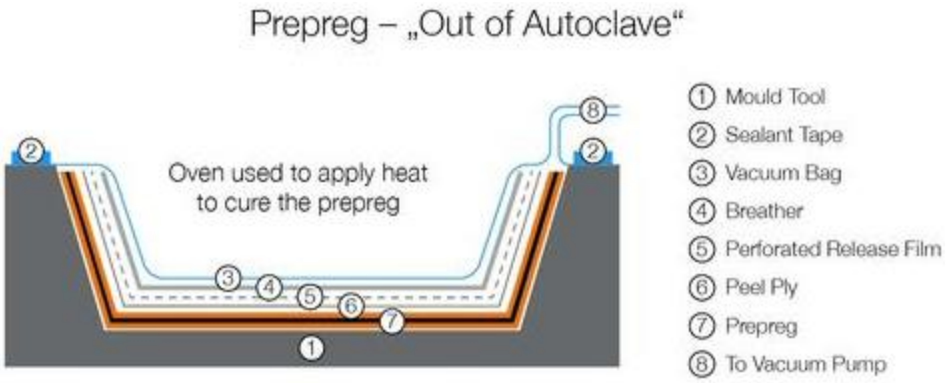


Figure 1.10 Diagram of prepreg method with autoclave

The Prepreg process can be summarized as follow, see Figure 1.11 (Sonat, 2021):

1. Surface will be prepared with sanding and cleaning.
2. Lay-up of the film adhesive (FM300K) and plies will be placed with required orientation.
3. Specimen will be bagged.
4. Cure process will be implemented with heat blanket.

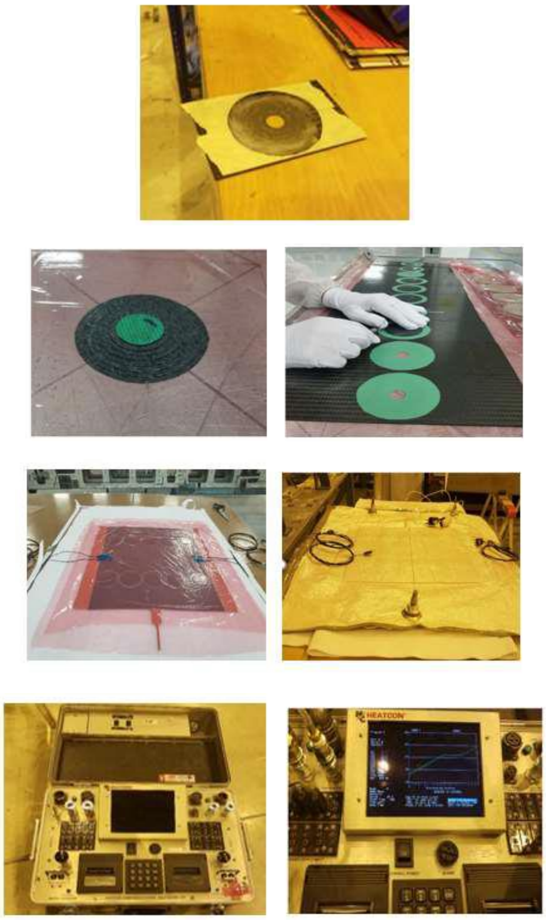


Figure 1.11 Steps of Prepreg repair & manufacturing method

In (Sonat, 2021) stepped, damaged, wet lay-up repaired, and prepreg repaired specimens were investigated with finite element analysis. In the light of experimental results, it seems that prepreg manufactured/repaired specimens are by far more resistant to load(N) than wet woven and other methods. These experimental and FEA results can be seen in the figure below (Sonat, 2021).

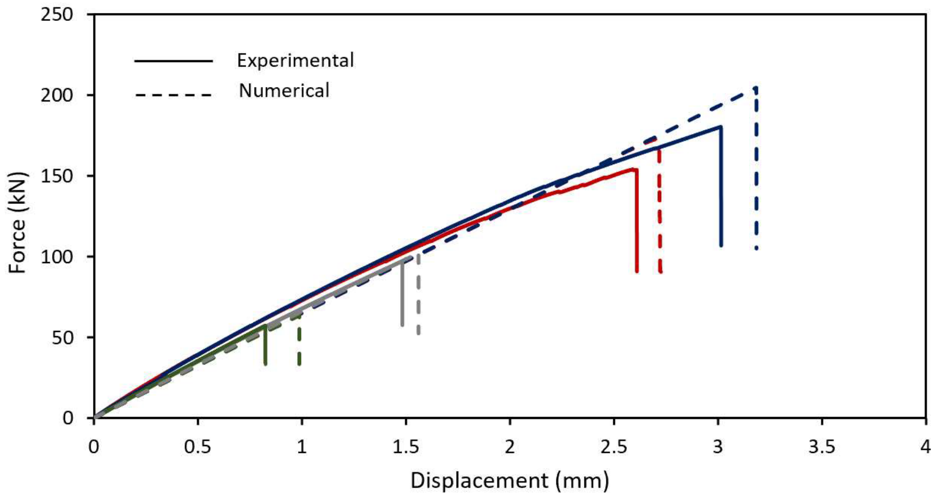


Figure 1.12 Force-Displacement graph for wet-woven and prepreg method

1.4. Literature Exploration of Impact Effects in Composite Defects

The text named "*Defects and Damage in Composite Materials and Structures - Rikard Benton Heslehurst*" discusses the various types of defects that composite components may encounter, totalling 52 distinct types. These defects vary from microscopic fiber faults to substantial impact damage. Each defect is described in detail within the chapter, and they are subsequently categorized into specific groups. This categorization aids in identifying defects that pose particular concerns regarding the in-service life of composite and bonded aircraft structures. In Figure 1.13 (Heslehurst, 2014), delamination between layers and matrix crack in a layer can be observed.

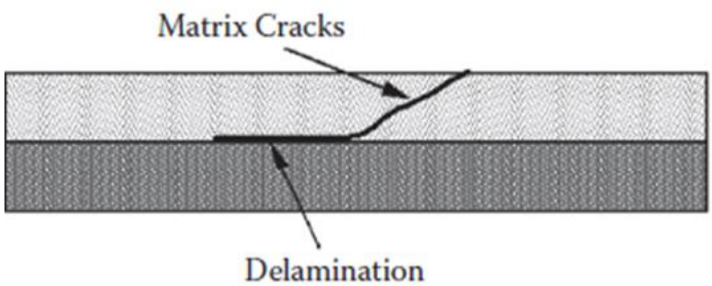


Figure 1.13 Delamination & matrix cracks defect type

Delamination, also known as interlaminar cracking, is one of the common types of defects encountered in advanced composite materials. Delaminations occur as a result of matrix defects. In-plane matrix cracks occur when cracks propagate parallel to the fiber directions within or between the layers of a laminate. Delaminations can occur under both static and cyclic loading conditions, but they are typically associated with compression as a flaw, leading to a significant decrease in compressive and shear strengths of the component. The response of delaminations, their size and location within the laminate, laminate orientation/stacking sequence, and test environment all influence their behavior. The larger and deeper the delamination within the laminate, the greater the loss of strength. Delaminations near the surface only grow steadily but result in negligible strength loss. Small delaminations cause minimal strength loss. Delaminations result in localized interlaminar crack stresses. These effects are summarized in Figure 1.14 (Heslehurst, 2014).

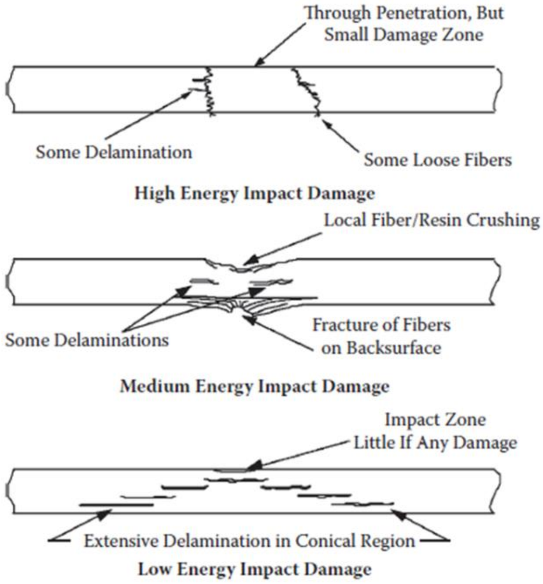


Figure 1.14 Energy levels of impact damage

Another type of defect, known as debonding, refers to separations occurring in secondary adhesive bonds or sandwich surfaces. This defect can occur during impact damage, thermal fluctuations, excessive loading, or freeze-thaw cycles. Debonding will decrease the local stiffness of a component, but it does not always affect the strength of the component, see Figure 1.15 (Flake C. Campbell, 2004). In summary, debonding is the term given to delamination between bonded structures.

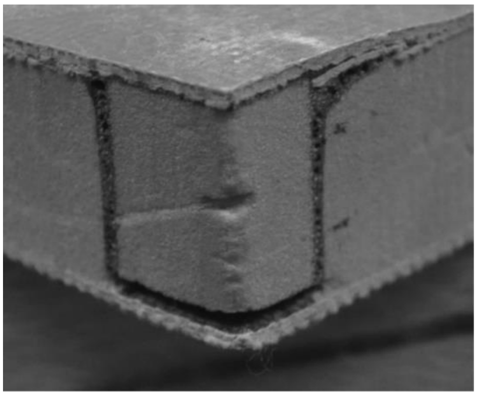


Figure 1.15 Debonding by the poor junction between the surface and the core.

1.5. Understanding Destructive and Non-Destructive Testing: Methods and Applications

1.5.1. Destructive testing

Destructive testing is carried out to ascertain the physical and mechanical characteristics of a material. Through these assessments, one can evaluate the strength, hardness, toughness, fatigue resistance, and other properties of the material to make informed judgments about it. Destructive testing serves as a crucial method for assessing the performance and quality of materials. These tests can determine whether a material is appropriate for a particular application. Destructive testing is extensively utilized in various sectors, including the aerospace industry, to obtain insights into the design, manufacturing, quality assurance, performance, and lifespan of materials, as well as to evaluate their damage and wear.

The tests we can conduct on the component once it is provided to us are as follows:

1.5.1.1. Tensile testing:

The tensile test is a destructive testing method where a material specimen is subjected to deformation by being pulled from one end. This test is the most commonly used type for determining the stress-strain behavior of a material. The force applied to the specimen is measured using a force gauge. Changes in the specimen's length and diameter are measured with an extensometer. One end of the specimen is attached to the jaws of the tensile testing machine, while the other end is connected to the extensometer.

The tensile test consists of the following steps:

1. A small initial stress, known as the initial stress, is applied to the specimen.

2. The changes in the specimen's length and diameter are measured with the extensometer.

3. A gradually increasing force is applied to the specimen.

4. The changes in the specimen's length and diameter are measured at each step.

5. The force is continuously applied until the specimen breaks.

6. The results of the tensile test are presented as a graph showing the material's stress-strain behavior. This graph is used to determine the material's yield point, tensile strength, elongation at break, and fracture characteristics.

Tensile Strength: The maximum stress level the material can withstand before breaking.
Elongation at Break: The amount of stretch the material undergoes before breaking.
Fracture Characteristics: The manner in which the material breaks.
These points are combined to create the graph shown in figure below (Lim & Hoag, 2013).

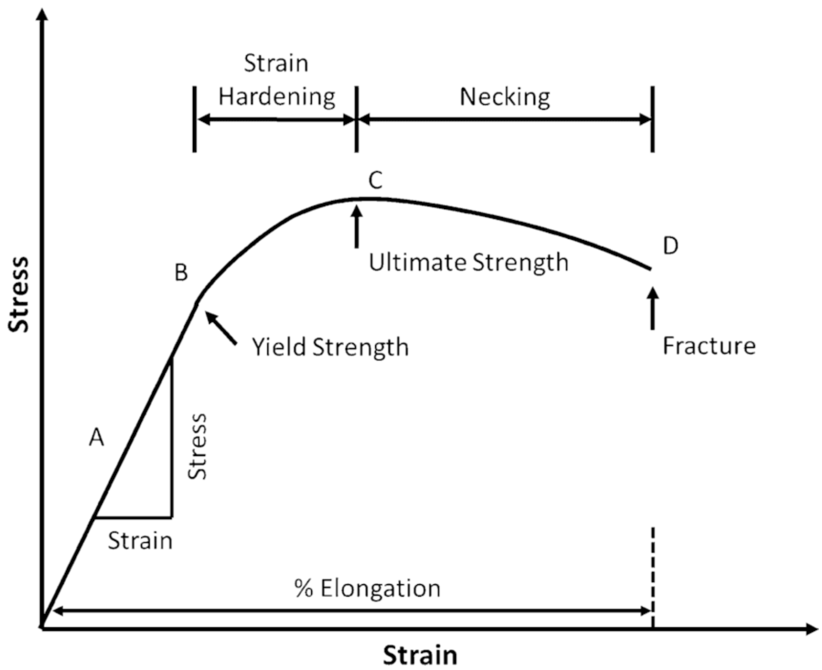


Figure 1.16 Stress-Strain graph and important point

The stress-strain graph is a fundamental tool in materials science and mechanical engineering for understanding how materials behave under different loads. This graph reveals how much deformation (strain) a material undergoes under applied stress (stress) and the properties of the material during this deformation.

Proportional Limit: It refers to the highest stress point at which the material exhibits a linear relationship between stress and strain. Up to this point, Hooke's Law is valid and stress is linearly proportional to stress. Up to this point, the material returns to its original shape when the applied load is removed.

Elastic Limit: It is the highest stress level that the material can withstand without permanent deformation. Beyond this point, the material will undergo permanent deformation, i.e. the material will not return to its original shape when the applied load is removed.

Yield Point (Yield Strength): It is the stress level at which the material begins to deform plastically. At the yield point, the material begins to show a significant amount of deformation, and this occurs without a significant increase in stress in response to the increase in deformation. This point refers to the critical point at which permanent deformation begins in the design of structures. In some materials, especially metals, there may be a difference between the upper and lower yield points. The upper yield point is the maximum stress and then decreases, while the lower yield point is the stress at which the material shows plasticity.

Ultimate Tensile Strength (UTS): The highest level of stress that a material can withstand before significant reduction in dimensions (necking). This point represents the maximum load capacity that the material can carry. Beyond the maximum tensile strength, the cross-sectional area of the material begins to decrease significantly, and this is called necking.

Necking: The significant reduction in the cross-sectional area of a material in a defined area. During necking, the material cannot carry the applied load evenly and localized deformation occurs. This results in a reduction in the load carrying capacity.

Fracture Point (Breaking Point): The point at which the material breaks or ruptures. This point indicates where the material finally fails and breaks. The breaking point is critical to understanding the rupture properties of the material.

