



**TÜRKİYE CUMHURİYETİ
ADANA ALPARSLAN TÜRKEŞ SCIENCE AND TECHNOLOGY
UNIVERSITY**

**GRADUATE SCHOOL
MECHANICAL ENGINEERING DEPARTMENT**

**FRACTURE ANALYSIS OF MATERIALS USED IN HIGH PRESSURE
HYDROGEN STORAGE TANKS**

ADEM AVCU

Ph.D.

ADANA 2024



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ADANA, 2024

CERTIFICATION OF APPROVAL

FRACTURE ANALYSIS OF MATERIALS USED IN HIGH PRESSURE HYDROGEN STORAGE TANKS

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In this thesis study, which was prepared following the thesis writing rules of Adana Alparslan Türkeş Science and Technology University Institute of Graduate School, I declare that I provide all the information, documents, evaluations and results in accordance with scientific ethics and moral codes without resorting to any means or assistance that would be contrary to scientific ethics and traditions. I also declare that I refer to all of the articles I used in this study with appropriate references and accept all moral and legal consequences if a situation is found contrary to my statement regarding my work.

26/06/2024

Adem AVCU

ÖZET

YÜKSEK BASINÇLI HİDROJEN DEPOLAMA TANKLARINDA KULLANILAN MALZEMELERİN KIRILMA ANALİZİ

Adem AVCU

Doktora, Makine Mühendisliği Anabilim Dalı

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Bu çalışma, tip III kompozit basınç tankının kırılma tokluğunun belirlenmesine odaklanmıştır. Bu amaçla tip III kompozit basınçlı tanktan alınan numuneler üzerinde belirtilen yöntemlere uygun olarak deneysel ve sayısal çalışmalar yapılmıştır. Bu çalışmanın temel amacı klasik dayanım yaklaşımına ek olarak boru veya basınçlı tank gibi dairesel şekilli malzemelerin kırılma tokluğunun doğru bir şekilde belirlenmesidir. Bu amaçla, tankın çember çekme mukavemeti ve kırılma tokluğunu belirlemek için universal test makinesinde kullanılmak üzere fiktürler üretildi. Daha sonra basınç tankından alınan numuneler ile bölünmüş disk çekme aparatı (split disk tensile test – SDT) kullanılarak çekme testleri yapılmıştır. Tankın çekme mukavemeti belirlendikten sonra elastisite modülü de belirlenmiştir. Ayrıca tank gövdesi Abaqus ile sonlu elemanlar yöntemi kullanılarak düz plaka olarak modellenmiş ve deneysel sonuçlarla karşılaştırıldığında elastisite modülü %98,34 doğrulukla tahmin edilmiştir. Çekme testinin ardından tankın kırılma tokluğunu belirlemek için kavisli CT (compact tension) numuneleri kullanılarak deneysel çalışmalar yapıldı ve deneysel sonuçlar düz olarak modellenmiş CT sayısal modeliyle karşılaştırıldı. Deneysel ve sayısal mod I gerilme yoğunluk faktörü değerlerinin 36,90 ve 35,89 $\text{MPa}\sqrt{m}$ %2,7 sapma ile birbirine yakın elde edilmiştir. Son olarak PRNB (pipe ring notched bending) yöntemi ile deneysel ve sayısal çalışmalar yapılmıştır. Bu yöntemin sayısal modeli kullanılarak basınç tankının kırılma tokluğu 35,73 $\text{MPa}\sqrt{m}$ olarak hesaplanmıştır. Bu model aynı zamanda mod I kritik gerilme yoğunluk faktörüne odaklanarak, çatlak uzunluğunun değişiminin tankın depolama

basıncı üzerindeki etkisini araştırmak için de kullanıldı. Çalışmalar sonucunda çatlak uzunluğu/genişlik oranı (a/w) 0,1 olduğunda depolama basıncının 38 MPa olduğu, a/w oranı 0,5 olduğunda depolama basıncının 7 MPa değerine düştüğü belirlendi. Bu sonuçlardan tank gövdesindeki mevcut çatlakların çatlak uzunluğuna bağlı olarak depolama basıncını ciddi şekilde etkilediği sonucuna varılmıştır.

Anahtar Kelimeler: Kompozit tank, bölünmüş disk çekme testi, eğik kompakt çekme testi, çekme mukavemeti, gerilme yoğunluk faktörü.



ABSTRACT

FRACTURE ANALYSIS OF MATERIALS USED IN HIGH PRESSURE HYDROGEN STORAGE TANKS

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This work focused on determination of fracture toughness of a type III composite pressure tank. For this purpose, experimental and numerical studies were carried out on specimens taken from the type III composite pressure tank in accordance with the specified methods. The main purpose of this study was to accurately determine the fracture toughness of circular-shaped materials such as pipes or pressure tanks in addition to the classical strength approach. For this aim, fixtures were manufactured for use in the universal test machine to determine hoop tensile strength and fracture toughness of the tank. Subsequently, split disk test (SDT) were carried out on specimens taken from the pressure tank. After determining the hoop strength of the tank using SDT method, its modulus of elasticity was also determined. In addition, the tank body was modeled as a flat plate with Abaqus using finite element method, and the modulus of elasticity was predicted with 98.34% accuracy with experimental results. Following the hoop tensile test, experimental studies were performed using curved compact tension (CCT) method to determine fracture toughness of the tank and their results compared by flat compact tension (CT) numerical model. The values of the experimental and numerical mode I stress intensity factor were measured that, experimental and numerical mode I stress intensity factor values are 36.90 and 35.89 MPa $\sqrt{m}$, respectively. Consequently, the values found were close to each other with a deviation of 2.7%. Finally, experimental and numerical studies of the pipe ring notched bending (PRNB) method were carried out. Using the numerical model of this method, the fracture toughness of the pressure tank was computed as

35.73 MPa $\sqrt{m}$. This model was also used to investigate the effect of varying the crack lengths on the storage pressure of the tank, focusing on the mode I critical stress intensity factor (K_{IC}). As a result of the studies, it was determined that when the crack length to width ratio (a/w) was 0.1, the storage pressure was 38 MPa, and when the a/w ratio was 0.5, the storage pressure decreased to 7 MPa. From these results it was concluded that the existing cracks in the tank body seriously affected the storage pressure depending on the crack length.

Keywords: Composite tank, split disk test, curved compact tension, hoop tensile strength, stress intensity factor.



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LIST OF ABBREVIATIONS

AFC	: Alkaline Fuel Cell
AFM	: All Fracture Mode
Al	: Aluminum
AST	: Arc-Shaped Tension Specimen
BFP	: Bipolar Flow Plate
BMC	: Bulk Molding Compound
C/C	: Carbon-Carbon Composites
CCT	: Curved Compact Tension
CL	: Catalyst Layer
CMCs	: Ceramic Matrix Composites
CNC	: Computer Numerical Control
CNG	: Compressed Natural Gas
CNT	: Carbon Nanotube
COPV	: Composite Overwrapped Pressure Vessel
CRS	: Crack Rail Shear
CTOD	: Crack Tip Opening Displacement
CTS	: Compact Tension Specimen
CTPB	: Curved Three Point Bending
CTSR	: Compact Tension Shear Rotation
Cu	: Copper
CVN	: Charpy V-Notch Test
DCB	: Double Cantilever Beam
DMFC	: Direct Methanol Fuel Cell
ENDB	: Edge Notched Disc Bend
ECT	: Edge Crack Torsion
ELS	: End Load Split
ENF	: End-Notched Flexure
EPFM	: Elastic-Plastic Fracture Mechanics
ERCT	: Edge Ring Crack Torsion

FCV	: Fuel Cell Vehicles
FET	: Fibre-Elongation-Tracking
FRP	: Fiber Reinforced Composite
FW	: Fiber Winding
GDL	: Gas Diffusion Layer
GFRP	: Glass Fiber Reinforced Plastic
HDPE	: High Density Polyethylene
HTTDFM	: High Temperature Time Dependent Fracture Mechanics
LEFM	: Linear Elastic Fracture Mechanics
LHFB	: Longitudinal Half Fixed Beam
LLDPE	: Low Linear Density Polyethylene
MEA	: Membrane Electrode Assembly
MCFC	: Molten Carbonate Fuel Cell
MCT	: Modified Compact Tension
Mg	: Magnesium
MMB	: Mixed Mode Bending
MMCs	: Metal Matrix Composites
MT	: Middle Tension
PAFC	: Phosphoric Acid Fuel Cell
PEMFC	: Proton Exchange Membrane Fuel Cell
PMCs	: Polymer Matrix Composites
PRNB	: Pipe Ring Notched Bend
RE	: Renewable Energy
RHTT	: Ring Hoop Tension Test
RTM	: Resin Transfer Molding
SCB	: Semi-Circular Bend
SDT	: Split Disk Tensile Test
SENB	: Single Edge Notch Bend
SMC	: Sheet Molding Compound
SOFC	: Solid Oxide Fuel Cell
Ti	: Titanium
VARTM	: Vacuum Assisted Resin Transfer Molding
VCT	: Visible-Crack-Tracking