1.5.1.2. Compression Test

The compression test involves subjecting a material specimen to deformation by compressing it from both ends, see Figure 1.17 (Pan et al., 2021). This test is used to determine the material's behavior under compressive forces. The force applied to the specimen is measured using a force gauge. Changes in the specimen's length and diameter are measured and recorded using an extensometer.

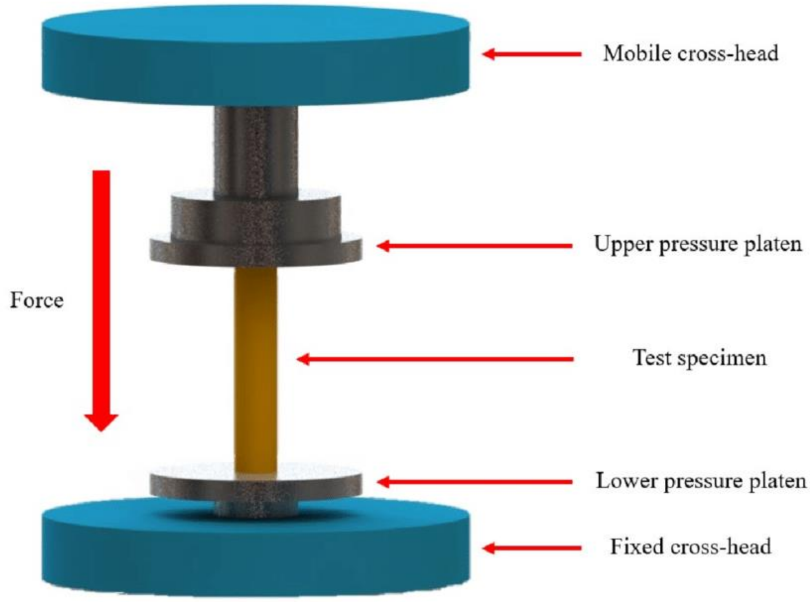


Figure 1.17 Compression test machine and its components

The compression test comprises the following steps:

- Both ends of the specimen are secured to the jaws of the compression testing machine.
- A small initial pressure, referred to as the initial pressure, is applied to the specimen.
- Alterations in the specimen's length and diameter are measured with an extensometer.
- Gradually increasing pressure is applied to the specimen.
- Changes in the specimen's length and diameter are recorded at each step.
- Pressure is continually applied until the specimen loses its original shape.
- The results of the compression test are displayed as a graph illustrating the material's behavior under compression. This graph, as depicted in the Figure 1.18 (Abd Malek et al., 2015), is used to determine the material's compressive strength, elongation at break, and fracture characteristics.

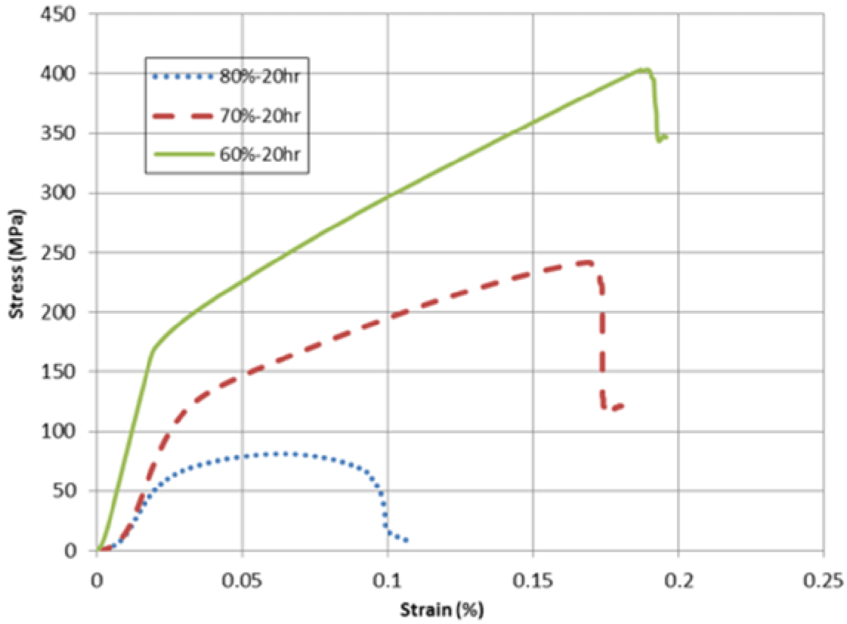


Figure 1.18 Critical evaluation on structural stiffness of porous cellular structure of cobalt chromium alloy defined by compression testing

Compressive Strength: The maximum level of compressive force the material can endure before breaking.

Elongation at Break: The amount of deformation the material experiences before breaking.

Fracture Characteristics: The manner in which the material breaks.

1.5.2. Non-Destructive testing

Non-Destructive Inspection (NDI) methods are used in three ways in the repair process of composite and bonded structures. These are:

- Damage location
- Damage assessment, determining the type, size, shape and internal location of the damage
- Post-repair quality assurance.

The first and most important activity in the repair process is to identify the defect or damage. Assessment of the damage is initially carried out by visual inspection. Detailed non-destructive testing is essential when dealing with composite and bonded structures, where often the damage is hidden inside the structure, with hardly any indication on the surface. An example of composite damage is shown in Figure 1.19 (Katleen Vallons, 2009).

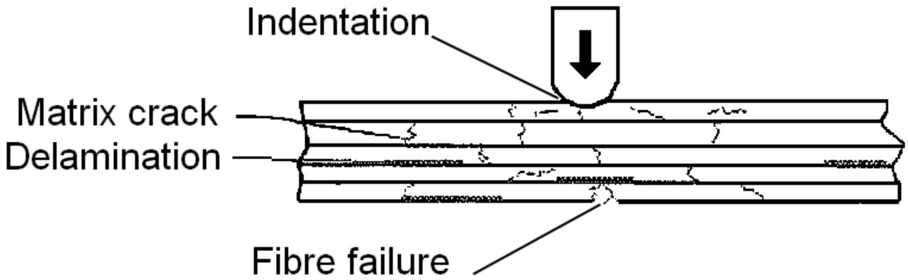


Figure 1.19 Delamination and fibre failure which is the type of composite damage

The types of NDI (Non-Destructive Inspection) methods currently available are:

- Visual, optical magnification and error enhancement methods
- Acoustic methods
- Ultrasonic methods
- Thermography
- Interferometry
- Radiography
- Microwave method
- Material property changes

Most of the non-destructive testing methods that can be used on composite and bonded structures have been successfully used on metal structures. However, the application of these methods on composite and bonded structures requires some changes in the operating parameters and interpretation of the results. Due to the diversity that can be found in composite structures, several methods may be needed to determine the exact damage condition. Therefore, when several methods are needed to find and assess the type of damage of composite structures, there is a need to invest in more non-destructive testing equipment and correspondingly more highly trained non-destructive testing assessors.

1.5.2.1. Visual inspection

Even very small surface imperfections can be identified with basic magnification, in addition to the assessor's own eyes, provided that the defect is clearly visible. Defects or matrix cracks can be made more visible by enhancing them with a dye penetrant. Boroscoping techniques can also be used to detect some internal flaws. A visual examination of the joint line allows for some estimation of the resin flow. Simple visual tools can be used to assess typical resin flows from the edge of the bonded joint, as shown in figure below (Qing et al., 2021).

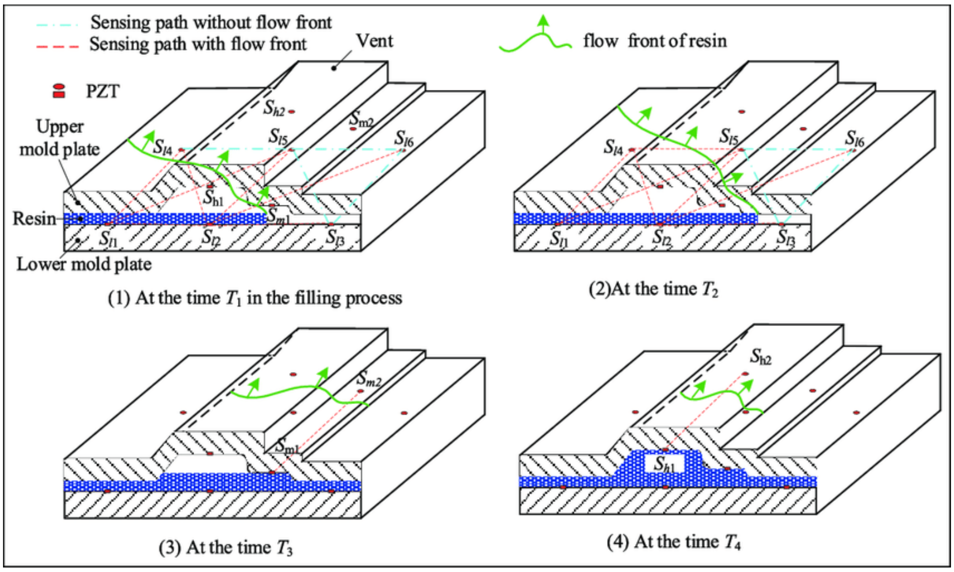


Figure 1.20 In-Situ Monitoring of Liquid Composite Molding Process Using Piezoelectric Sensor Network

One class of inspection techniques that is typically simple, inexpensive, and low skill level is visual methods. These techniques work well for addressing surface imperfections but do require a reasonably clean problem surface. In many different industries, visual methods are preferred because of these benefits. However, depending on the specifications and properties of the object to be inspected, these methods' efficacy may vary.

One kind of inspection technique used to find material surface flaws is paint-penetrant method. The surface that will be studied using this method needs to be contaminated beforehand. The part must be thoroughly cleaned both before and after using this method, which is typically limited to the detection of surface flaws. To get precise results, these cleaning steps are crucial. This approach is relatively easy to implement and portable, making it suitable for use in a variety of industrial settings. It should be mentioned, though, that some operator skill is necessary. This ability is necessary to get precise results and find material flaws efficiently.

1.5.2.2. Acoustic Methods

For composite structures, every acoustic emission technique under consideration now requires the operator or acoustic noise detection equipment to listen for the development and movement of cracks through acoustic changes in sound produced by a small impact or elastic wave energy propagation.

An inspection technique called the "hammer method", see Figure 1.21 (Bilal Afzal, 2020), is employed to find surface flaws. It is very easy to use, but it is limited to shallow defects, or defects that are close to the surface. But this approach relies heavily on geometry, which frequently calls for two-sided access, particularly when examining unique structures like sandwich panels. This approach's portability makes it applicable to various industrial settings. The ability to detect flaws through the knocking sound depends on the operator's experience, so having good hearing is essential for the efficient use of this method.

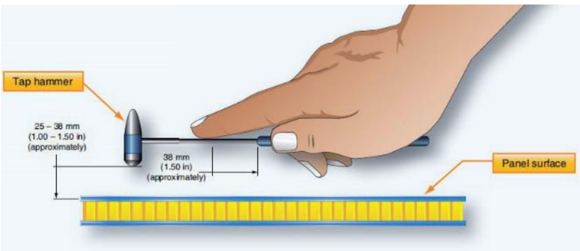


Figure 1.21 Tap hammering method

The acoustic emission method is an inspection technique that records transmitted sound waves in order to detect material defects. It has a few key components. Experienced operators are needed to install the system, and their ability to correctly interpret the results also depends on their level of experience. This method requires the operator to have strong technical knowledge because it produces complex outputs that must be understood. Acoustic emission can be used in a variety of settings due to its portability, and one benefit of this approach is that data can be recorded. Additionally, a more accurate and thorough inspection is possible because of this method's high sensitivity to even minute changes in defects.

1.5.2.3. Ultrasonic Methods

With regard to the equipment needed to carry out the procedure, the use of ultrasonic inspection can range from being relatively cheap to being highly expensive. The techniques can only give precise information about the topography of subsurface flaws. There are two fundamental ultrasonic techniques. These techniques are transmission (C-scan) or pulse-echo (A-scan). Both techniques track how much the sound attenuates, or loses amplitude, as it moves through the region of interest.

The pulse-echo method is a technique used in materials inspection and has a number of features. In this method, the amplitude of the return signal is displayed against time and a coupling agent is used to transmit the sound wave to the part. The method provides detailed information on defect type, size, location and depth. It is particularly sensitive in detecting small defects. It requires a standardized sample to compare results and needs experienced operators. (Heslehurst, 2014)

Its portability allows the pulse-echo method to be applied in different locations and the ability to record the data obtained are among its advantages. The test machine and procedure can be seen in following figure (Mayank Mishra, 2013).

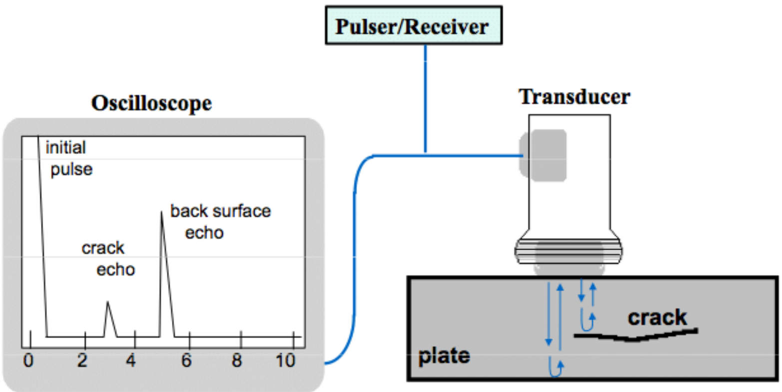


Figure 1.22 A Scan plot and A Typical Ultrasonic pulse echo system

The transmission method of inspection has certain characteristics. It is automated and therefore allows for a faster inspection process. It ensures complete coverage of the component, but may require double-sided access. The transmission method is only used to detect internal defects and only accurately identifies the size and position of the defect. This method focuses on examining the internal structure and has limited ability to identify external defects. Therefore, the transmission method is generally preferred for the detection of internal defects.

1.5.2.4. Thermography

A non-destructive testing method called thermography gauges a structure's reaction to the release of thermal energy. Techniques for passive thermography are used to locate non-contact internal defects where heat energy propagates at a slower rate. When a defect is present, active thermography activity causes the structure to vibrate or load cycle, which increases heat and causes localized stress. Every thermography technique has some features. In order to guarantee the accuracy of the data acquired, they first need standards for the results' verification. Moreover, these techniques' portability and data-recording capabilities enable them to be used in various contexts and store the collected data.

To assess the outcomes, they need skilled operators and interpretation. Accurately analysing the thermal images obtained is crucial in order to detect any potential defects on the material under inspection. Additionally, they are geometry-dependent, meaning that the evaluation of thermal images varies based on the composition and form of the material under study. These qualities play a significant role in the effectiveness and dependability of thermography techniques.

1.5.2.5. Interferometry

Optical interferometry is the process of identifying flaws using light and its reflective qualities. One type of inspection technique that has specific features is interferometric methods. Initially, these methods necessitate costly equipment, which may pose a financial strain on the organizations using them. In order to apply the method effectively, they also need skilled interpreters and equipment operators, which takes expertise. They must frequently be used in a specific location and are frequently immobile, which can restrict inspection procedures. However, they have the advantage of being able to offer a full-field record of defect behavior under load, which is very helpful in demonstrating how the defect and structure respond to load. Because of their high sensitivity, interferometric techniques enable in-depth examination of flaws and structures.

1.5.2.6. Radiography

For in-depth inspections, radiography—a non-destructive testing method—is indispensable. The two main types of radiography are X-ray and neutron radiography. Because X-ray radiography is simple to interpret, the data can be evaluated and understood. It offers a permanent record for defect identification and monitoring, making it perfect for inspecting honeycomb sandwich panels. It does, however, necessitate costly equipment, which puts a financial strain on organizations. Because of its portability, it can be used anywhere, but its use may be restricted by rigorous safety regulations. For a thorough inspection, it can be combined with other inspection techniques like dye penetration, but accurate results are dependent on skilled operators. Though fundamentally similar to X-rays, neutron radiography uses neutron beams to study internal structures. It is particularly useful for in-depth analyses of composite materials and identifying characteristics such as moisture trapping. Neutron radiography offers better resolution, enabling the observation of smaller and more complex structures, despite its high cost, which limits its applicability. As a result of its sophisticated capabilities, it is frequently employed in expensive and specialized applications.

1.5.2.7. Microwave Methods

By measuring microwave absorption, the microwave method is primarily applied to non-metallic materials to ascertain their moisture content level. A technique used in materials inspection is the microwave method, which has specific application requirements. It is crucial to safeguard metal components during the inspection process, as this approach necessitates two-sided access on composite panels or structures. Operator safety is of utmost importance, and appropriate measures must be implemented. Additionally, using the microwave method produces more accurate and dependable results when the material is cleaned before inspection. These guidelines have been put in place to guarantee the efficient and safe execution of microwave inspections.

1.5.2.8. Material Property Changes Methods

The two main material property-based inspection methods are dielectric and hardness. Adhesive or composite cure degree is determined by dielectric analysis using inductance, whereas changes in hardness are evaluated by theoretical analysis and mechanical testing. Both approaches have drawbacks; some variants include optical fibers, piezoelectric sensors, and embedded strain gauges.

When embedded in laminated structures, optical fibers can help localize damage and help identify the exact location of harm in the event of damage, particularly in impact damage that is difficult to see with the naked eye. Optical fibers are usually placed at suitable intervals close to the surface of vulnerable areas to guarantee accurate damage detection. When exposed to voltage, piezoelectric sensors produce an electric current, which helps them detect localized overload conditions and out-of-plane loads in particular. For efficient monitoring, piezoelectric sensors are positioned in high-risk or possibly damaged areas, much like optical fibers. Figure 1.23 shows an example of how data from a project can be displayed (Oruç et al., 2022).

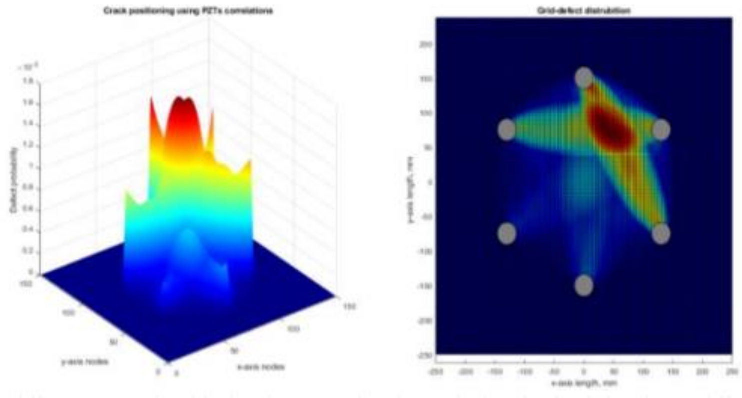


Figure 1.23 Structural Health Monitoring of Aircraft Wings

Embedded strain gauges generate readings of excessive strain in order to identify local overload conditions. While sensor placement and data interpretation are critical for reliable overload results, sensor repair in damaged composites remains a significant challenge. Selecting the appropriate technique and hiring qualified staff is essential for effective non-destructive testing. Factors to consider include component configuration, material, defect type and size, accessibility, and operator availability. Inspectors need to be skilled in a variety of methods, set up and maintain equipment, accurately interpret data, and follow safety regulations. For non-destructive testing to identify damage in adhesive-bonded and composite structures with accuracy, it needs the right tools, facilities, operators with the right training, and comparative samples.

1.6. Assessing Material Integrity: Bonding and Adhesives

Bonding techniques include various methods used to join materials and these techniques are used in a wide range of modern engineering applications. Bonding methods are generally divided into two main categories: adhesive bonding and mechanical bonding. Other techniques such as welding, soldering and interference fit are also available, but adhesive and mechanical bonding are the most prominent methods due to their popularity and wide range of applications.

1.6.1. Mechanical bonding

Mechanical bonding is a method of joining materials using mechanical fastening elements. In this method, physical bonding elements such as screws, bolts, rivets or clips are used. This technique is highly resistant to shape and size changes of materials and usually provides a reversible bond. Mechanical fastening methods are widely used in applications where heavy loads need to be transported, and in addition to being a frequently used method, it also provides convenience in assembly and disassembly processes.

1.6.2. Adhesive bonding

Today, composite materials are frequently used in many sectors from automotive to aviation and the prevalence of composite materials is increasing. With the widespread use of composite materials, the joining of composite materials is important. These joiners are critical in many areas such as ensuring composite structural integrity, increasing functionality and reducing cost. In this context, many different techniques have been developed for bonding composite materials. Among these, mechanical fastening, adhesive bonding, fusion bonding are the main bonding techniques used. Each method has its own advantages and disadvantages. Choosing the right bonding method depends on many different parameters such as material properties, environmental factors, project requirements. The most preferred bonding methods among these are adhesive bonding and mechanical bonding.

Adhesive bonding has become increasingly popular with the widespread use of composite materials. Adhesive bonding is a joining technique for bonding dissimilar or identical composite materials. Adhesive bonding stands out due to its robust and lightweight bonding properties, especially in industries such as aerospace, automotive and marine where structural complexity is increasing day by day. Compared to traditional bonding methods, adhesive bonding offers advantages such as fast assembly process, improved damage tolerance and reduced structural weight. However, adhesive bonding also comes with some disadvantages. The disadvantages include surface preparation requirements and sensitivity of the adhesive to environmental conditions.

Metin girmek için buraya tıklayın.The durability of adhesives used in composite materials depends on many factors. These factors mainly include the chemical properties of the adhesive, the type and geometrical properties of the composite material, surface preparation and environmental conditions. Adhesive durability is also one of the most important factors in the long-term performance of the composite structure. Adhesive durability can be affected by environmental factors such as temperature, humidity and chemicals, which can adversely affect adhesive performance over time. In addition to all these, factors such as the compatibility of the adhesive with the surface and the thickness of the adhesive play an important role in the strength and integrity of the bond.

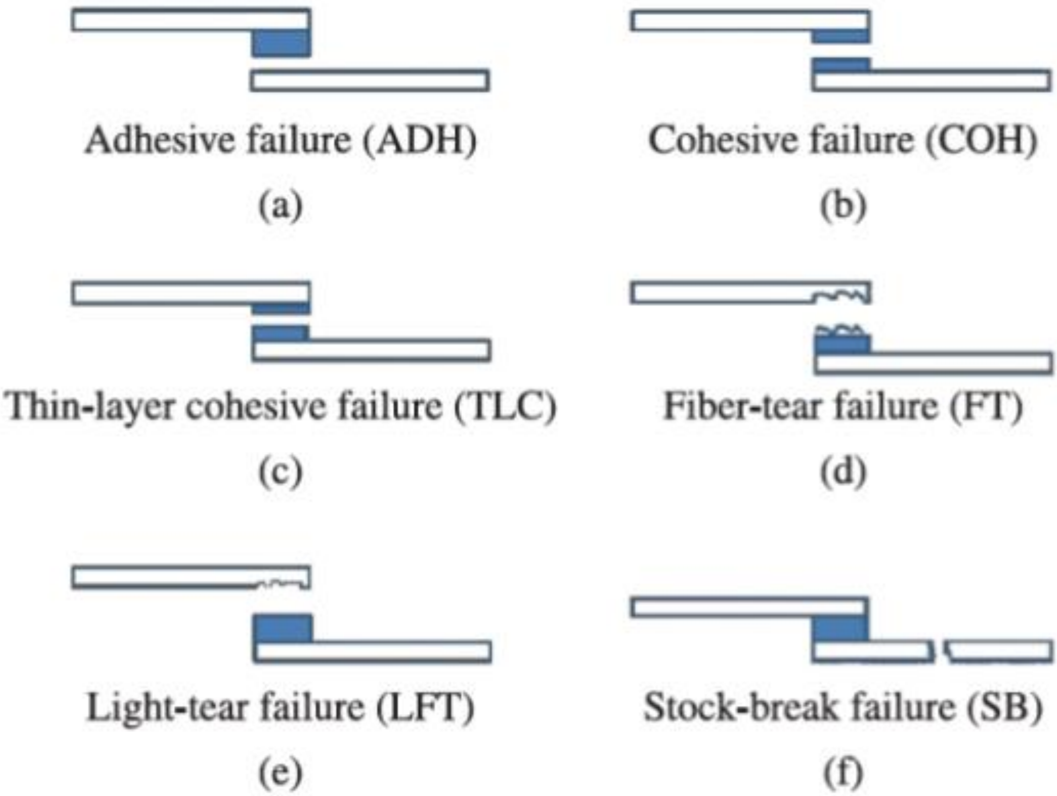


Figure 1.24 Bonding procedures and mechanisms about failure

There are six fracture mechanisms associated with adhesive bonding procedures shown in Figure 1.24(İplikçi, 2022) ; however, two of them are typically observed. There are two distinct kinds of fracture processes: cohesive and adhesive fractures. Advanced adhesives such as FM300K are known for their high temperature resistance and superior mechanical properties. FM300K is an adhesive with excellent chemical and environmental resistance that can operate over a wide temperature range from -55°C to 121°C. This adhesive is often used in high performance industries such as aerospace and automotive. Adhesive **Adhesive Failure (ADH):** This occurs at the interface between the adhesive and the adherend, often due to poor adhesion or surface preparation.

Cohesive Failure (COH): This takes place within the adhesive layer itself, usually indicating that the adhesive has reached its maximum stress capacity.

Thin-Layer Cohesive Failure (TCL): Similar to cohesive failure but occurs in a thin layer of the adhesive.

Fiber-Tear Failure (FT): The failure propagates into the fibers of the composite, indicating strong adhesion but insufficient fiber strength.

Light-Tear Failure (LFT): A partial tear within the adherend or the adhesive layer.

Stock-Break Failure (SB): A complete break through the adherend material

The performance of adhesive joints can be significantly enhanced by optimizing surface treatments to improve adhesion, controlling the adhesive application process, and designing joint geometries to minimize stress concentrations.

Criteria		Bolts / Screws	Rivets	Welding	Spot Welding	Clinching	Clip Fastening	Adhesive Bonding
Joining dissimilar materials	Use of most suited materials	●	●	○	–	●	●●	●●
Calculability of joint	Simplicity to design and calculate	●●	●●	●●	●●	●	○	●
Thermal Distortion	Additional process steps (sanding)	●●	●●	–	–	●	●●	●●
Occupational physiology	Noise, chemical emissions	●	○	○	○	○	●●	●
Sealing of Joint	integrated sealing function	–	–	●	○	○	○	●●
Susceptibility to corrosion	Preventive measures do guard against corrosion	○	–	●	○	●	○	●
Strength Development	How quickly can a part be moved. Integration into production cycle	●●	●●	●●	●●	●●	●●	●/○
Temperature resistance of joint	Need to take into account extreme exposures	●●	●●	●●	●●	●●	●/○	●/○
Ease of disassembly	Ease of repair / recycling	●●	●	○	○	●	●	●

●●: very suitable ●: suitable ○: partly suitable –: not suitable

Source: Verlag Moderne Industrie, Sika: Elastic Bonding

Figure 1.25 Compression of various bonding and fastening methods

This Figure 1.25(Verlag Moderne Industrie, 2022) shows that adhesive bonding is the most suitable option for joining different materials, as it is compatible with a wide range of materials. This method is especially preferred for joining materials with different properties, such as composite materials, and offers a significant advantage in applications where sealing is required with its integrated sealing capacity.

As adhesive bonding usually requires a chemical process, the engineering calculations of the joint are more complex; however, the resulting joint offers excellent strength and durability over a wide temperature range, especially when using high performance adhesives such as FM300K. FM300K adhesives are characterised by short curing times and excellent mechanical properties in the 120-180°C range. This makes it possible to obtain a robust and reliable joint resistant to high temperatures.

On the other hand, mechanical fastening methods (e.g. screws, rivets) offer the advantages of high calculability and simple design. These methods are advantageous against thermal degradation due to their resistance to high temperatures and are particularly favoured in applications requiring high temperature resistance. Mechanical connections may have some negative impacts on occupational health and safety such as noise, vibration and chemical emissions. The corrosion resistance of these connections can be increased by protective measures. In addition, since mechanical connections are usually detachable, they facilitate maintenance and repair operations. This makes them ideal for easily repairable and recyclable applications.

As a result, each bonding method offers various advantages and disadvantages for specific applications. Adhesive bonding methods are characterised by properties such as sealing and corrosion resistance, while mechanical connections offer advantages such as ease of calculation and high temperature resistance.

Adhesive and mechanical bonding methods each offer certain advantages and disadvantages. The comparison between adhesive bonding and mechanical bonding varies according to the application area and requirements.

1.6.2.1. Advantages and Disadvantages of Adhesive Bonding:

Advantages:

- Provides a homogeneous stress distribution on the surface, which increases structural integrity and reduces stress concentrations.
- Excellent compatibility when bonding dissimilar materials (e.g. metal-plastic).
- Provides high strength and durability; FM300K is an adhesive used in the aerospace industry and works effectively at temperatures from -55°C to 121°C with excellent chemical resistance.
- Aesthetically, it provides a cleaner look because the fasteners are not visible from the outside.

Disadvantages:

- The bond may take time to form and may require curing time.
- Some adhesives work within certain temperature ranges, even advanced adhesives such as FM300K have certain limitations to temperature fluctuations.
- There may be a loss of performance at high temperatures or in humid. environments, so environmental conditions should be considered.

1.6.2.2. Advantages and Disadvantages of Mechanical Bonding:

Advantages:

- Provides fast assembly and disassembly, which facilitates ease of maintenance and repair.
- It provides high mechanical strength and is an effective solution for handling heavy loads.
- Fasteners are generally low cost and readily available.