Zn-Al	: Zinc-Aluminum
Zr-2.5Nb	: Zirconium Alloy
Zry-4	: Zircalloy



LIST OF SYMBOLS

A	: Crack Area
A	: Plane Stiffness Matrix
$\dot{A}$	: Crack Surface Area Growth Rate Per Unit Time
B	: Bending- Extension Coupling Matrix
γ	: Energy Required to For Creating New Surface Area
D	: Bending Stiffness Matrix
ds	: An Increment of the Contour Path
E_I, E_{II}, E_{III}	: Modulus of Elasticity for Mode I, II, III
e^-	: Electron
E	: Modulus of Elasticity
ε	: Strain
$\varepsilon_x, \varepsilon_y, \varepsilon_z$	: Strains
$f_I(x)$	: Mode I Correction Factor
G	: Strain Energy Release Rate
G_I	: Mode I Strain Energy Release
G_{II}	: Mode II Strain Energy Release
G_{III}	: Mode III Strain Energy Release
G_C	: Critical Strain Energy Release Rate
G_T	: Total Strain Energy Release
H^+	: Hydrogen ion
H_2	: Hydrogen
H_2O	: Water
Θ	: Angle
J	: Release of Potential Energy per Unit Extension
k	: Lamina Number
K	: Curvature
$\dot{K}$	: Kinetic Energy
K_C	: Critical Mode-I Stress Intensity Factor
K_I	: Mode I Stress Intensity Factor

K_t	: Stress Concentration Factor
K_{IC}	: Critical Mode-I Stress Intensity Factor
M_x, M_y, M_{xy}	: Tensile and Shear Forces
N	: Number of Lamina
N_x, N_y, N_{xy}	: Tensile and Shear Forces
O_2	: Oxygen
P	: Applied Load
P_c	: Critical Load
$\sigma_{applied}$	: Normal Applied Stress
σ_{max}	: Maximum Stress
$\sigma_{r\theta}$	: Shear Stress
σ_{rr}	: Radial Stress
σ_x	: Crack Direction Stress
σ_y	: Normal Direction Stress
$\sigma_{\theta\theta}$	: Hoop Stress
σ_{∞}	: Remote Stress
$\tau_{xy}, \tau_{xz}, \tau_{yz}$	: Shear Stresses
Q	: Reduced Stiffness Matrix
$\bar{Q}$	: Transfer Matrix
r	: Radius
Γ	: The Integral Path Near Crack
$\dot{\Gamma}$	: Energy Per Unit Time
R_h	: Radius of Hole
t	: Thickness
T_i	: Traction Vector at a Point on the Path Γ
$\dot{U}_E$	: Rates of Change of The Internal Elastic Energy
u_i	: Displacement Vector at a Point on the Path
$\dot{U}_P$	: Plastic Energy
ν	: Poisson's Ratio
V	: Volt
w	: Width
$\dot{W}$	: Work Performed Per Unit Time

x : Crack Direction
 y : Normal Direction
 Z_i : Distance of the i -th Lamina from the Center Plate



1. INTRODUCTION

Energy requirements are correspondingly increasing with the world population. Energy is supplied by traditional methods and this causes more damage to the earth. Similarly, traditional energy methods are reducing the habitability of the world and posing a threat to healthy life through the release of harmful gases. As the world's population increases, renewable energy sources become more important. Electricity generation from hydrogen is one of the clean energy sources and it is preferred in fuel cell vehicles due to its positive features such as not releasing harmful gases to the environment, not creating noise, low maintenance requirement, and high efficiency. In addition, excess electrical energy obtained from solar and wind can be stored in gaseous hydrogen form, which increases the significance of technologies hydrogen storage. Therefore, the trend toward renewable energy sources is advancing for minimization of harmful gas emissions for a livable world. The increasing energy requirement with the enhancement world population has made clean energy sources more important and accelerated research and development studies on this subject. Among the clean energy sources, hydrogen is an important property among other renewable energy sources because it does not produce a harmful substance by creating water, energy, and heat after chemical reactions, so it is sustainable. To utilise hydrogen energy, hydrogen storage can be done in solid liquid or gas forms. But gas storage is more prominent than other methods due to its low cost, fast filling and discharging, and storage capability under room conditions. In hydrogen fuel cell cars, hydrogen is supplied from high-pressure composite tanks. Type III or type IV tanks are preferred for the hydrogen storage. These types of tanks are made of composite materials that can withstand high pressures. The tanks can have the desired high strength properties with different layer thicknesses and different filament winding angles. However, high pressures create high stresses in the body of pressure vessels, and this may create undesirable safety conditions, especially in the presence of defects, gaps, or cracks that may develop on the body during operation. Because incomplete or incorrectly determined working conditions of the composite pressure tank cause a danger to humans or the environment. For this reason, safe usage of hydrogen storage tanks requires detailed investigation to measure hoop tensile strength and fracture toughness.

1.1 Statement of Problem

There are various experimental techniques for tensile and fracture testing of flat plates, but fewer methods have been developed for tensile and fracture tests on curved structures. For a safe use, it is important to determine the tensile strength and fracture toughness of pressure tanks or pipes that are widely used in many applications. Composite pressure tanks are used for hydrogen storage in fuel cell vehicles. These tanks store hydrogen at high pressure. High pressure gases used in fuel cells create high stress in the body of pressure vessels, which can create a critical situation especially in the presence of defects, voids or cracks on the body that may develop during operation. It is difficult to determine the tensile strength and fracture toughness of the pressure tanks by classical methods. Because these tanks do not have a flat bodies but have a curve shape. It is also difficult to take samples in a flat shape, especially at a small radius. In addition, it is a challenge to flatten the samples taken from their composite bodies due to their thermoset properties. Even if it can be straightened taking samples in the form of a circle and making them flat can affect the existing mechanical properties. To determine hoop tensile strength and fracture toughness of the tanks, using convenient methods considering their shape provides more accurate results. In particular, the lack of standards for measuring the fracture toughness of pressure tanks is a prominent concern in the safe gas storage of high-pressure tanks. Therefore, hoop tensile strength and fracture toughness of pressure tanks should be determined correctly.

1.2. Research Objectives

This study aims to determine the hoop tensile strength and mode-I fracture toughness of a type III pressure vessel with appropriate methods for measurement. How to accurately measure the hoop tensile stress and fracture toughness values of pipes or pressure tanks where it is difficult to take flat samples will be determined with an alternative approach. This approach involves first conducting experimental studies and then comparing numerical studies with experimental results. Additionally, it will be examined how critical the size of the intralaminar crack in a tank can be. As a result of these studies, answers to the questions of how to determine the mechanical properties of pipes or pressure tanks, which methods can be

used, and how the crack size affects the storage pressure of the tank will be answered. It is also aimed to be a guide study in determining the safe operating ranges of tanks and pipes.

1.3. Research Methodology

The focus of the study was determination of the mechanical properties of a type III composite pressure vessel employing appropriate methods. Particularly, a different approach was proposed for determination of fracture toughness, because current standards have inadequate characterization for the fracture toughness determination of circular shape materials. Experimental and subsequently numerical studies are performed on specimens that are taken from the supplied type III pressure tank. The methodology of the study consists of the following steps.

- Procurement of Type III composite pressure vessel
- Manufacturing of split disk tensile, compact tension, and pipe ring notched bending fixtures for experimental studies
- Preparation of appropriate dimension specimens from the pressure tank
- Carrying out experimental studies to determine hoop tensile strength by split disk tensile test method
- Modeling of tensile test with Abaqus and comparison with experimental results
- Measurement of fracture toughness of the pressure tank by curved compact tension method
- Numerical modeling with compact tension specimen and comparison with curved compact tension
- Analytical relationship proposal for the use of pipe ring notch bending method with LEFM approach
- Carrying out experimental studies with the pipe ring notch bending method
- Determination of fracture toughness by numerical modeling and comparison with the results of the curved compact tensile method
- Comparison of fracture toughness values at different crack sizes in the tank by pipe ring notch bending method and discuss internal storage pressure based on crack length

1.4 Organization of Thesis

In Chapter 1, the importance of determining the mechanical properties of composite pressure tanks used in hydrogen storage was put into words. Besides, it is mentioned why it is necessary to determine the fracture toughness of these tanks, pipes, or similar shaped materials.

Chapter 2 provides comprehensive information on hydrogen energy, its production methods, its use with renewable energy sources, storage methods, gas storage tank types, composite tanks, and composite manufacturing methods. A literature review on fracture toughness was also carried out. Two different approaches to fracture toughness, plain stress, and plain strain are represented through equations. The fracture modes Mode-I, Mode-II, Mode-III, and the methods in which their combinations can be applied are described in this section as general information.

In Chapter 3, the material of the Type III tank and its properties were mentioned. Subsequently, the split disc tensile method, curved compact tensile method, and pipe ring notch bending method were put into words for the determination of the hoop tensile strength and fracture toughness of the tank respectively. Numerical models of these methods were presented, as well as a thorough explanation of each step in the modeling process. In addition, a different analytical suggestion for calculating fracture toughness using pipe ring notch bending is proposed and this approach is explained using visuals.

In Chapter 4, a comparison of the results from the circular specimens with the results from the numerical modeling was presented. In the characterization of the tank material, tensile strength, and fracture toughness were studied as flat plates and compared with the experimental results. In addition to tensile and fracture toughness, fracture energies at various crack lengths were compared in the numerical model of the pipe ring notch bending method. The criticality of the crack length and the relation of internal storage pressure were also evaluated.

Chapter 5 summed up the results of the experimental and numerical studies for determining mechanical properties and described the contributions of this work to the literature.

2. THEORETICAL FOUNDATIONS AND LITERATURE REVIEW

2.1 Hydrogen Energy

Hydrocarbon (fossil) fuels supply most of the energy needs of the world. While fossil fuel sources are decreasing, the population of the planet is increasing as well as the augment of energy demands. As shown in Figure 2.1, it is predicted that energy demand will rise with the increasing population. Therefore, renewable energy (RE) resources such as solar, and wind are getting attention. But, RE resources require large-scale energy storage systems for procurement the increasing energy needs. For this reason, hydrogen (H_2) is seen as a good alternative source. Besides, it can meet these requirements with positive sides such as maintaining energy sustainability and minimising the climate change. Energy resources are presented in Figure 2.2 with their usage and emission ratios. Nowadays, the production of energy from hydrogen gas is becoming more popular due to not releasing harmful gas into the environment and not creating deleterious chemical reactants, so this property of hydrogen is significant for the decarbonization of our planet [1], [2]. The most advantage of hydrogen is that it can be used as a carbon-free fuel. In addition, electricity energy obtained from renewable energy resources can be stored as hydrogen gas by electrolysis, so it can work as a hybrid with other energy resources [3], [4], [5], [6]. Hydrogen production methods have been classified into four main groups which are photolysis, electrolysis, thermolys and biolysis. In the literature, some papers categorized hydrogen production methods as blue, green, and grey. Generally, grey hydrogen is addressed polluting type due to releasing harmful gas directly or indirectly. Production hydrogen from natural gas process is named as blue hydrogen. This process creates CO_2 gas, but the gas is captured and not release to nature. Green hydrogen refers to sustainable and renewable hydrogen production methods [1], [2]. Hydrogen production methods are illustrated in Figure 2.3.

World Primary Energy Consumption
(Million Metric Tons of Oil Equivalent, 1950-2050)

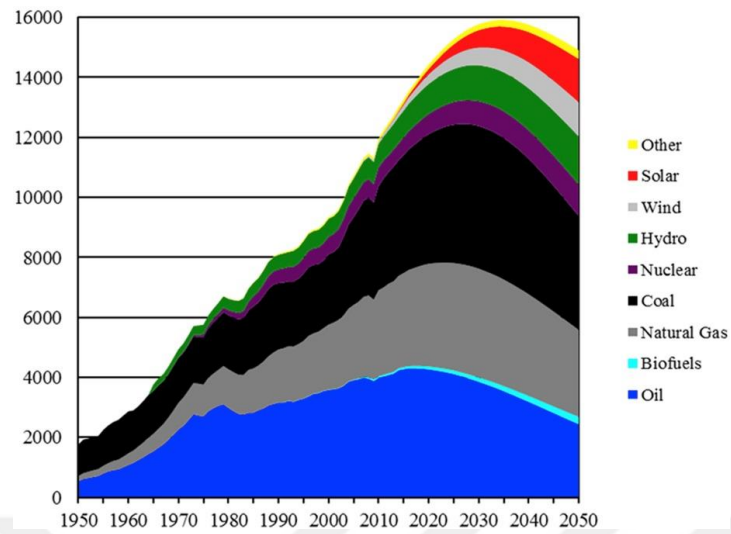


Figure 2.1. Estimated energy consumption of world [7]

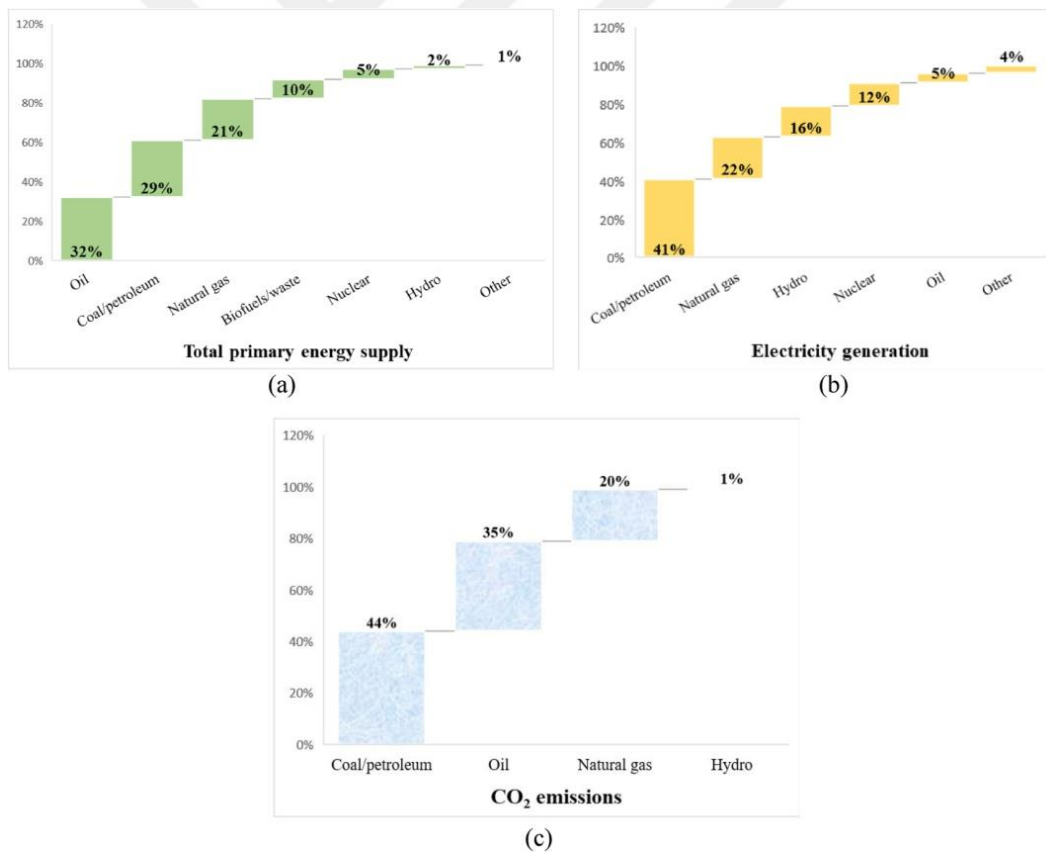


Figure 2.2. Energy resources with their usage and emission ratios: (a) Global energy supply (b) electricity generation and (c) CO₂ emissions [2]