Disadvantages

- They can create localised stress concentrations on the surface, which can lead to structural weaknesses.
- Aesthetically, fasteners may be visible from the outside, which is a disadvantage in some applications.
- Joining dissimilar materials can be difficult and can lead to problems such as galvanic corrosion.
- As a result, adhesive bonding and mechanical bonding are two important methods of joining materials, each offering particular advantages and disadvantages. The use of advanced adhesives, such as FM300K, demonstrates that adhesive bonding offers a high performance and durable solution, while the practicality and durability of mechanical bonding is particularly important in applications where heavy loads need to be handled.

1.7. Finite Element Analysis for Composite Materials: Modelling, Simulation, and Optimization

Finite Element Analysis is a critical tool for analysing the complex structural behaviour of composite materials. Composite materials are materials that are formed by combining components with different mechanical properties and offer superior properties such as high strength and light weight. One of the most important advantages of these materials is that they show higher performance with the synergistic effect of different components. However, in order to use composite materials successfully, the components must be combined correctly. In this context, adhesive bonding methods play an important role in the joining of composites. Adhesives form high-strength and durable joints, preserving the delicate structure of the composites. In this process, especially high-performance adhesives such as FM300K offer excellent solutions for composite structures. The viscoelastic properties of the adhesives optimise stress distribution at the joints, ensuring homogeneous distribution of mechanical loads. Modelling and simulation of adhesive bonding processes using FEA is critical to predict the performance and longevity of these joints. Advanced FEA software such as Abaqus allows detailed analysis of the interactions of adhesives and composites. This allows engineers to select the most suitable adhesive material and bonding method for composite structures, achieving optimum design and performance.

We aim to model and analyse the failure of an adhesive which have various thicknesses to bonds two substrates made of CFRP woven. Determine the Mode I critical energy release rate by using VCCT.

FM 300K film adhesive is known with properties of high elongation and toughness, along with a high ultimate shear strength. These properties ensure the material convenient for distributing high shear stress concentrations in graphite epoxy to metal bonds. It can also adjust to composites' poor interlaminar shear strength.

The adhesive properties can be found in Appendix 1(MatWeb, n.d.).

1.7.1. Linear Limit (LL)

The Linear Limit (LL) is the maximum stress at which the adhesive bond behaves in a linear elastic manner. Up to this point, the relationship between stress and strain is linear, meaning that the adhesive deforms in proportion to the applied load and returns to its original shape when the load is removed. Beyond the Linear Limit, the bond begins to exhibit nonlinear behavior, indicating the onset of permanent deformation.

1.7.2. Knee (KK)

Knee is the point at which there is a distinct change in slope in the stress-strain curve. This is usually the point at which the material changes from elastic to plastic behavior. It represents the onset of significant plastic deformation within the adhesive layer. After the knee, the adhesive begins to deform plastically, meaning that it does not fully return to its original shape when the load is removed.

1.7.3. Lap Shear

Lap shear is a measure of bond or adhesive strength of a material. It relates to the maximum stress that an adhesive bond can resist before failure under a shear loading case.

In below figure(Pacific Composites, 2011) Linear Limit (LL), Knee (KK) and, Ultimate Failure were compared.

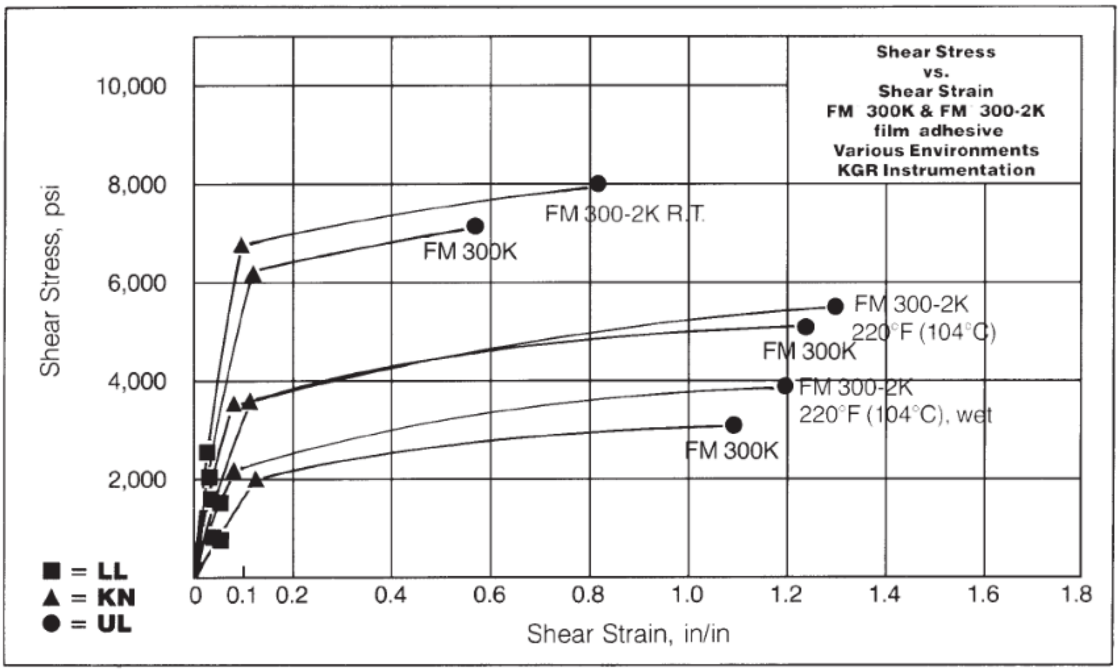
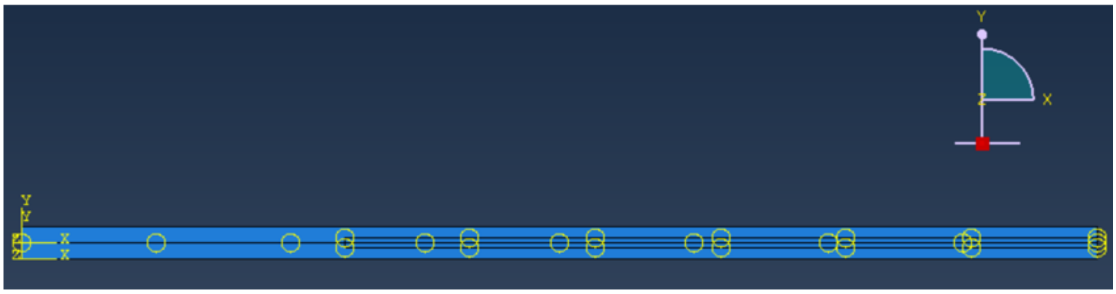


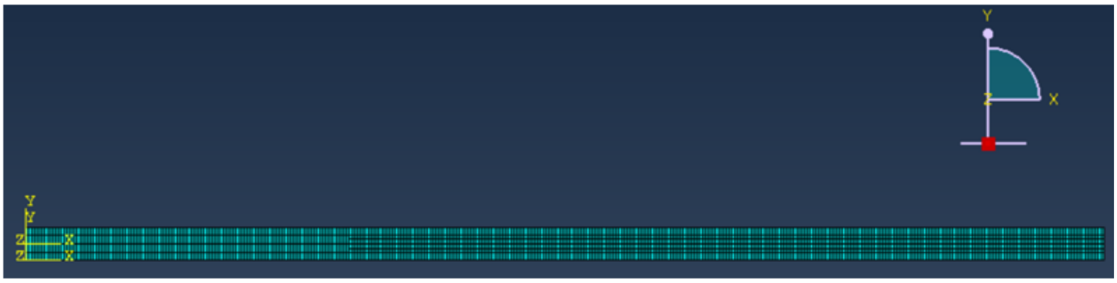
Figure 1.26 Stress-Strain graph of FM300K vs FM300-2K in various environments

1.7.4. Finite element modelling and analysis application

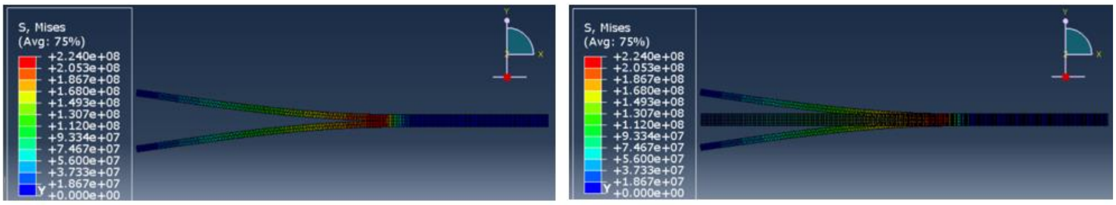
In this content, primarily the physical and mechanical properties of the adhesive and composite will be found and described. The properties of FM300K can be found in *Appendix 1*. The specimen will then be modelled in ABAQUS software. The modelling domain will be 2D planar, the model type will be deformational and the basic feature will be shell. The specimen size will be assumed to be approximately 250 mm, this size may change as new specimens are produced. The model will start with a rectangular shape. Then the top cantilever will be selected and a planar wire will be formed on it. Next, a smaller rectangle will be placed from the start to a point. Then another wire will be created from one point to another and the upper right and lower right parts of the smaller rectangle will be joined. To model the adhesive layer, a new 2D planar, deformational and shell-based part will be created and another rectangle thinner than the first one will be placed. Then go to the module panel and select the properties option. Select the material manager to define the material properties. In this tab a new material called composite will be created. Then, density, Young's modulus and Poisson's ratio will be defined. Then, another material will be created for the adhesive and Young's modulus and Poisson's ratio will be defined for both materials, in this context both materials will be isotropic. Then, select the section panel and create the solid category and homogeneous type for the composite part, then associate it with the composite material and tick the "plane stress/strain thickness" option with the value 0.025. Then, another solid category and homogeneous type will be created for the adhesive part and the previous steps will be applied again. Then select the option to assign selections from the left tab, select part 2 and select the adhesive section in the section panel. Then the same procedure will be applied for part 1 and this time composite will be selected as the cross section. From the joining module, a sample will be created for part 1 and part 2 of independent type and the option "automatically offset from other samples" will be selected. Then, select the option to move the sample from the left tab and select the adhesive part 2 and associate its upper right corner to the lower left corner of the upper bracket and the upper right corner of the lower bracket to the lower left corner of the adhesive. A new step will be created from the step module and this step will be named "Step-1", this step will be initial and static, general. Then, from the same tab, a field will be created and the failure/fracture option will be selected, then ENRRT (strain energy release rate) and EFENRRTR (effective energy release rate) and BDSTAT (bond status) and DBT (time to bond failure) options will be selected. Then the interaction module will be selected for model 1 and step 1. Then the top and bottom console will be selected and removed from the top tab. In the Tools section, the administrator will be set and the visible ones will be deleted. Sets named AdhTop and AdhBot will be created. Select the top of the adhesive for AdhTop and vice versa for AdhBot. Then select tools surface manager and create surfaces. Create AdhTop and AdhBot again and select the relevant edges, see Figure 27. Then, using the top bar, all will be replaced and the top and bottom surface of the specimen will be created. Next, the interaction feature will be created and this will be named Contact. From the Mechanical tab, define the fracture criterion and define critical energy release rates of 400, 900 and 1100 for modes I-II and III respectively, setting the exponent n=1. Then, another interaction will be created and this will be set as step 1 and will be of the surface-to-surface contact (standard) type. Surfaces will be defined from the bottom right; in this context, the top cantilever will be selected as primary and the top surface of the adhesive (AdhTop) as secondary. For the primary surface, AdhTop, 0.2 degree offset and limited bonding shall be selected. Then, the same procedure will be applied for the bottom of the adhesive and the lower cantilever; however, in this case, it will need to be limited to AdhBot. Next, the fracture manager will be selected from the custom tab and the debond will be created using VCCT. The initialisation step will be step 1 and the first contact will be the top and the debonding force will be the step. Then similar procedure will be done for the lower part. From the load module, first the boundary condition (BD) will be created for step 1 in the mechanical category and with symmetry and the end edge of the specimen will be selected as ENCASTRE. Then, on the upper cantilever and on the right corner of the smaller rectangle defined before, an intense load will be generated as CF2 = 1400, this load will be uniform and ramp amplitude. The same procedure will be applied for the lower specimen as CF2 = -1400. For the whole cantilever, the estimated spherical dimension of 0.001 will be determined with the seed part sample and applied for the whole model with the mesh part sample and selected as complete. As element type, mismatched modes will be selected. A job will be created and submitted from the job manager and the results can be viewed from this tab (Poe Jr, 1984), see Figure 1.27(Enaiyat Ghani Ovy, n.d.).



(a)



(b)



(c)

Figure 1.27 Steps of Finite Element Analysis Application: (a) Defined Relations of Adhesive Upper and Lower Cantilever (b) Creating Mesh Width Incompatible Modes, (c) Results

1.8. A Brief Overview of Fracture Mechanics in Adhesive Joints

Fracture mechanics is an engineering field that seeks to understand how cracks and fractures behave within and between materials over their service life. Fracture mechanics, especially began its journey with Griffith's studies on his energy based theory in 1920 and Irwin's essential contributions in 1958. This field primarily addresses some key questions below: (Yayla, 2007)

1. Will a crack propagate under a specific load?
2. Is there a maximum permissible crack length for a given stress in the part?
3. Under what stress value will a specific crack in a part propagate?
4. How long will it take for a given crack to reach the critical length?
5. Will the crack propagate rapidly in an unstable manner or slowly?
6. If the crack propagates slowly and steadily, at what rate will it propagate?

Fracture mechanics examines the behaviour of cracks and defects under three types of loading, see Figure 1.28 (Anderson, 2005):

Mode I: Also known as the opening mode or tensile mode, it is the most commonly occurring and extensively studied crack propagation mode.

Mode II: Known as the sliding or in-plane shear mode, it involves a shear component acting in the direction of the x-axis.

Mode III: Referred to as the tearing mode or anti-plane shear mode, it also involves a shear component acting in the direction of the x-axis.

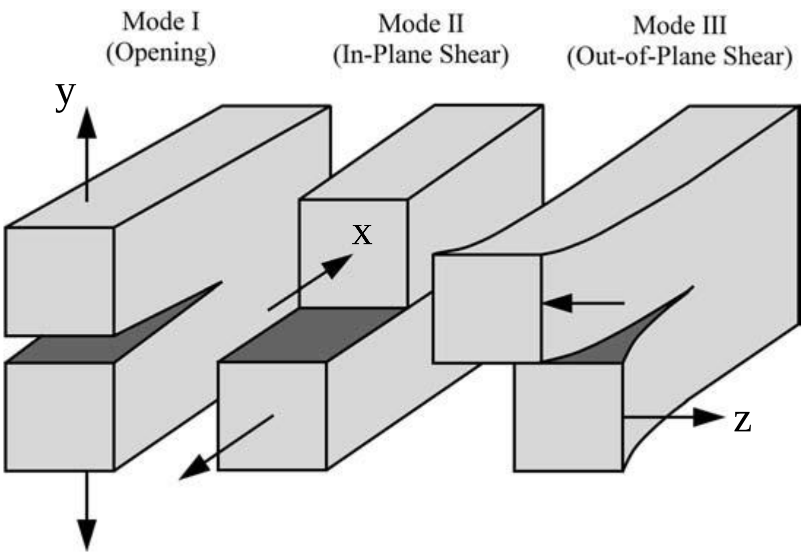


Figure 1.28 The Three Modes of Loading

1.8.1. Fracture Behaviour of Adhesively Bonded Composites Under Mode I Loading

Comprehending fracture mechanics is essential for understanding how cracks behave in materials, especially in the adhesively bonded joints found in composite structures. These joints are complex due to the anisotropic properties of composite materials and the viscoelastic behaviour of adhesives. A thorough understanding of how cracks start and spread within the adhesive layer, at the interface between the adhesive and the composite, and within the composite material itself is crucial for anticipating joint behaviour and potential failure.