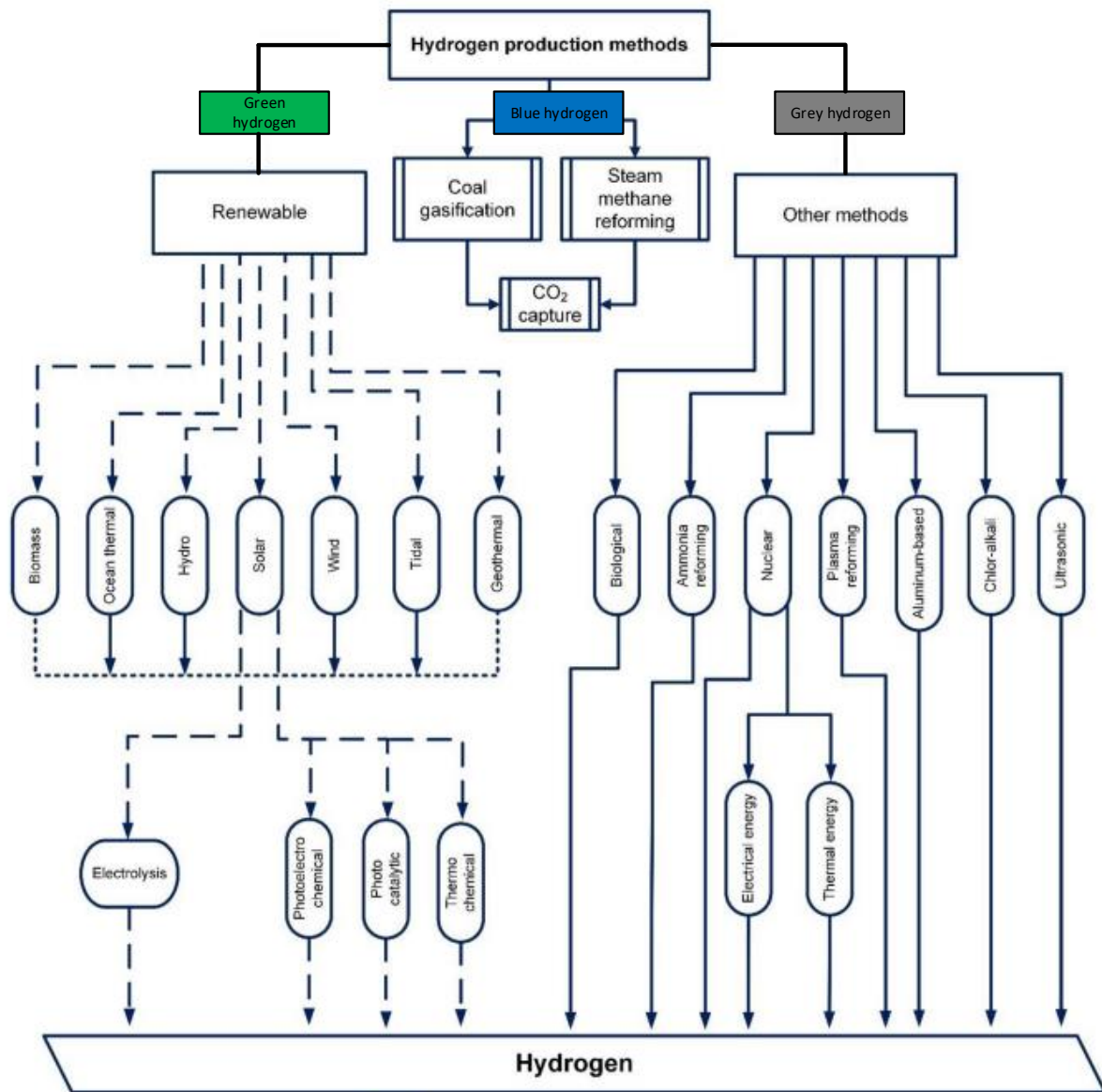


Figure 2.3. Hydrogen gas production methods (Reedited from [2])

Electrolysis is a useful principle to generate hydrogen gas from water (H₂O). This principle works basically with water and two electrodes. In an electrolysis cell, two electrodes are placed in the electrolyte. It is connected to the power supply for conducting current. If high voltage is applied between electrodes, enough water is decomposed and produces hydrogen and oxygen (O₂) on the cathode and anode, respectively. Adding an electrolyte increases the conductivity of water and continuous flow electric current [8]. Principle of electrolysis is illustrated in Figure 2.4. The electrolysis overall reaction is given in the following expression.

Electrolysis reaction: $2 \text{H}_2\text{O} + \text{electricity} + \text{heat} \rightarrow 2 \text{H}_2 + \text{O}_2$

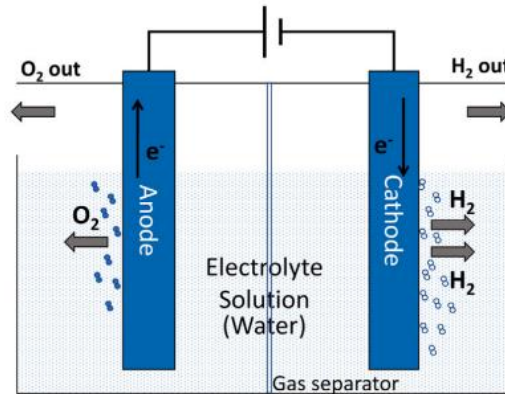


Figure 2.4. Water electrolysis principle [8]

Generally, storing excess electrical energy from solar and wind sources is utilized with hydrogen gas storage. Excess energy is converted from alternating current to direct current produced from these energy sources. By electrolysis process, electrical energy is transferred to hydrogen gas. When the energy requirement increases, the stored hydrogen is transformed into electrical energy by using a fuel cell [8], [9]. Examples of the relation of renewable energy with hydrogen production and its storage are illustrated in Figures 2.5 and 2.6 for solar and wind energy.

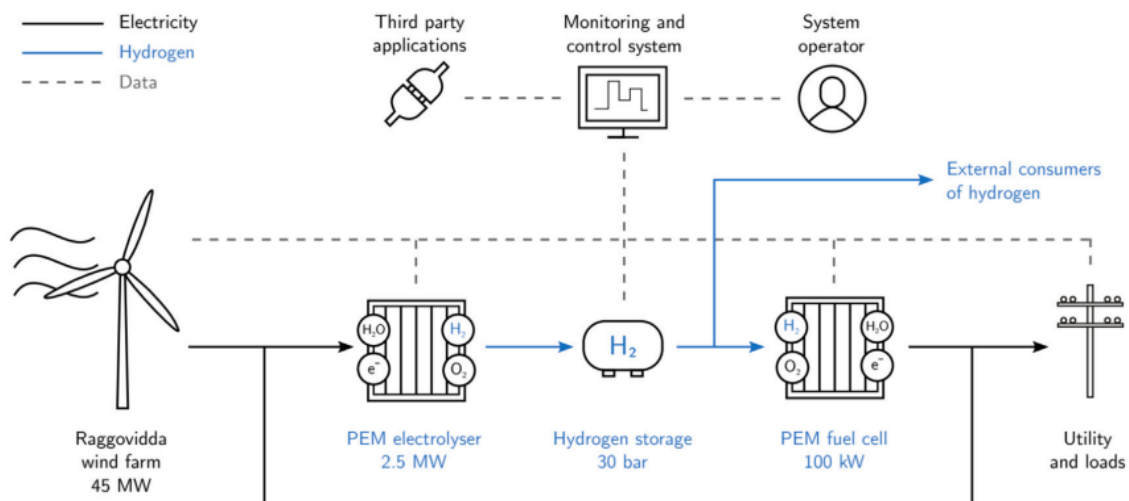


Figure 2.5. A schematic diagram for hydrogen production of wind energy [8]

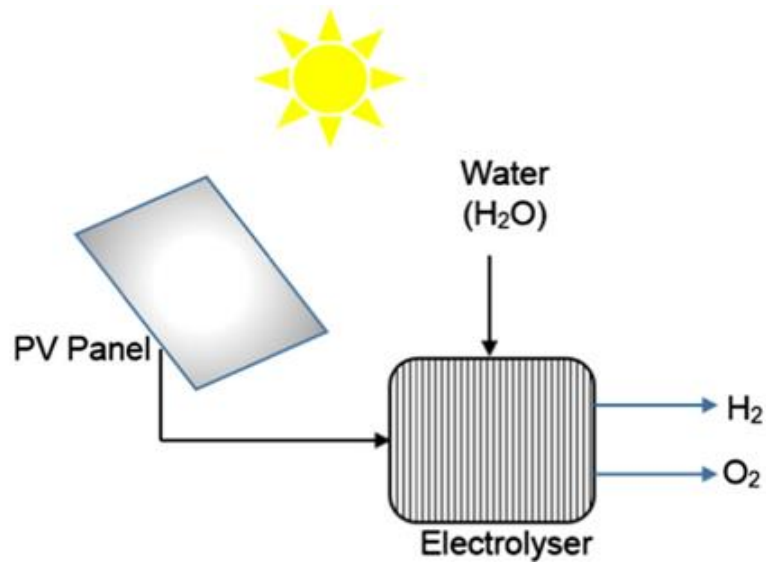


Figure 2.6. (a) Solar energy and hydrogen production [10]

Hydrogen is known as an element that has wide usage areas. As illustrated in Figure 2.7, hydrogen can be used in renewable form or transformed from other energy resources [3]. The property is an advantage for hydrogen which is seen as the energy source of the future and facilitates the transition to technologies that use hydrogen.

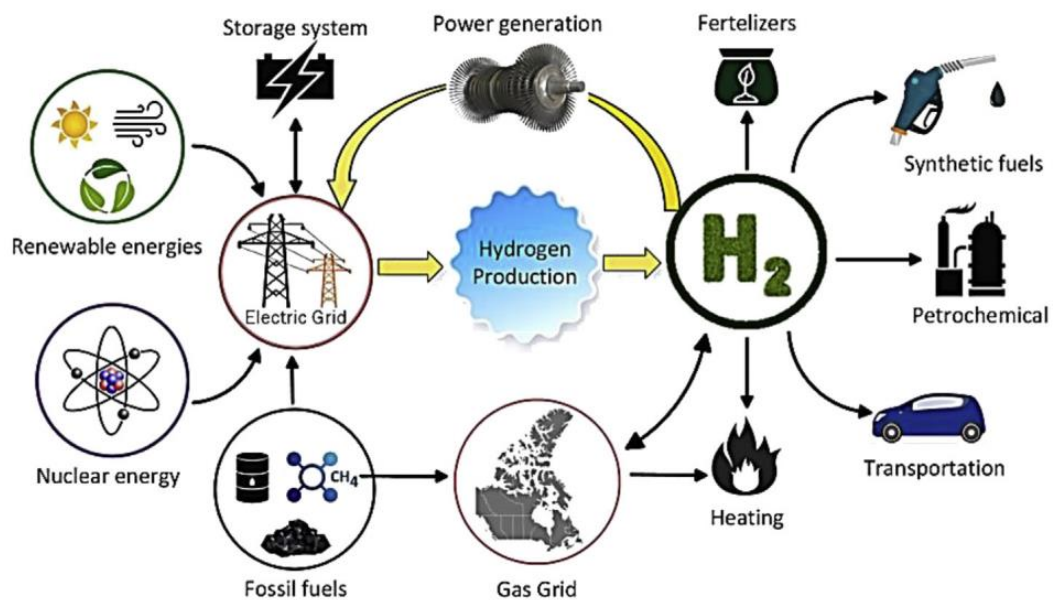


Figure 2.7. Hydrogen utilization in different energy types [3]

Hydrogen is non-toxic and much lighter than air and disperses quickly when released, and it is safer than other fuels due to this feature. But some properties such as lower ignition and easy flammable with air require additional engineering precautions therefore hydrogen storage is a key factor in ensuring safe usage. [1]. There are distinct methods to storage of hydrogen, and are categorized as compressed gas, underground storage, liquid hydrogen, and solid hydrogen is shown in Figure 2.8 [8], [11].

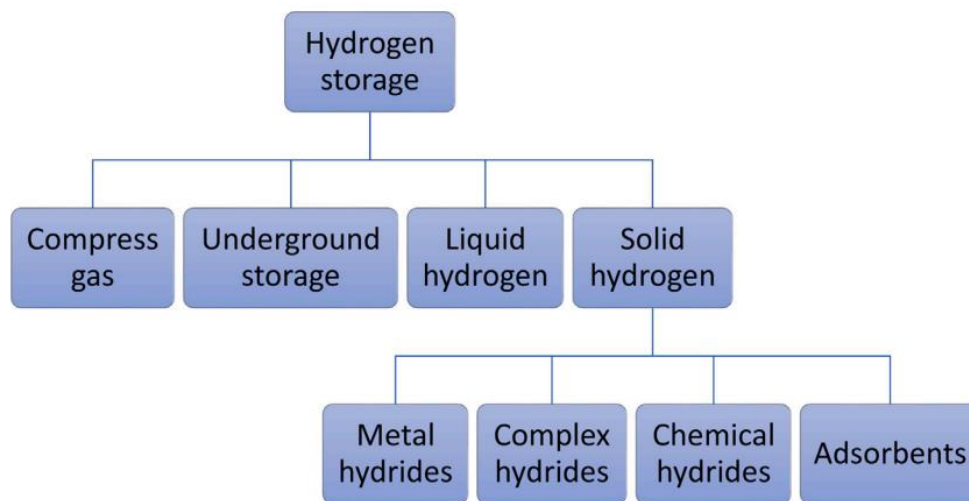


Figure 2.8. Hydrogen storage types [8]

2.2 Fuel Cells

Fuel cells are electrochemical power source devices that generate electrical energy using the chemical reaction of hydrogen and air. The main principle of the fuel cell is the transfer of hydrogen electrons from the anode to the cathode. This process continues up to deplete fuel and air supplication. After this conversion, electrical energy, heat, and water are produced from the fuel cell. Besides, there are great properties of fuel cells. They are clean and environmentally devices, are not releasing harmful gases, have high electrical efficiency, are working quite due to no moving mechanical parts, and have low maintenance needs. Fuel cells, which were initially used in space technology, have been developed to meet different needs for electrical energy production in time.

There are different fuel cell types, and are categorized in relation their electrolytes, and named as alkaline fuel cell (AFC), direct methanol fuel cell (DMFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC), and proton exchange membrane fuel cell (PEMFC). Among them, PEMFC has superior properties then the other type fuel cells which are low temperature operation, work ranging from -40 to 120 $^{\circ}\text{C}$, high power density, portable transportation and stationary applications. Work principle of PEMFC is illustrated in Figure 2.9. Hydrogen ions are transferred from the anode to the cathode by a membrane, whereas hydrogen electrons pass through an external circuit. After this process, hydrogen electrons react with their ions, so electrical energy is generated [12], [13], [14], [15], [16].

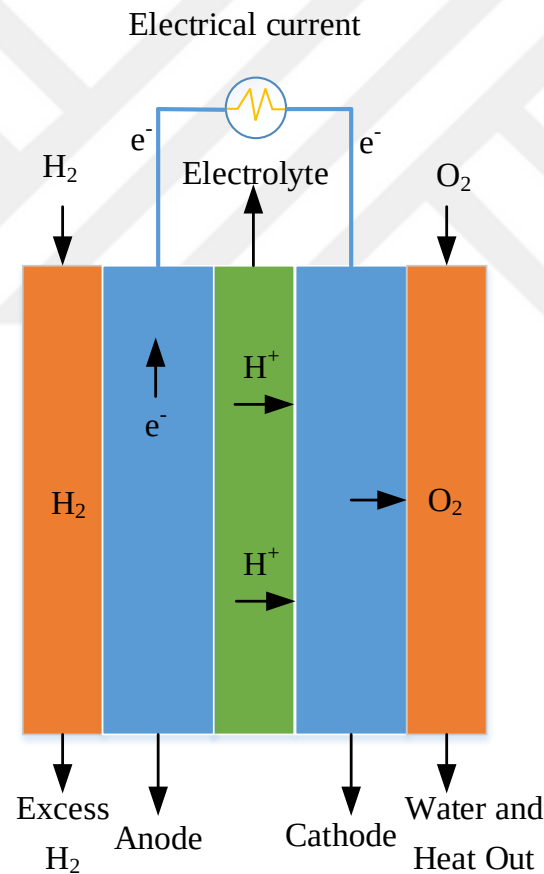


Figure 2.9. Working principle of PEMFC

Chemical reactions in fuel cell are stated in the following equations at anode, cathode and overall reactions [16], [17].

Anode reaction: $2 \text{H}_2 \rightarrow 4 \text{H}^+ + 4\text{e}^-$

Cathode reaction: $\text{O}_2 + 4 \text{H}^+ + 4\text{e}^- \rightarrow 2 \text{H}_2\text{O}$

Overall reaction: $2 \text{H}_2 + \text{O}_2 \rightleftharpoons 2 \text{H}_2\text{O}$

PEMFC is formed with a membrane, gas diffusion layer (GDL), catalyst layer (CL), bipolar flow plate (BFP), and end plate. Membrane, GDL and CL are assembled together, and it is called as membrane electrode assembly (MEA). PEMFC parts are shown in Figure 2.10. A single fuel cell can produce about 0.7 - 1.2 volts (V), but fuel cell stacks can generate more current or voltage for the requirement. [14], [18]. Fuel cell single and stack forms are illustrated in Figure 2.11.