Several factors can affect the propagation of cracks in adhesive joints:

1. Adhesive Properties: How the adhesive responds to stress and how cracks form and spread can be influenced by its toughness, modulus, and strength.
2. Adhesive-Composite Interface: Cracks may start at the interface between the adhesive and the composite substrate, particularly if there are issues like inadequate surface preparation or excess moisture before bonding.
3. Composite Material: The anisotropic nature of composites means that cracks may spread differently depending on the direction of the fibers and the type of matrix material used.

When a crack starts to propagate and two new surfaces are created, an amount of energy is consumed. G_{1c} is designated as the energy required to propagate a unit area of crack under opening, mode I, loading. It expresses the existing amount of energy for crack growth per unit area of the crack surface. G_{1c} is an essential parameter to be determined for predicting when the crack starts to grow. If the energy release rate due to the opening load exceeds G_{1c}, the crack will be propagating.

Griffith set the energy balance for an incremental increase in the crack surface area ΔA. To cause a crack growth, ΔW_{ext} is done by the external forces and the strain energy within the body of the component changes by ΔU.

$$G_1 = -\frac{d}{dA}(U - W_{ext}) \qquad 1\text{-}1$$

$\Pi = U - W_{ext}$ is commonly known as potential energy.

$$G_1 = -\frac{d\Pi}{dA} \quad \textit{1-2}$$

Above equation is quite essential to evaluate the energy release rate of the system and to get G_1 as always positive.

Displacement, δ, is the product of compliance and force. Assuming constant force,

$$\delta = CP \Rightarrow d\delta = PdC \quad \textit{1-3}$$

$$d\Pi = -\frac{1}{2}Pd\delta \Rightarrow d\Pi = -\frac{1}{2}P^2dC \quad \textit{1-4}$$

dA = Bda and,

$$G_1 = \frac{P^2}{2B}\frac{dC}{da} \quad \textit{1-5}$$

For experimental studies, G_1 is usually calculated by the methods of the modified beam theory, which is also used for this study. Here are the methods for calculating G_1:

1. <u>Beam Theory:</u>

The beam theory expression for the energy release rate of a perfectly built-in double cantilever beam is as follows:

$$G_1 = \frac{3P\delta}{2Ba} \quad \textit{1-6}$$

2. <u>Modified Beam Theory:</u>

In practice, the previous expression will overestimate G_1 because the beam is not perfectly built-in. In modified beam theory a rotation, that may occur at the delamination front, is considered. Correcting of this rotation is achieved by assuming our crack lengths are slightly longer, a + |Δ|. Δ is determined by generating a plot of the cube root of compliance, $C^{1/3}$, as a function of crack length, a, see in the Figure 1.29. Δ is the value of "a" where the linear trend line intersects zero. Compliance is calculated via experimental results, it is the ratio of the load point displacement to the applied load, δ/P.

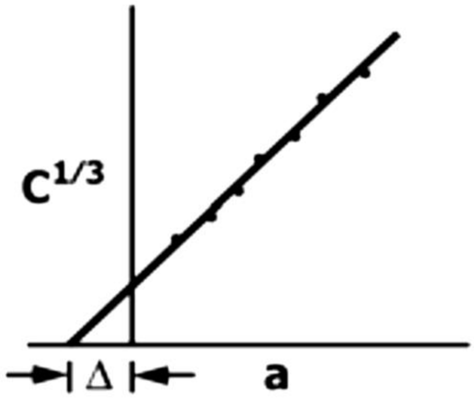


Figure 1.29 The Cube Root of Compliance, $C^{1/3}$, As A Function of Crack Length, a

The expression for Modified Beam Theory:

$$G_1 = \frac{3P\delta}{2B(a+|\Delta|)} \qquad \textit{1-7}$$

3. <u>Compliance Calibration Method:</u>

For the Compliance Calibration Method, the plot of log(C) versus log(a) is created, then the least-squares-fit-line of this plot is drawn. The slope of this line is recorded as “n”. The expression for Compliance Calibration Method is written as:

$$G_1 = \frac{nP\delta}{2Ba} \qquad \textit{1-8}$$

4. <u>Modified Compliance Calibration (MCC) Method:</u>

The least squares plot of the crack length normalized by specimen thickness, a/h, as a function of the cube root of compliance, $C^{1/3}$, using the visually observed delamination onset values and all the propagation values. The slope of this line is A_1. So, the equation for the MCC method:

$$G_1 = \frac{3P^2C^{2/3}}{2A_1Bh} \qquad \textit{1-9}$$

1.8.1. A Literature Review for Adhesive Joints

There is a lot of interest in understanding the behaviour of materials joined with adhesives. Here are some research and topics related to this subject:
(B. R. K. Blackman et al., 2008) explored the effects of pre-bond moisture on the fracture behaviour of adhesively bonded composites. They found that pre-bond moisture could significantly reduce fracture energy and alter the fracture morphology and glass transition temperature (T_g) of the adhesive.

(B. Blackman & Kinloch, 2001) investigated the toughening mechanisms in adhesive joints and how these mechanisms affect the overall fracture performance. They emphasized the importance of understanding the interaction between the adhesive and the composite substrate.

(B. R. K. Blackman et al., 2009) focused on the impact of adhesive thickness and joint configuration on fracture behavior. Their work highlighted that optimal adhesive thickness is crucial for maximizing joint strength and minimizing stress concentrations that lead to crack initiation.

(B. Blackman & Kinloch, 2001) emphasized the importance of adhesive toughness in enhancing joint performance. It was found that toughened adhesives could significantly improve the fracture resistance of joints compared to brittle adhesives.

(B. R. K. Blackman et al., 2009) investigated the role of adhesive modulus in load transfer efficiency. Their findings suggested that a balanced modulus is essential for optimizing joint strength without compromising flexibility.

(B. R. K. Blackman et al., 2012) explored how different adhesive strengths affected joint performance. High-strength adhesives were shown to improve load-bearing capacity but required careful consideration of joint design to avoid stress concentrations.

The field of fracture mechanics in adhesive joints is complex and multifaceted, involving the interplay of adhesive properties, interface characteristics, and composite material behaviour. Advances in numerical modelling and experimental techniques have significantly improved the understanding of crack initiation and propagation in these joints. However, challenges remain, particularly concerning environmental effects and the development of multi-scale models. Future research should continue to address these challenges to enhance the reliability and durability of adhesively bonded joints in composite structures.

2. MATERIALS and METHOD

2.1. Sample Properties and Preparation for Test

Our samples Carbon Fiber Reinforced Composites (CFRP) were cut from a scrap panel produced by TAI (Turkish Aerospace Industries). The samples were manufactured using the wet lay-up method and exhibit woven properties. During the manufacturing process, teflon was placed in each sample to create an initial crack, considering the tests to be conducted. FM300K adhesive was used as the adhesive between the composite materials. FM300K was preferred due to its high ultimate shear strength along with high elongation and toughness. The selection of FM300K is further justified by its high thermal resistance, resilience to various chemicals and environmental factors, as well as its ability to provide high strength and flexibility upon curing. Additionally, it offers durability against vibrations and impacts. Mechanical properties of FM300K are presented in Table 2.1 (Sonat, 2021) below.

Table 2.1 Mechanical Properties of FM300K

Property	Symbol	Value
Tensile Modulus (GPa)	E	3.12
Shear Modulus (GPa)	G	0.9
Tensile Strength (MPa)	t_n^0	72
Shear Strength (MPa)	t_s^0, t_t^0	42
Tensile Stiffness (N/mm^3)	K_n	15600
Shear Stiffness (N/mm^3)	K_s, K_t	4500
Toughness in Tension (N/mm)	G_{IC}	1.1
Toughness in Shear (N/mm)	G_{IIC}, G_{IIIC}	3.8

In the first stage, 16 specimens were produced, 4 of each adhesive thickness with adhesive thicknesses of 0.5, 1, 4, and 6 mm respectively. The geometrical properties of the specimens are given in Table 2.2 and the parameters can be seen in Figure 2.1.

Table 2.2 Geometrical Properties of The Specimens

Specimen	a_0(mm)	I(mm)	I_2(mm)	I_3(mm)	b(mm)	H(mm)	h(mm)	h_1(mm)
Type 1	15.5	250	12.5	25	25	12.5	2	0.5
Type 2	15.5	250	12.5	25	25	12.5	2	1
Type 3	15.5	250	12.5	25	25	12.5	2	4
Type 4	15.5	250	12.5	25	25	12.5	2	6

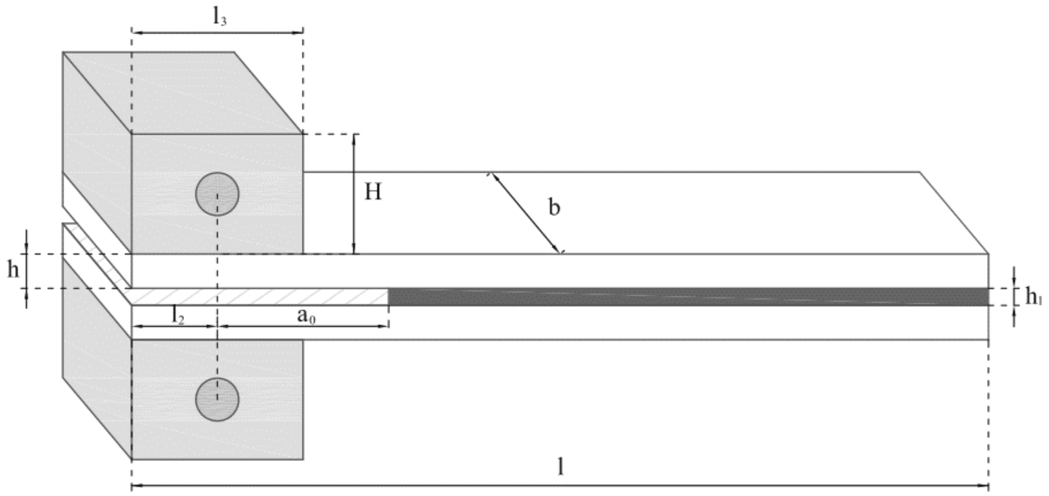
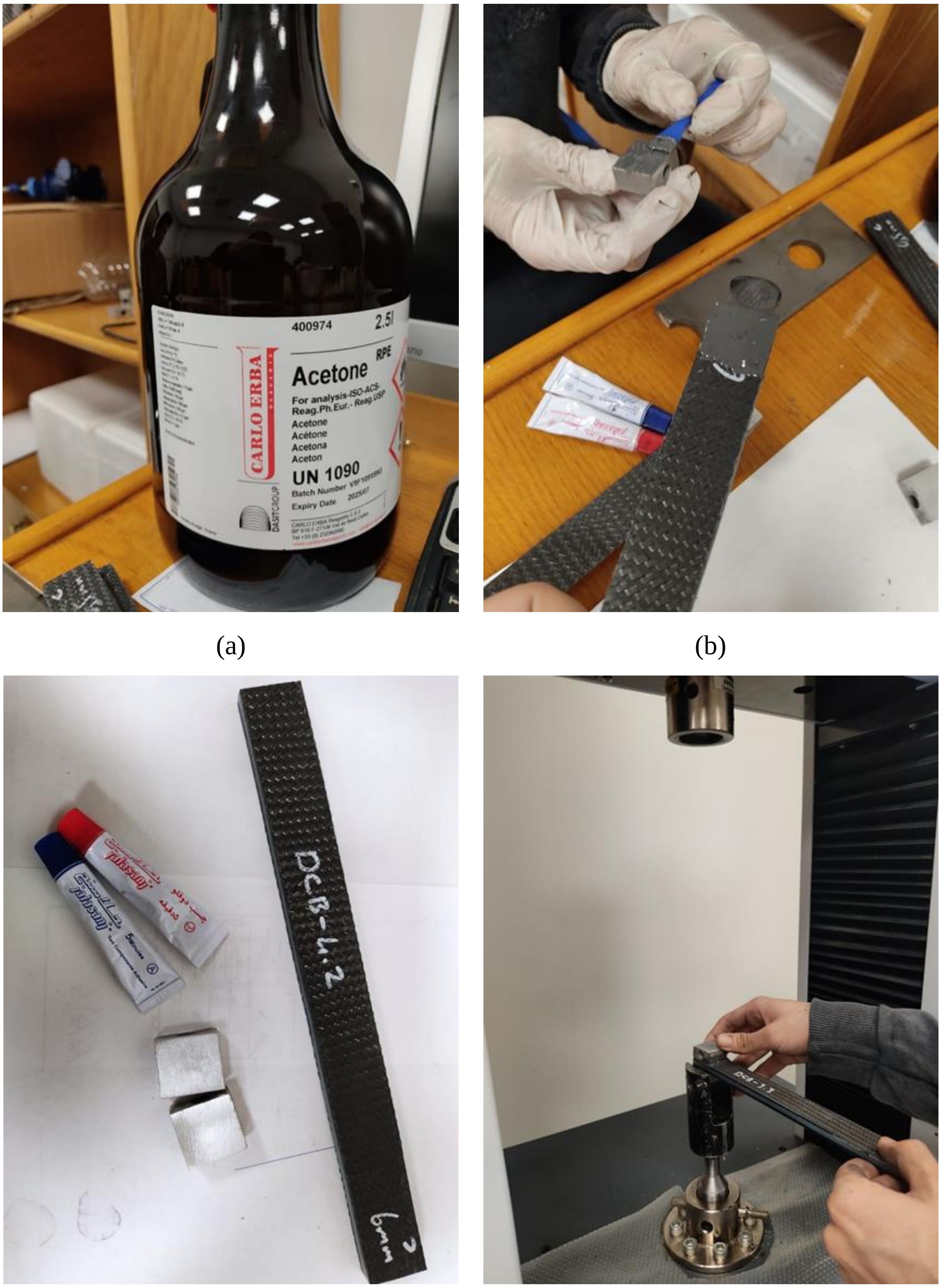


Figure 2.1 Double Cantilever Beam Setup with Loading Blocks

After the CFRP samples were supplied by TAI, they underwent several stages to be prepared for testing. The prepared samples were then subjected to the necessary tests in accordance with ASTM D5528M.(ASTM, 2021)

Initially, the samples provided by TAI were prepared for the Double Cantilever Beam test on the Shimadzu Precision Universal Testing Machine in our university laboratory using aluminum load blocks, see Figure 2.2 2.2. The aluminum load blocks, which were suitable for the dimensions of the samples, were cleaned with acetone to ensure proper adhesion to the sample surface. An epoxy adhesive was applied between the aluminum blocks and two outer faces of specimen. The adhesive was allowed to cure for approximately 24 hours to ensure proper adhesion of the aluminum blocks and to avoid any issues during testing.



(a) (b)

(c) (d)

Figure 2.2 Preparation Of Specimens: (a) Cleaning Process Of Aluminium Blocks, (b) Bonding Process Of Aluminum Blocks, (c) Adhesive, Aluminum Block And Composites, (d) Placing The Sample In The Testing Device

2.2. Test Method for Mode I Loading: DCB Test

One often used technique to evaluate the fracture resistance (G_1) of adhesive joints under opening forces, or mode I, is the Double Cantilever Beam (DCB) test. Because DCB tests are simple to create, easy to conduct, and adhere to established standard testing protocols, they are widely used to assess the fracture properties of adhesives.

Before subjecting our specimen to the test, we cut a small section with the help of a utility knife to determine the starting point of the fracture and to focus the stress on a certain point. Then we inserted our specimen into the test machine, Shimadzu AGS-X 50 kN, see Figure 2.4(Shimadzu Excellence in Science, 2024), Tensile Test Machine. The crosshead rate was selected to be 2 mm/min, and the test was initiated, see Figure 2.3. During the test, the place where the first fracture started was marked with a permanent marker to measure it later. The points where the fracture continued at certain intervals during the test were also marked with a permanent marker. To easily observe these marked points in the data on the computer, compressive force was applied to the test arm. This procedure was repeated at certain intervals until the sample failed.

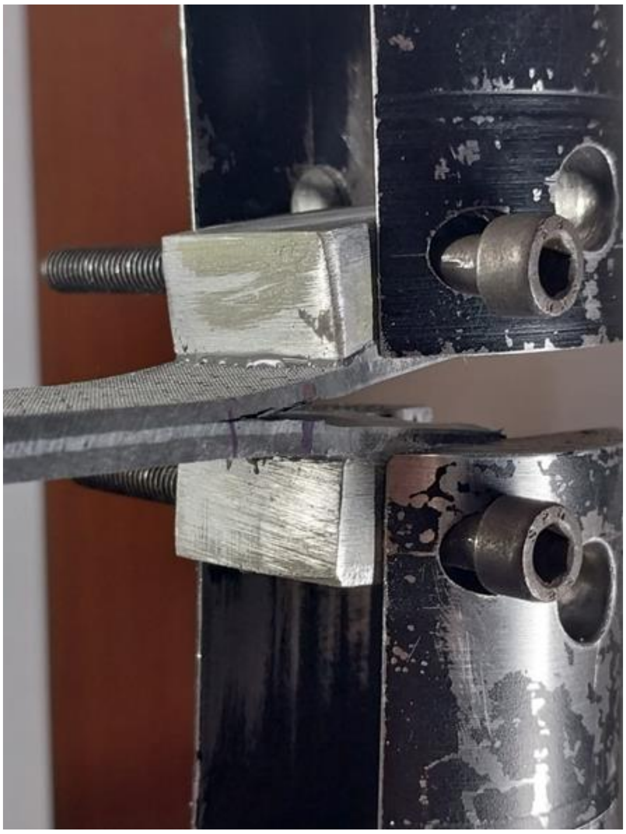


Figure 2.3 DCB Test Configuration

Figure 2.4 Shimadzu AGS-X 50 kN Tensile Test Machine

3. RESULTS and DISCUSSIONS

3.1. Comparative Analysis of Results

In the beginning, we expected the adhesive material to fail cohesively. However, we observed various types of failures. Ply bridging occurred in all samples, but it was unclear which plies were affected. Most, if not all, samples exhibited two steps of openings between composite layers. As a result, we will designate these as the first and second openings.

The failure types identified in this study are as follows:

Type I: Opening between the adhesive and adherent

Type II: The first opening occurs between the composite layers

Type III: The second opening occurs between the composite layers

Let's examine these damage types through the graph of a sample, Figure 3.1. Here is the G_{1c} vs a graph of a DCB specimen with 4 mm adhesive thickness:

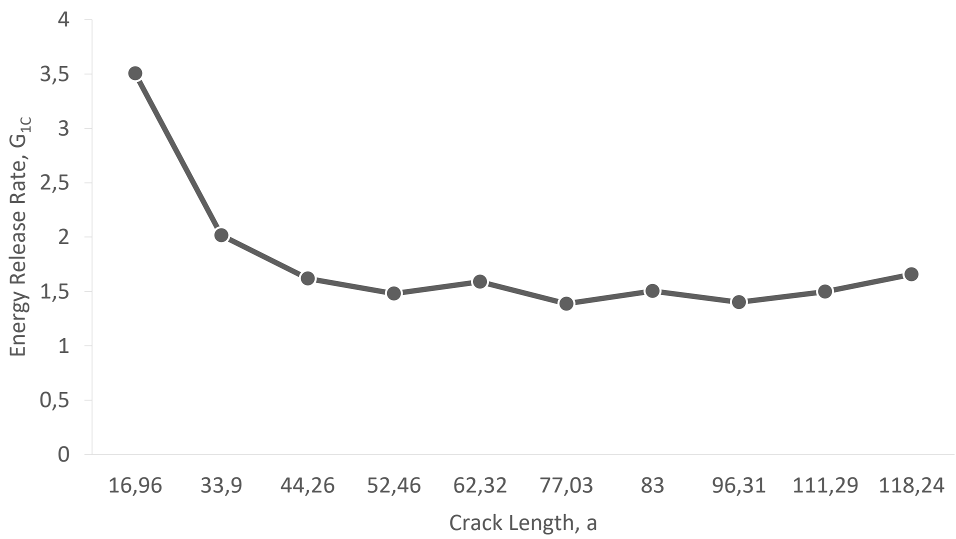


Figure 3.1 G_{1c} vs a Graph of DCB 3.3

The first highest release rate seen in Figure 3.1 3.1 is caused by crack propagation that begins between the adhesive and adherent after the opening is separated from the Teflon film. Energy release values after the 3rd crack are the result of both type I and type II damages, until 6th crack. At this point, only type II began to be seen, then type III failure was observed along with type II. Since the resistance to fracture increased due to bridging, there was no significant decrease in the energy release rate after bridging occurred. It can be seen on Figure 3.2 that which damage type areas on where in the actual sample.

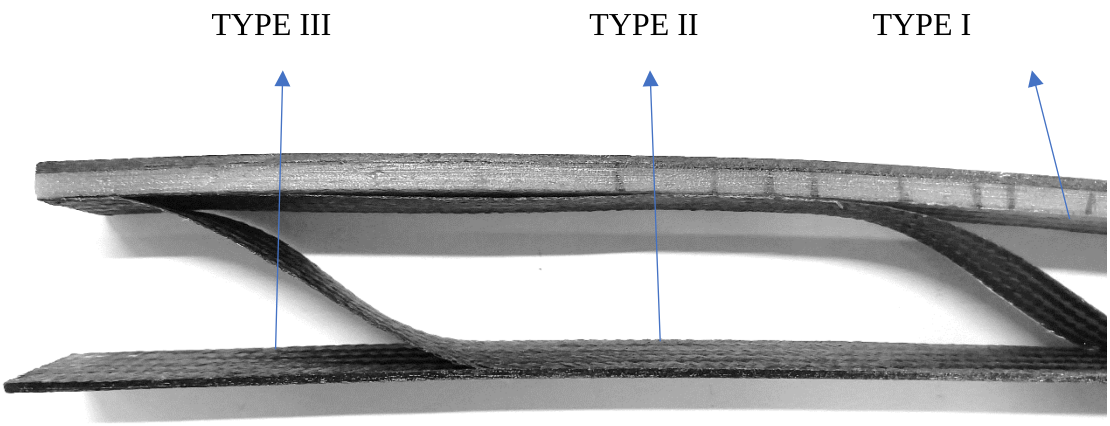


Figure 3.2 The Failure Types Identified in This Study Are Shown in DCB 3.3

All critical results are tabulated in Table 3.23.2. In order to make a true selection for optimum adhesive thickness, one-way ANOVA analysis in Minitab Software were held based on these data.

Table 3.1 Mean and Standard Deviation of Each Group

Thickness	G_{1c}	Standard Deviation
0.5	1.150	0.486
1	1.533	0.487
4	3.323	1.138
6	4.050	2.31

According to Table 3.13.1, the highest G_{1c} values are observed with an adhesive thickness of 6 mm. However, the results for the 6 mm group exhibit more inconsistency compared to the other groups.

Figure 3.3 Boxplot of G_{1c} for Different Thicknesses

A box plot was created to better observe this situation, Figure 3.3. As the adhesive thickness increases, it is observed that the G1c values and crack resistance also increase. These results indicate that adhesive thickness has a significant impact on structural integrity and durability, and thicker adhesives are more effective in increasing crack resistance. However, the high standard deviation values suggest the need for a more detailed examination of the variability in measurements and differences observed at certain thicknesses. As clearly seen in the Figure 3.3, the intertwining of G1c values at 0.5 mm and 1 mm adhesive thicknesses may suggest that there is no significant difference in crack resistance between these two adhesive thicknesses. That is, crack resistance may be at similar levels between these two groups. However, the accuracy of this situation should be examined by increasing the number of tests.

Through this analysis, information was also obtained about the quality of the model to be created with this data. The R-sq(pred) value, 15.13%, which expresses the predictive ability of a model to be built with this data, was much lower than expected. It is expected to be at least around 50% to 70%. This low value indicates that the model's performance in predicting future observations is limited and the model does not explain the variance in the data effectively. Several factors could contribute to this low predictive performance. One significant factor contributing to this low predictive performance is the quality and quantity of the data. Incomplete, noisy, or insufficient data can lead to poor predictive accuracy. Additionally, high levels of noise or inappropriate data distribution can negatively impact the model's performance, resulting in a low R-sq(pred) value.

Table 3.2 Critical Point Values of All Samples

Specimen	Adhesive Thickness(mm)	Maximum Load(N)	Stroke(mm)	Crack Length(mm)	G_{1c}(N/mm)
DCB 1.1	0.5	105.9	1.74	16.2	0.654
DCB 1.2	0.5	107	2.92	16.5	1.134
DCB 1.3	0.5	92.8	5.47	16.3	1.814
DCB 1.4	0.5	97.7	3.12	17.85	0.999
DCB 2.1	1	101.7	3.36	13.14	1.504
DCB 2.2	1	158.7	2.91	15	1.788
DCB 2.3	1	127.6	3.11	11.71	1.977
DCB 2.4	1	107.5	1.98	14.7	0.862
DCB 3.1	4	127.6	5.13	20.1	1.802
DCB 3.2	4	154.1	6.89	13.12	4.559
DCB 3.3	4	125	9.13	16.96	3.505
DCB 3.4	4				
DCB 4.1	6	143.9	8.74	14.94	4.664
DCB 4.2	6	133.7	8.28	14.95	4.115
DCB 4.3	6	167.6	8	11.76	6.499
DCB 4.4	6	198.1	1.33	16.19	0.938

3.2. Results for Each Test and Discussion of Causes for Abnormalities

In three of the samples with an adhesive thickness of 0.5 mm, energy release rate values were observed to increase unusually, as seen in 3.4 a, c, and d. Under normal circumstances, it would be expected to decrease and remain constant after the peak point. Although testing and production methods have an impact on this, ply and short fiber bridging formation may have effects.

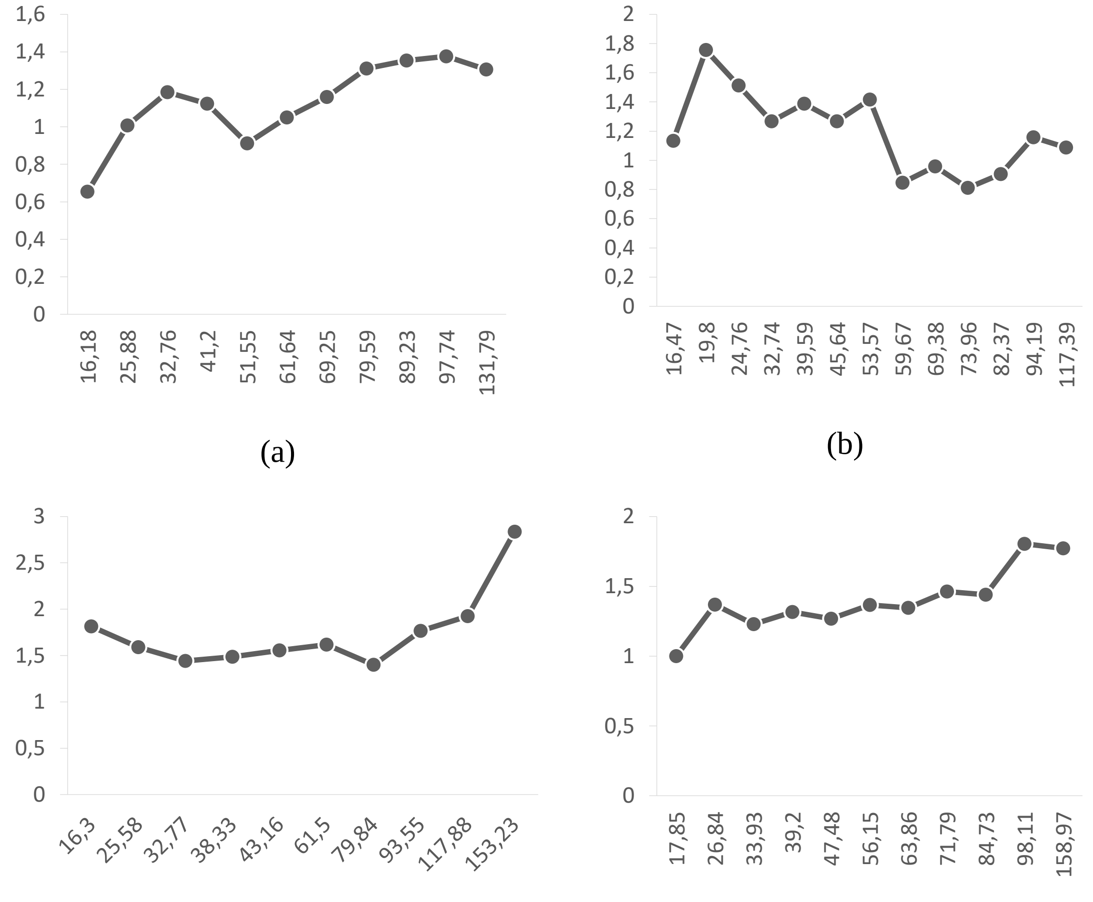
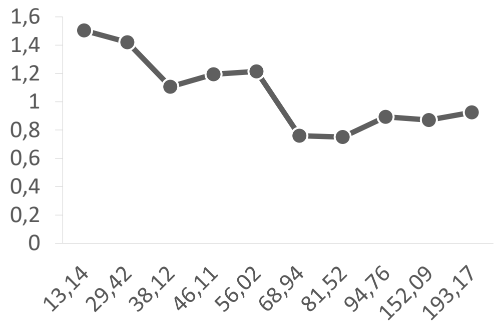
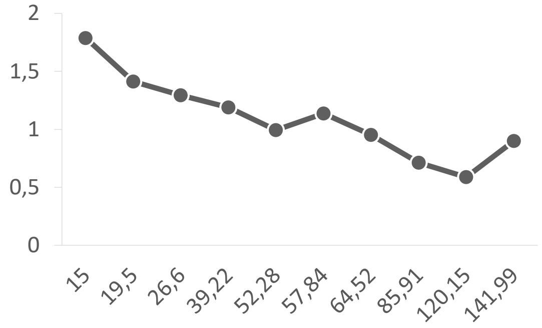


Figure 3.4 "G_{1c}" vs "a" Graphs of the ones with adhesive thickness of 0.5 mm: (a) DCB 1.1, (b) DCB 1.2, (c) DCB 1.3, (d) DCB 1.4

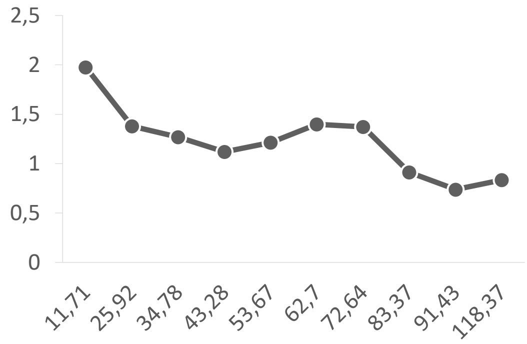
Samples with 1 mm adhesive thickness mostly produced similar and reasonable results, see Figure 3.5.5. The ups and downs seen in the graphs may be related to the formation of a new surface during ply bridging formation.