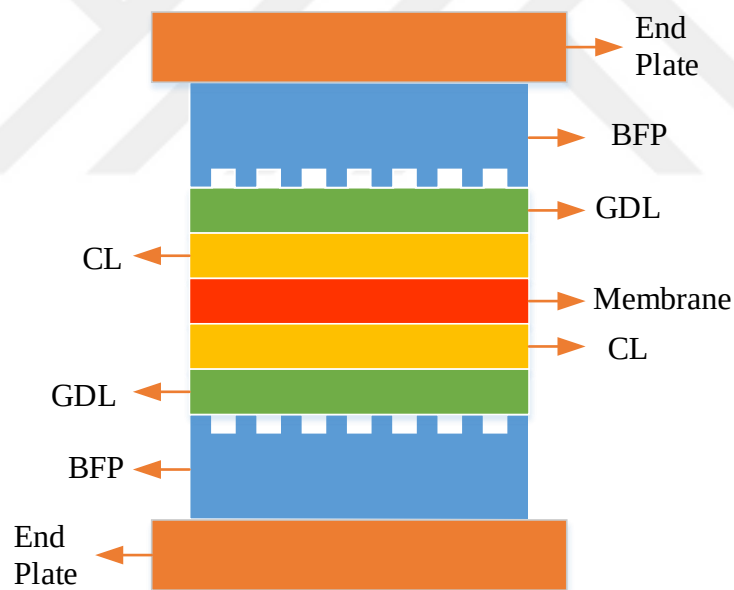


Figure 2.10. PEMFC parts

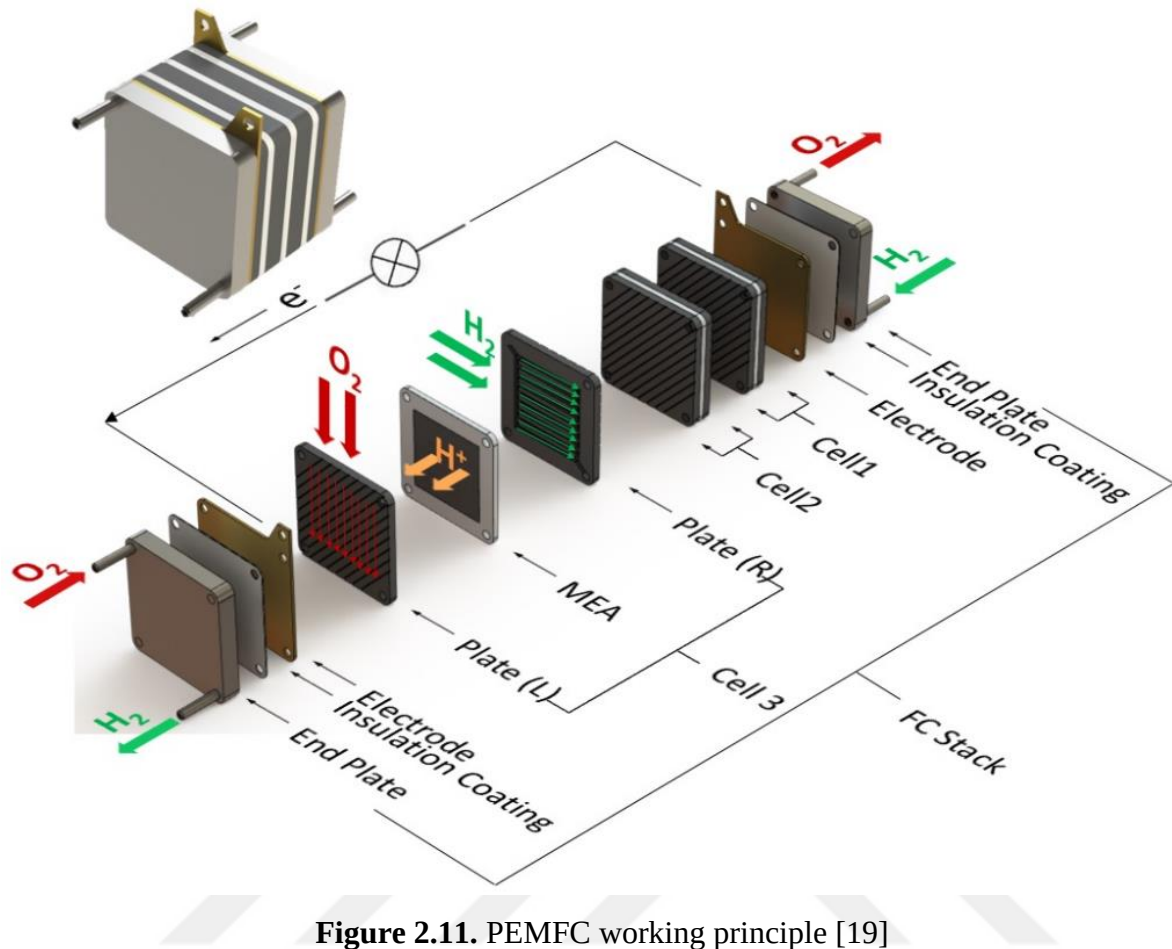


Figure 2.11. PEMFC working principle [19]

Fuel cell vehicles (FCV) have been developed for 1990 years. Among the fuel cell types, PEMFC has been given attention due to its properties such as high power density, lower operating temperature, excellent dynamic characteristics, and fast start-up. Therefore, it has been used in fuel-cell vehicles or other transportation applications. There is enormous attention to FCV, and this augments continuously, but the cost of fuel cells is still high, and this condition is a major obstacle to FCV preference and becoming widespread [18], [20], [21], [22]. In Figure 2.12, a prediction cost of the fuel cell and its components are shown. It can be seen that fuel cell stack cost decreases over the years [23].

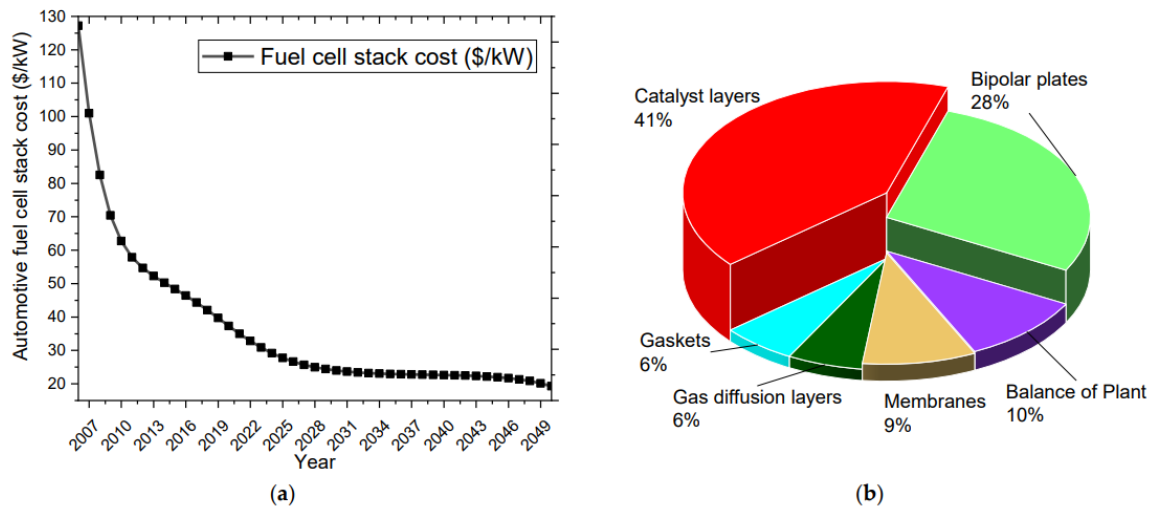


Figure 2.12. Forecast of fuel cell stack cost (a), overall cost fuel cell components (b) [23]

As seen in Figure 2.13, the main component of FCV consists of a battery, fuel cell stack, hydrogen storage tank, power control unit, and traction motor. Hydrogen is stored in a hydrogen storage tanks that reached up to 700 bar. With the controller, it adjusts the required power as well as hydrogen for the instantaneous movement of FCV. The fuel cell stack generates electrical energy using hydrogen and air, and the controller transmits it to its electric traction motor. A battery is utilized for storing excess electricity, recovery of brake energy, or supplying instant power demand. [24].

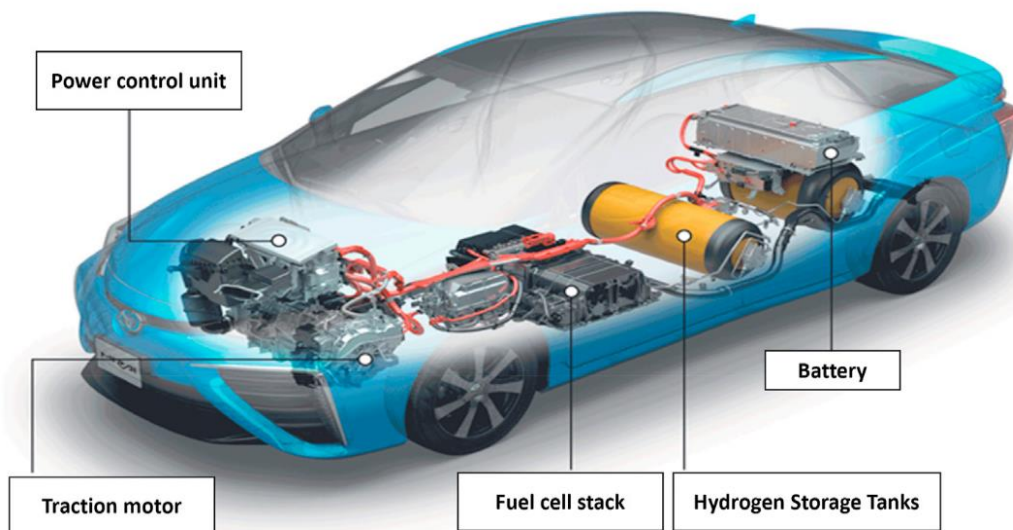


Figure 2.13. FCV basic components [24]

Fuel cells are not only used in cars, they can be utilized in transportation vehicles, and stationary power generation devices. As illustrated in Figure 2.14, the fuel cell has a wide range of uses as cars, buses, trucks, trains, bikes, boats, ships, and electronic devices. Some governments foresaw fuel cells as a key technology in the near time. For example, the Japanese, China, and United States governments aim to commercialize fuel cell cars in the near future. Therefore fuel cell technology has an intensive attraction, so research and development studies continue on this area [25].

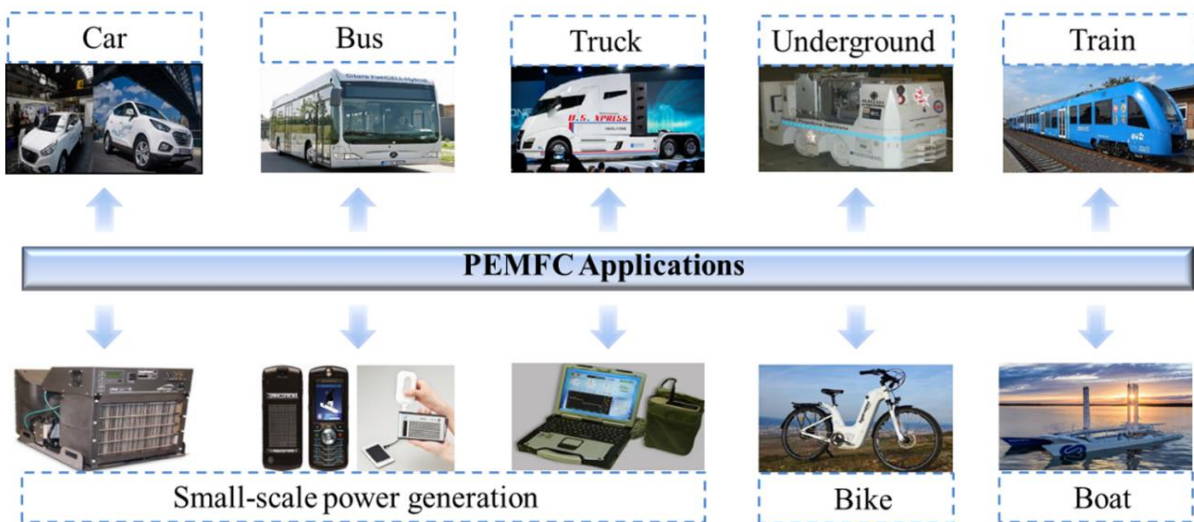


Figure 2.14. Fuel cell technology applications [25]

2.3 Composites

Composite materials consist of two or more distinct materials to improve their mechanical properties. They generally are composed of reinforcement and matrix materials. Metal, polymer, and ceramics are utilized as matrix, while particles, fibers, flakes, and fillers are used as reinforcement materials. Matrix materials cover fillers and bond materials together and prevent external impacts. Reinforcement or filler materials increase the mechanical properties of composite materials regarding stiffness and strength, therefore carries the applied load. So, the composite materials have more superior characteristic features than their individual forms [26], [27].

Composite materials can be classified regard as matrix and reinforcement types separately. In the case of the matrix type, they are categorized as polymer matrix composites (PMCs), metal matrix composites (MMCs), ceramic matrix composites (CMCs), but some papers counted one more type as carbon-carbon composites (C/C). For C/C composites, both matrix and reinforcement materials are formed with carbon [28], [29]. PMCs are composed of thermoplastic or thermoset matrices by reinforcement with glass, carbon, and aramid fibers. Thermoset matrices are preferred more than thermoplastics due to their high-temperature resistance and high strength. Thermosets can not reshape after application however thermoplastics can be re formed, also they are recyclable and reusable for other applications. MMCs are created using metal matrices with ceramic or metal reinforcement. For matrices, aluminum (Al), magnesium (Mg), copper (Cu), titanium (Ti), and zinc-aluminum (Zn-Al) are used. Aluminum-based MMCs are widely utilized in automotive and aerospace industries due to positive features such as superior strength, lower density, and higher stiffness with functionality and processability. CMCs are formed with ceramic matrix and reinforcement such as fibers, nanotubes, particulates, graphene, and metal. They have remarkable properties: good wear resistance and fracture toughness, resistance to high temperature and thermal shock, and excellent strength. These types of materials are widely used in the aerospace, defense, automotive, power, electronic, chemical, and biomedical sectors. Examples of composites based on matrix types are illustrated in Figure 2.15.

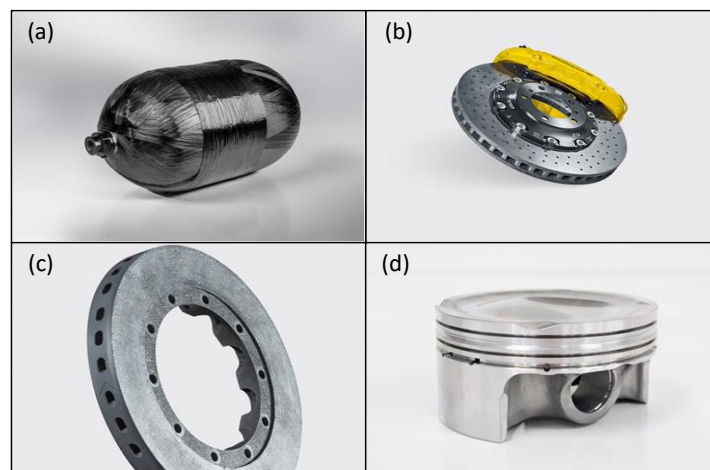


Figure 2.15. Different composites materials: a) Composite overwrapped pressure vessel an example PMC (Source: <https://l24.im/CK8i>), b) car brake disk an example CMC, c) racing brake disk an example C/C (Source: <https://l24.im/IxLVN7t>), d) combustion engine piston an example MMC (Source: <https://l24.im/9dHrvnh>)

In the case of reinforcement based classification, composites are named as fiber reinforced composites (FRP), particle reinforced composites, and sheet molded composites forms. In fiber reinforced composites, synthetic or natural fibers are dispersed in matrix. These type composites are addressed with fiber length that are continuous or discontinuous. Continuous fiber-reinforced composites are classified into fiber directions as unidirectional and bidirectional. In discontinuous fiber reinforcements, fibers are called aligned or randomly oriented regarded as the dispersion of fibers. Particle based composites are chosen when wear resistance is important. Besides they have some advantages that are easy production and forming, and low cost. Sheet molded composites are termed as sheet molding compounds (SMC), and they are formed applying compression molded to generate flat shape with unsaturated resins as matrix and generally combining glass fibers as reinforcement. [26], [28], [30], [31], [32], [33]. Classification of composites based on matrix and reinforcement is illustrated in Figure 2.16.

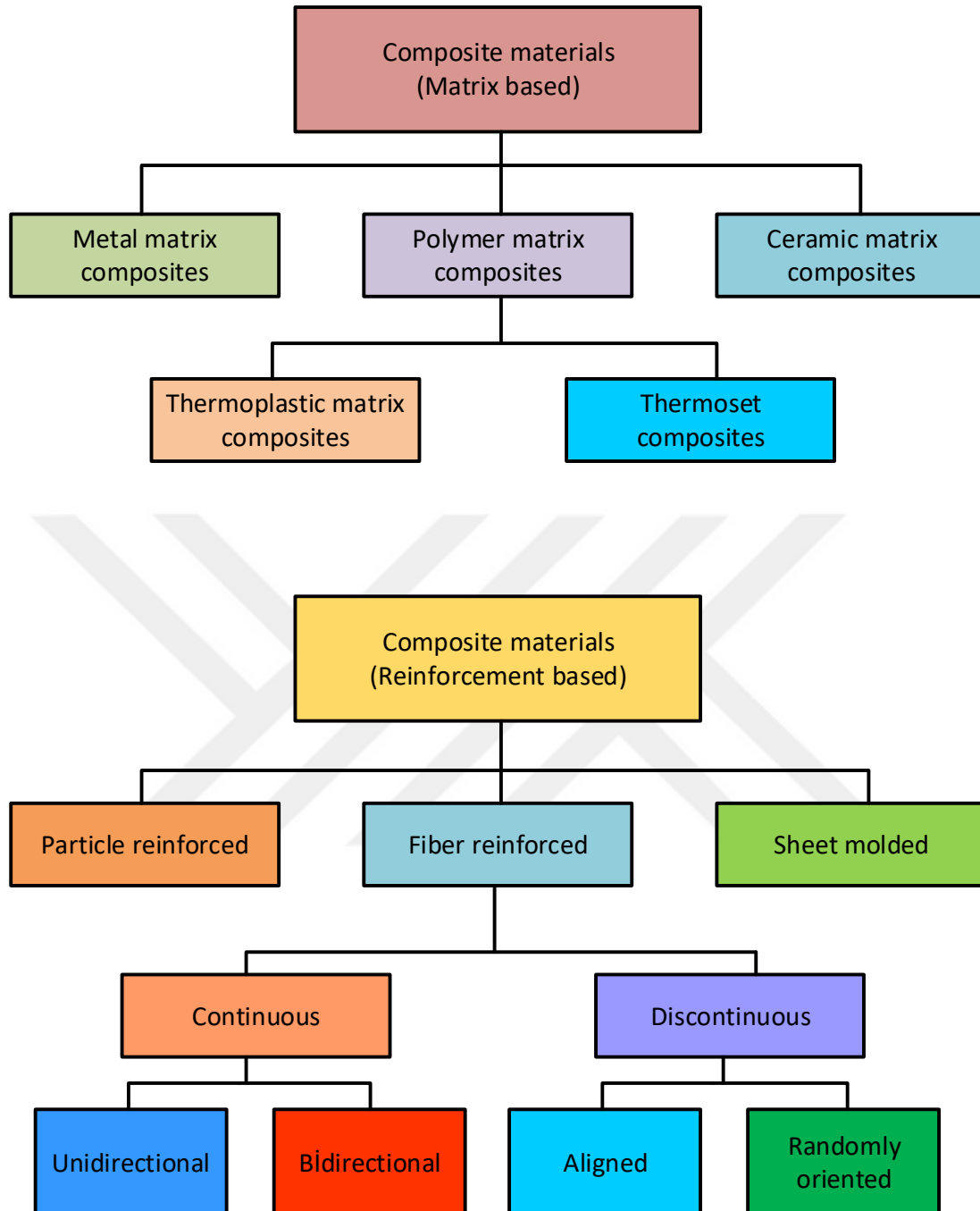


Figure 2.16. Classification of composite materials

There are many several ways of manufacturing techniques of composites which can be listed as hand layup, prepreg layup, bag molding, autoclave processing, compression molding, resin transfer molding, pultrusion, and filament winding. Manufacturing methods are decided to their advantages or limitations [27].