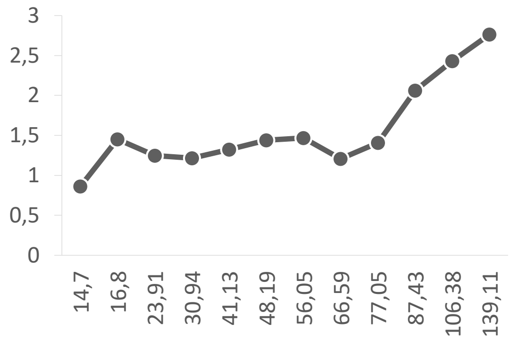
(a)



(b)



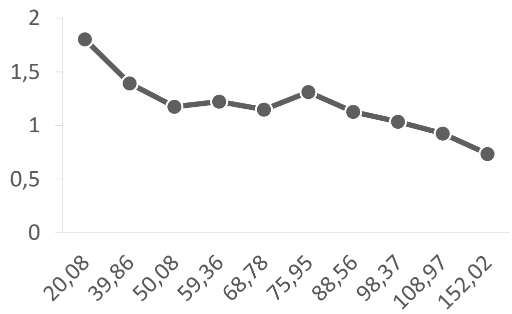
(c)



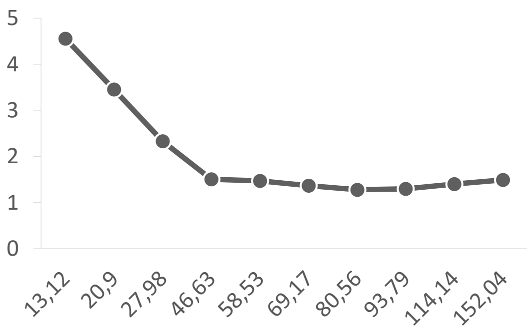
(d)

Figure 3.5 "G_{1c}" vs "a" Graphs of the ones with adhesive thickness of 1 mm: (a) DCB 2.1, (b) DCB 2.2, (c) DCB 2.3, (d) DCB 2.4

Samples with an adhesive thickness of 4 mm were also able to produce reasonable results, see Figure 3.6.6, but here one of the samples broke during the test and could not be completed. The average of these three was taken as the fourth value in the analyses.



(a)



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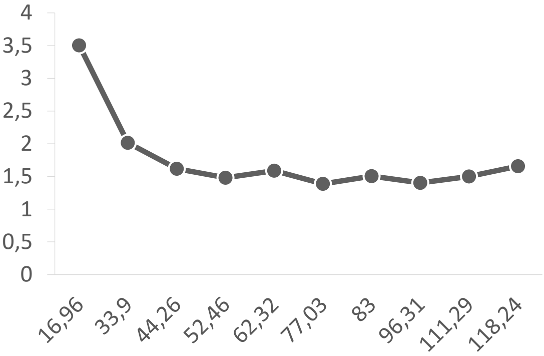
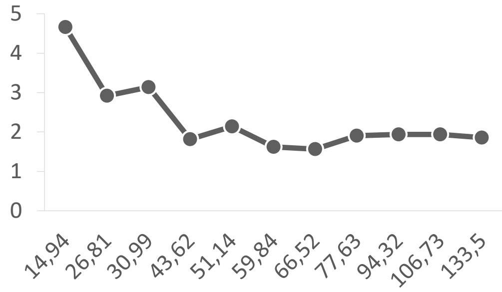


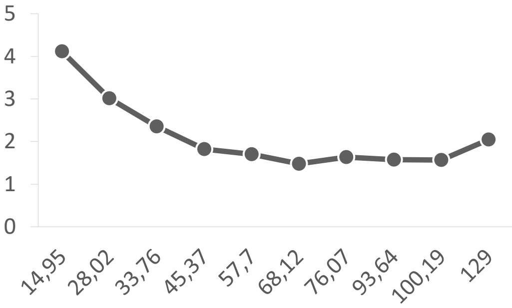
(c)

Figure 3.6 “G_{1c}” vs “a” Graphs of the ones with adhesive thickness of 4 mm: (a) DCB 3.1, (b) DCB 3.2, (c) DCB 3.3

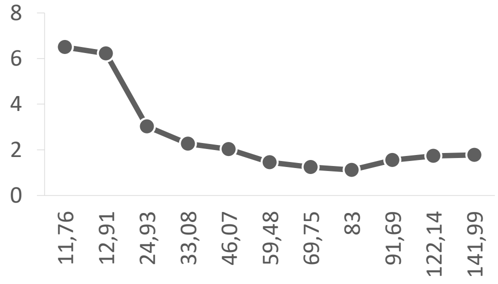
Finally graphs of ‘G_1’ vs ‘a’ for thickness of 6 mm are given in the Figure 3.73.7. Mostly reasonable results were obtained at 6 mm, and a gradual increase was observed in one of them. In addition, a much lower energy release rate was calculated in this sample than in general and expected. This may be due to measurement errors and deficiencies in testing and sample production.



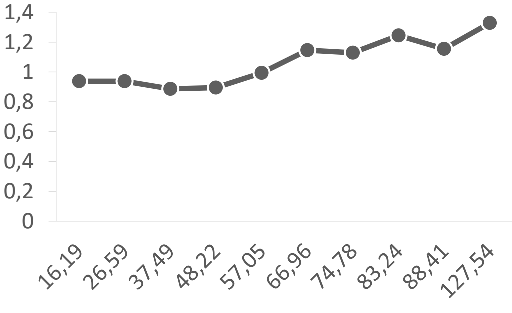
(a)



(b)



(c)



(d)

Figure 3.7 “G_{1c}” vs “a” Graphs of the ones with an adhesive thickness of 6 mm: (a) DCB 4.1, (b) DCB 4.2, (c) DCB 4.3, (d) DCB 4.4

There can be many reasons of increasing G_1 and different failure types other than cohesive. Here are explanations of some possible causes.

Test Set Up:

During our DCB test, due to the lack of a tight fit between the aluminum block and the test machine's connection point, the sample was positioned at an angle downward at the beginning of the test due to the effect of gravity. Additionally, our test results generally indicated adhesive failures, which caused the side with the adhesive to be heavier. This weight difference led to excessive bending of the side without adhesive in Figure 3.8. This situation may have caused the DCB test result to be erroneous.

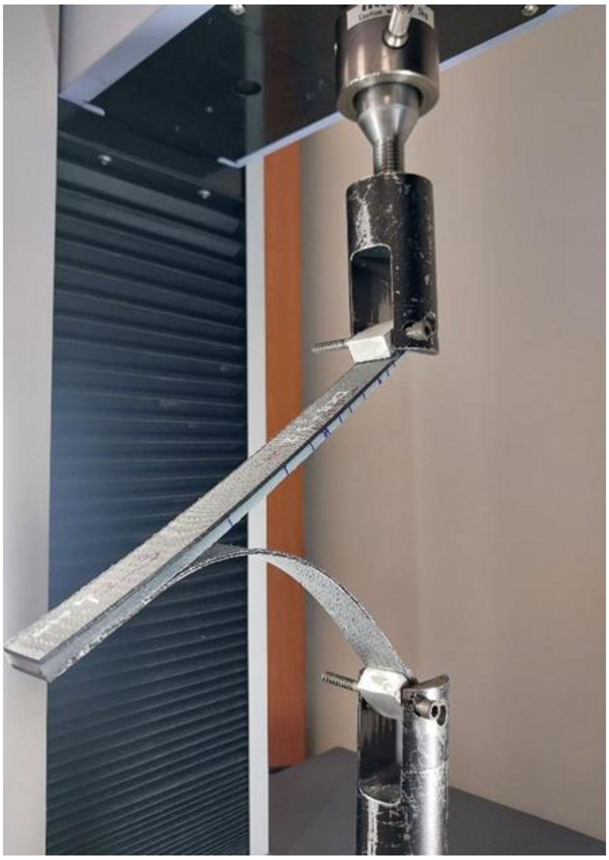


Figure 3.8 Adhesive Failure

Furthermore, the application of the pre-crack load, both with the addition of teflon and with a scalpel to facilitate the initiation of fracture, may have affected the test result. The teflon size was not determined in accordance with the standards during sample production and varied between samples. Since the force value of the initial crack, we applied with the scalpel could not be measured, this force value may have been excessive or insufficient. The application of different force values for the same sample type may have led to different results and even erroneous readings.

Sample Quality:

Issues such as microcracks, production mistakes, or material flaws in the sample can lead to an elevated energy requirement for crack propagation. These internal defects disrupt the material's uniform structure and result in stress concentrations, necessitating a higher energy concentration at the crack tip. Consequently, the G_1 values obtained during sample testing may consistently rise, indicating variability in the material's crack resistance due to microstructural disparities and defects. Therefore, the significance of sample quality and manufacturing process controls is underscored, as these directly impact the material's performance and dependability. Improving production processes and enhancing sample quality can lead to more consistent and reliable G_1 values.

Sample Manufacturing Methods:

Unexpected results in the G_1 values of a composite specimen in the DCB test can be caused by various production method errors. These errors can negatively affect the mechanical properties and G_1 values of the materials.

It may have originated on the basis of the following substances:

1. Inadequate Mixing: Insufficient mixing of fibres and resin can lead to localised fibre density zones in the sample. This can be caused by factors such as incorrect settings in manual or mechanical mixing techniques, insufficient mixing time or use of unsuitable mixing equipment.

2. Incorrect Resin Impregnation: Insufficient penetration of the resin into the fibres can lead to a poor interface between the fibres and the resin. This can be caused by factors such as insufficient resin quantity, incorrect resin injection or insufficient fluidity of the resin.

3. Pore and Gap Formation: Pores and voids can mislead G_1 values by creating stress concentration points.

Problems arising directly from the production process may be as follows:

1. Insufficient Pressure Application: Insufficient pressure application may cause the resin not to fully penetrate the fibres and cause pores to form in the sample. This is usually caused by the following reasons:
2. Incorrect Pressure Settings: Incorrect pressure settings used during moulding can result in insufficient pressure being applied. This can be caused by factors such as faults in the mould equipment, operator error or incorrect manufacturing procedures.
3. Inadequate Vacuuming: Incomplete removal of air bubbles from the resin mould can result in the formation of pores in the sample. This can be caused by factors such as inadequate vacuuming equipment, incorrect vacuuming procedure or insufficient vacuuming time.
4. Inadequate Curing: Inadequate curing can reduce G_1 values by preventing the resin from fully solidifying. This is usually caused by the following reasons:
5. Inadequate Curing Time: If the curing time is not long enough, it can prevent the resin from fully hardening. This can be caused by factors such as incorrect curing parameters, delays in the production schedule or equipment failures.
6. Low Curing Temperature: If the curing temperature is not high enough, it may prevent the resin from fully curing. This can be caused by factors such as incorrect curing parameters, equipment malfunctions or inadequate heating system.
7. Incorrect Curing Agent Use: The use of the wrong curing agent can cause inadequate curing by inhibiting the chemical reaction of the resin. This can be caused by factors such as incorrect material selection, operator error or incorrect manufacturing procedures.
8. Curing Under High Temperature and Pressure: Curing under high temperature and pressure can lead to a poor interface between fibres and resin, reducing G_1 values. This is usually caused by the following reasons:
9. Incorrect Curing Parameters: Too high curing temperature and pressure can damage the fibres and resin. This can be caused by factors such as incorrect curing parameters, equipment failures or inexperienced operators.

10. Excessive Curing: Excessive curing time or temperature can damage fibres and resin. This can be caused by factors such as incorrect production procedures, equipment failures or delays in the production plan.

11. Cutting and Drilling Errors: Errors during cutting and drilling can reduce G_1 values by creating stress concentration points in the specimen. This is usually caused by the following reasons:

12. Improper Cutting and Drilling Techniques: Improper cutting or drilling techniques can cause cracks or other damage to the specimen. This can be caused by factors such as inadequately trained operators, use of improper equipment, or incorrect manufacturing procedures.

13. Excessive Cutting Speed: Cutting speeds that are too high can cause heat to build up in the sample and damage the fibres. This can be caused by factors such as incorrect equipment settings, operator error or incorrect manufacturing procedures.

14. Inadequate Cooling: Insufficient cooling during cutting and drilling can cause heat build-up in the sample and damage the fibres. This can be caused by factors such as an inadequate cooling system, incorrect cooling procedure or insufficient cooling time.

In order to reduce the risk of experiencing unexpected results in G_1 values, it is critical to strictly adhere to manufacturing standards such as EASA and FAA and to perform the correct and necessary destructive and non-destructive tests. In addition to these measures, controlling material quality, monitoring the manufacturing process and analysing test data will also help to improve the reliability and consistency of G_1 values.

4. EVALUATION of CURRENT WORK from MUDEK PERSPECTIVE

4.1. Economic Analysis

This project was supported by the Lift-Up Program Turkish Aerospace Industry, and TUBITAK 2209B. Therefore, invoiced expenses were paid by TAI. All specimens were provided by TAI. All tests were held in the Mechanical Tests Laboratory of our university. A digital vernier calliper, sandpapers and adhesive for aluminum blocks were bought until this point of the project, see Table 4.1.

Table 4.1 Expenses

Products	Piece/Total	Price
Digital Vernier Calliper	1	200 TL
Sandpaper	5	150 TL
Adhesive for Aluminum Blocks	2	60 TL

4.2. Real-Life Conditions

Adhesives are increasingly being used to bond composites in aerospace applications. Composites are essential for aircraft due to their lightweight and durable qualities, while adhesives offer a more even load distribution than traditional mechanical fasteners, reducing weight and improving structural integrity. This technique is widely used in modern aircraft for wings and fuselage panels, leading to enhanced flight performance and fuel efficiency. Thorough testing is conducted to ensure the reliability and durability of adhesive bonds in different conditions, making this method vital for the development of more efficient and eco-friendly aircraft. For this purpose, we first optimized the adhesive thickness. We used low-cost production methods to achieve cost savings by comparing with other production methods.

4.3. Constraints

Unfortunately, a very affecting factor in this study is that the purpose of the project was not clear at the beginning. The topic determined as the thesis topic consists of a multi-stage research. Therefore, we can say that this study is one of these stages. In addition, the differences in the parts of the samples identified as initial cracks and the lack of clear material and production information made it difficult to reach the conclusion.

5. CONCLUSION

The study focused on examining the impact of different adhesive thicknesses on the mechanical behaviour of Carbon Fiber Reinforced Polymers (CFRP). The research revealed that the thickness of the adhesive plays a crucial role in affecting the mechanical durability of CFRP structures.

The study used DCB tests to investigate how adhesive thickness affects the energy release rate. The results demonstrated that adjusting the adhesive thickness significantly influences the material's crack resistance. It was found that optimizing the adhesive thickness is essential for maximizing the crack resistance of the material, increasing adhesive thickness improved crack resistance up to a certain point but led to inconsistencies beyond that.

Experimental results emphasized the importance of carefully controlling adhesive thickness in the design of CFRP structures, particularly in high-performance applications like aerospace and automotive. Optimizing adhesive thickness not only impacts mechanical strength but also has implications for material costs and production processes. Thinner adhesive layers result in material savings, but it's crucial to maintain a certain thickness for adequate mechanical strength.

In summary, the study highlighted the significance of optimizing adhesive thickness in CFRP structures to enhance material performance and durability. Future research will further support these findings through extensive experiments and advanced analysis techniques, contributing to the advancement of composite material technology.

6. FUTURE WORKS

This project will continue to work within the scope of TUBITAK 2209-B and LIFTUP projects in the future. TUBITAK 2209-B programme is a programme that encourages university students to research and provides financial support for their projects. In this context, our project team will have the opportunity to further advance our project by obtaining the necessary funds for the development of existing findings and the discovery of new research areas.

In addition, the LIFTUP is a platform that encourages the development of innovative technologies and university-industry collaboration. Through this programme, the integration of project results into industrial applications will be ensured and, together with our industrial partners, it will be aimed to transform the innovative findings obtained in the project into practical uses. The LIFTUP project will accelerate the transformation of knowledge and technologies coming out of university laboratories into commercial products, contributing to the significant impact of our project on real-world applications.

In line with these future plans, we will continue our research on improving the performance of composite materials and aim to contribute to scientific and technological progress by disseminating the results obtained to a wide audience. With the support of these projects, we will be able to expand our research capacity and develop more comprehensive and innovative solutions.

In the next phases of this project, we will move towards more sophisticated analyses such as adhesive thickness optimization and the study of prepreg composite materials. In line with the test and analysis results we have obtained so far, we will carry out a detailed investigation to understand the effects of adhesive layer thickness on mechanical performance and fracture resistance, especially based on key values such as critical mode II strain energy release rate (G_{IIc}) obtained from ENF tests, see Figure 6.16.1. In these analyses, we will use Abaqus software to model the effects of adhesive layer thickness on the structural integrity and crack propagation of composite materials under load. By determining how different adhesive thicknesses affect stress distribution and crack propagation at bonded joints, these studies aim to identify the optimum adhesive thickness that maximises the durability and strength of the joints. This is of particular importance for applications where the adhesion interface plays a critical role in the overall performance of the composite structure.

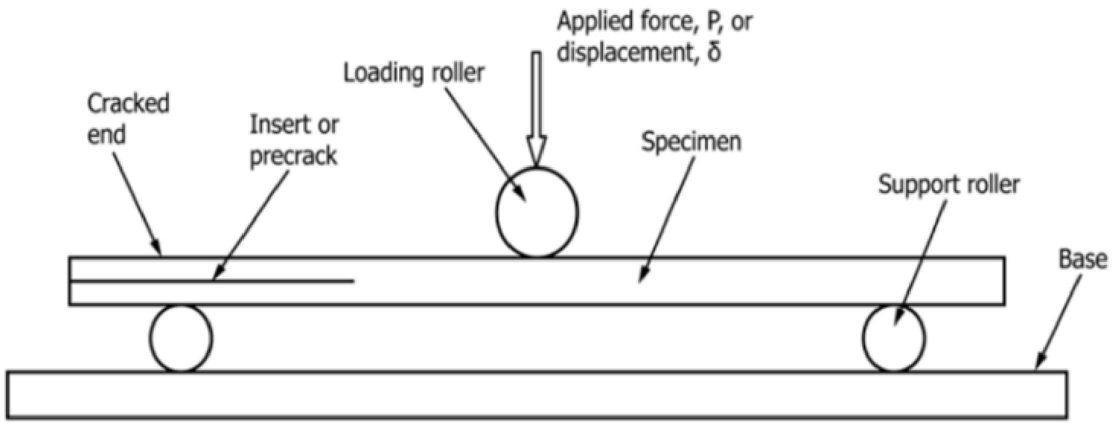


Figure 6.1 End Notched Flexure Test Geometry

We will also extend the project to include the development and testing of prepreg materials with superior mechanical properties, pre-impregnated with resin and cured under controlled conditions. These prepreg materials will be designed and manufactured with different adhesive layer thicknesses and tested under standard conditions to evaluate their performance in terms of crack propagation and overall structural behaviour. The experimental results will be used to validate our finite element models, ensuring that our simulations accurately reflect real-world performance. This integration will allow us to comprehensively evaluate the effects of different adhesive thicknesses and material compositions on the mechanical properties of composite structures.

Future work will help us to better understand how adhesive layers play a role in enhancing the durability and reliability of composite joints by studying various failure modes such as delamination and fibre-matrix separation. By leveraging Abaqus' detailed simulation and analysis capabilities, we aim to optimise the adhesive bonding process for composite materials and develop advanced composite materials with properties tailored for engineering applications. This research will contribute significantly to the development of composite technology in mechanical engineering. In this project, the effect of adhesive thickness on the mechanical properties of wet woven and prepreg composite specimens will be investigated in detail and an advanced finite element analysis (FEA) software, Abaqus, will be used for this purpose. Abaqus is a software with a wide modelling capacity that offers high precision results in solving and simulating engineering problems. The program is an ideal tool for evaluating the effects of different adhesive thicknesses because it can analyse complex material behaviour, multiple contact problems and fracture mechanisms with high accuracy. In these analyses, the material properties of wet woven and prepreg composite specimens will be modelled and simulated in detail to understand the effects of adhesive thicknesses on mechanical performance. Abaqus is capable of simulating the internal stresses, deformations and fracture behaviour of such composite materials and is also capable of studying the microstructural behaviour of the samples. In particular, detailed results will be obtained by performing structural integrity tests (DCB and ENF tests) and modal analyses to analyse how the specimens react depending on the thickness of the adhesive layer and how this layer affects the material strength. Using the finite element method of Abaqus, the loads applied on the specimens and the critical parameters such as stress and energy density caused by these loads will be calculated.

Another future direction of this work covers areas such as collecting more experimental data, developing Ansys models, extending the programme, validating the programme and conducting additional studies. The accuracy and scope of the programme will be extended by collecting more experimental data for a wider range of adhesive thicknesses and different loading conditions for different adhesive types and composite materials. The development of Ansys models will allow the models to include more complex geometries, advanced material models and elements such as thermal and hygroscopic effects. The extension of the programme will include enhancements such as predicting different crack types and fracture mechanics parameters and providing a user-friendly interface. Validation of the program will be carried out through comparative analyses with other programs, comparison with experimental data and validation in real-world applications. Additional work will examine how adhesive thickness affects other mechanical properties and long-term performance of composite specimens, the effects of different bonding techniques, and the application of this research in fields such as aerospace, automotive, civil, materials science and mechanical engineering. These future studies will help the programme to become an even more useful tool for the design and analysis of composite materials and contribute to significant advances in these fields.

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APPENDICES

Appendix 1

Appendix 1.1: Physical properties of FM300K

Physical Properties	Metric	Comments
Volatiles	<= 1.0 %	
Outgassing - Total Mass Loss	0.92 %	TWL
Collected Volatile Condensable Material	0.070 %	
Storage Temperature	-18.0 °C	Supported Grades
	4.50 °C	Unsupported Grades

Appendix 1.2: Mechanical properties of FM300K

Mechanical Properties	*Metric*	*Comments*
Tensile Strength	5.38 MPa	Flatwise, 150 °C for 7920 hrs
	6.55 MPa	Flatwise, 150 °C for 5760 hrs
	6.62 MPa	Flatwise, 150 °C for 2880 hrs
	6.83 MPa	Flatwise, 150 °C for 5040 hrs
	6.89 MPa	Flatwise, 150 °C for 4320 hrs
	9.51 MPa	Flatwise, Heat Aging Control
	2.34 MPa @Temperature 150 °C	Flatwise, 0.05 psf
	3.24 MPa @Temperature 150 °C	Flatwise, 0.08 psf
	7.10 MPa @Temperature 24.0 °C	Flatwise, 0.08 psf
	7.412 MPa @Temperature -55.0 °C	Flatwise, 0.08 psf
Shear Strength	42.02 MPa	0.08 psf, after 7 hays immersion in Hydrocarbon fluid
	42.3 MPa	0.08 psf, after 7 hays immersion in Hydraulic oil
	42.92 MPa	0.08 psf, after 30 days at 120 °F (50 °C), 95-100% RH3
	43.0 MPa	0.08 psf, after 7 hays immersion in JP-4 fuel
	43.26 MPa	0.08 psf, after 7 hays immersion in Anti-icing fluid
	43.8 MPa	0.08 psf, after 200 hours in Skydrol4 hydraulic fluid at 150 °F (66 °C)
	17.9 - 20.0 MPa	15 day Exposure at 54% RH

@Temperature 150 °C	
20.4 MPa	150 °C for 7920 hrs
@Temperature 149 °C	
20.44 MPa	0.05 psf
@Temperature 150 °C	
20.5 MPa	Heat Aging Control
@Temperature 149 °C	
21.75 MPa	0.08 psf
@Temperature 150 °C	
22.1 MPa	150 °C for 5760 hrs
@Temperature 24.0 °C	
22.5 MPa	150 °C for 7920 hrs
@Temperature 24.0 °C	
22.8 - 23.4 MPa	no exposure
@Temperature 150 °C	
23.4 MPa	150 °C for 2880 hrs
@Temperature 149 °C	
23.6 MPa	150 °C for 4320 hrs
@Temperature 149 °C	
23.8 MPa	150 °C for 5760 hrs
@Temperature 149 °C	
23.8 MPa	150 °C for 7200 hrs
@Temperature 149 °C	
24.3 MPa	150 °C for 5040 hrs
@Temperature 149 °C	
24.65 MPa	0.05 psf
@Temperature 120 °C	
24.7 MPa	150 °C for 7200 hrs
@Temperature 24.0 °C	
25.6 MPa	150 °C for 1140 hrs
@Temperature 149 °C	
27.0 MPa	150 °C for 5040 hrs
@Temperature 24.0 °C	
29.0 MPa	0.08 psf
@Temperature 120 °C	
29.6 MPa	150 °C for 4320 hrs
@Temperature 24.0 °C	
30.8 MPa	150 °C for 1140 hrs
@Temperature 24.0 °C	
32.4 MPa	150 °C for 2880 hrs
@Temperature 24.0 °C	
32.1 - 33.1 MPa	no exposure
@Temperature 24.0 °C	
33.8 - 35.9 MPa	15 day Exposure at 54% RH
@Temperature 24.0 °C	
36.8 MPa	0.05 psf
@Temperature 24.0 °C	
37.6 MPa	0.08 psf

	@Temperature -55.0 °C	
	40.3 MPa @Temperature 24.0 °C	0.08 psf
	41.9 MPa @Temperature 24.0 °C	Heat Aging Control
Peel Strength	4.03 kN/m @Temperature 24.0 °C	Floating Roller, 0.05 psf
	4.56 kN/m @Temperature 150 °C	Floating Roller, 0.08 psf
	4.91 kN/m @Temperature 24.0 °C	Floating Roller, 0.08 psf
	4.91 kN/m @Temperature -55.0 °C	Floating Roller, 0.08 psf
	4.91 - 5.08 kN/m @Temperature 24.0 °C	Floating Roller, no exposure
	4.91 - 5.08 kN/m @Temperature 24.0 °C	Floating Roller, 15 day Exposure at 54% RH
	11.9 - 13.1 kN/m @Temperature 150 °C	Floating Roller, no exposure
	12.1 - 13.1 kN/m @Temperature 150 °C	Floating Roller, 15 day Exposure at 54% RH

Appendix 1.3: Thermal properties of FM300K

Thermal Properties	Metric	Comments
Maximum Service Temperature, Air	150 °C	
Minimum Service Temperature, Air	-55.0 °C	

Appendix 1.4: Processing properties of FM300K

Processing Properties	Metric	Comments
Shelf Life	4.00 Month	Unsupported Grades
	12.0 Month	Supported Grades

Appendix 1.5: Descriptive properties of FM300K

Descriptive Properties	Metric	Comments
Color	Green	
Honeycomb Sandwich Peel	25 Nm/m	150 °C for 7920 hrs
	30 Nm/m	150 °C for 5760 hrs
	30 Nm/m	150 °C for 7200 hrs
	32 Nm/m	0.05 psf, 24 °C
	32 Nm/m	0.05 psf, 150 °C
	34 Nm/m	150 °C for 5040 hrs
	37 Nm/m	0.05 psf, -55 °C
	39 Nm/m	150 °C for 4320 hrs
	41 Nm/m	0.08 psf, 150 °C
	52 Nm/m	150 °C for 1140 hrs
	58 Nm/m	0.08 psf, -55 °C
	60 Nm/m	150 °C for 2880 hrs
	66 Nm/m	0.08 psf, 24 °C
	94 Nm/m	Heat Aging Control