Hand layup is an easy method and a low-cost process for composite production. It involves mainly four steps which are mold preparation, gel coating, layup, and curing. Dry reinforcement is placed into a mold then resin is applied to reinforcement. A hand roller is used to create uniform surface and remove air bubbles. This process continues until desired thickness is reached. The hand layup process is illustrated in Figure 2.17 [27].

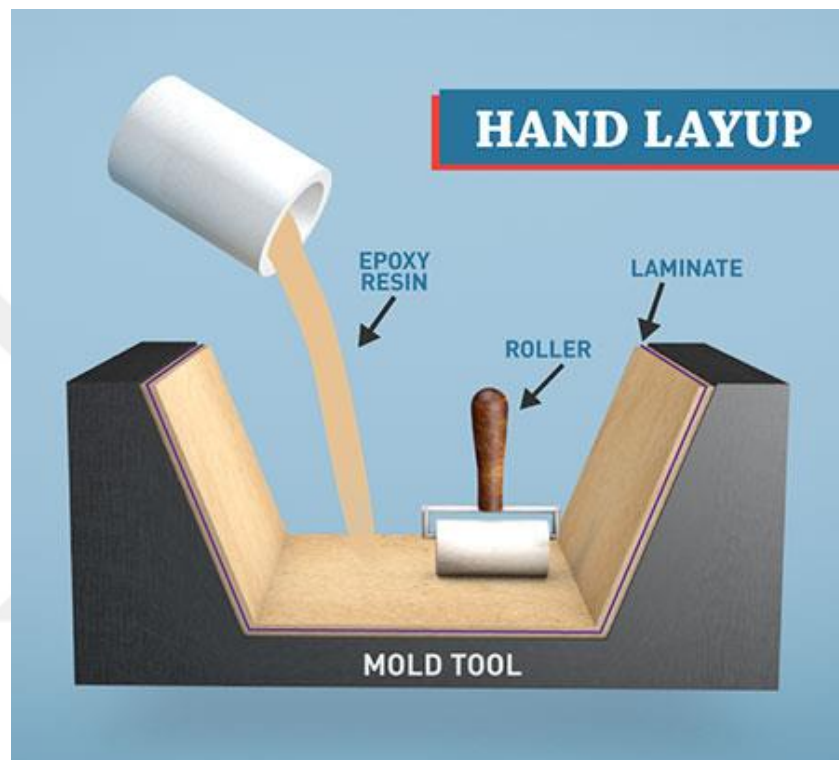


Figure 2.17. Hand layup process (Source: <https://l24.im/d8qPk>)

Prepreg layup has similar application process with hand layup but, it differs from hand layup due to being ready combination of matrix and reinforcement for manufacturing. This process may be divided into three basic steps that are placement prepreg into mold, removing air pockets, and curing. Most prepreps are made from epoxy resin materials and include reinforcements such as glass, carbon, and aramid fibers [27].

Bag molding or vacuum bag molding is a wet layup process. Unidirectional, bidirectional, or woven prepreg lamina is laid to mold, then resin is spread to the whole mold. After reaching desired laminate thickness, vacuum is applied to evacuate excess resins and air volatile solvents. In meanwhile, the vacuum pressure is distributed uniformly over the laminate. This

method allows to manufacturing high quality and low cost composite materials, but size of part is limited mold dimensions [27]. Bag molding process is shown in Figure 2.18.

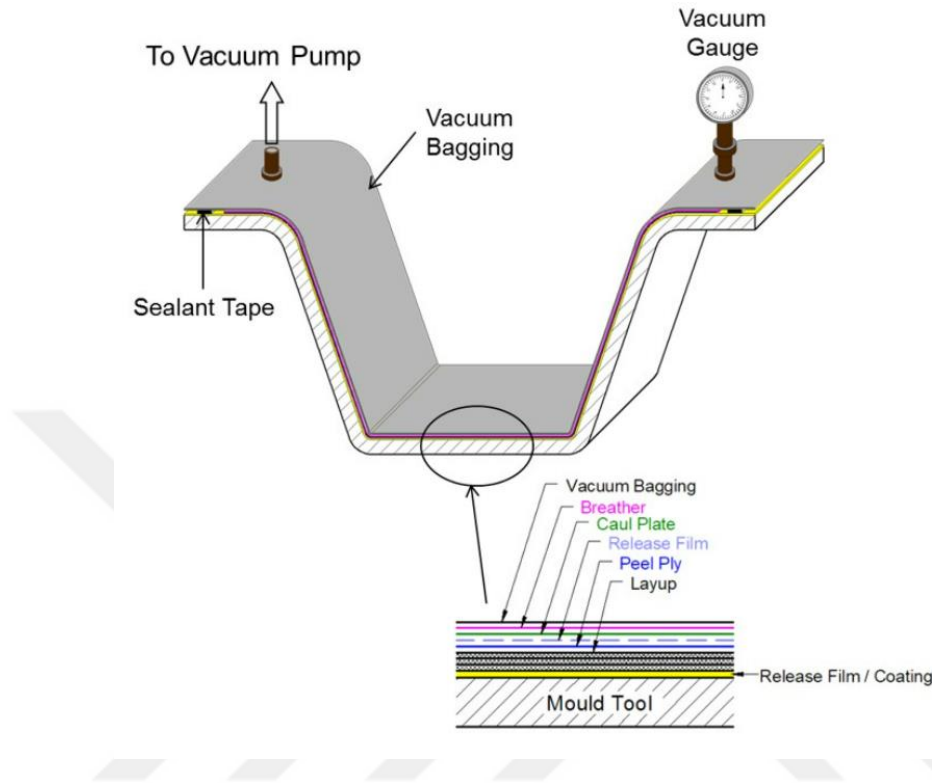


Figure 2.18. Bag molding process (Source: <https://124.im/NrEl>)

Autoclave processing is an advanced composite manufacturing method. The process composes of a pressure vessel, similarly bag molding, vacuum pressure is applied to the inner bag, while the outer surface is exposed to a pressure that is greater than atmospheric. So matrix is uniformly spread into reinforcement. For curing of composite material, temperature is increased to ensure consolidation. Therefore this process is chosen aerospace industry to fabricate complex parts with high quality composites [27]. Autoclave process is shown in Figure 2.19.

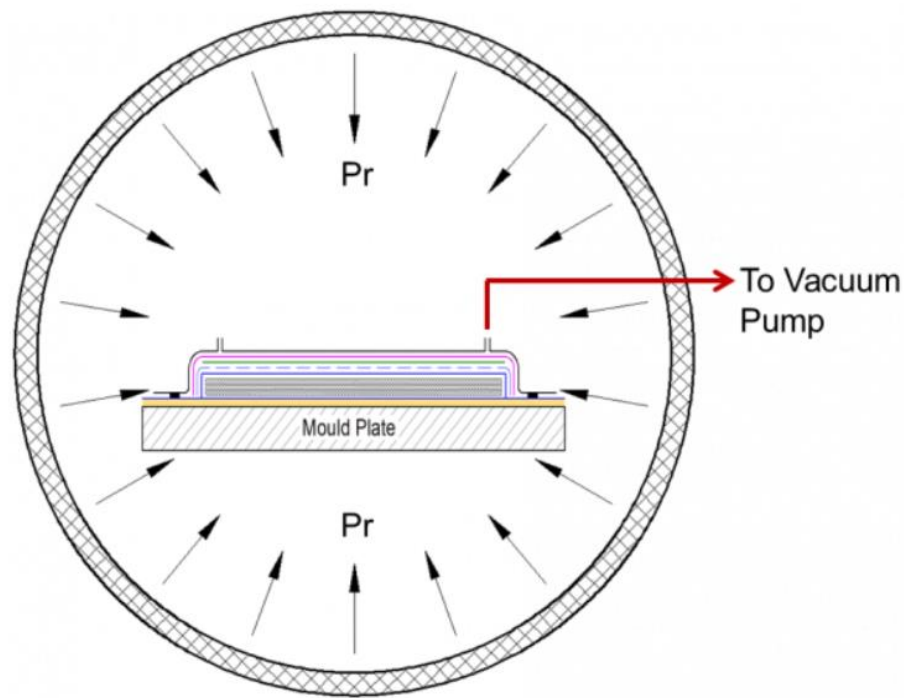


Figure 2.19. Autoclave process (Source: <https://l24.im/LSV>)

Compression molding is well established and easy process. Therefore, it reduces material waste, setup cost, finishing process, and manpower. The bulk charge or mixture is prepared by mixing resin with chopped fibers. The mixture is transferred to the mold cavity by an extruder. By applying compression and heat processes, the final composite part is manufactured. Thermoset resins have low viscosity, so the mold cavity can be filled more quickly compared to the use of thermoplastic resins. But, the curing process is required to ensure the solidification of the thermoset resins. Therefore, it requires more cycle time. On the other hand, thermoplastic materials have high viscosity and do not require a curing process. Therefore, the production time is shorter, so thermoplastic resins are preferred in the automotive sector. Bulk molding compound (BMC) and sheet molding compound (SMC) are known applications that use the compression molding process [27], [34]. In Figure 2.20, the compression molding process is illustrated.

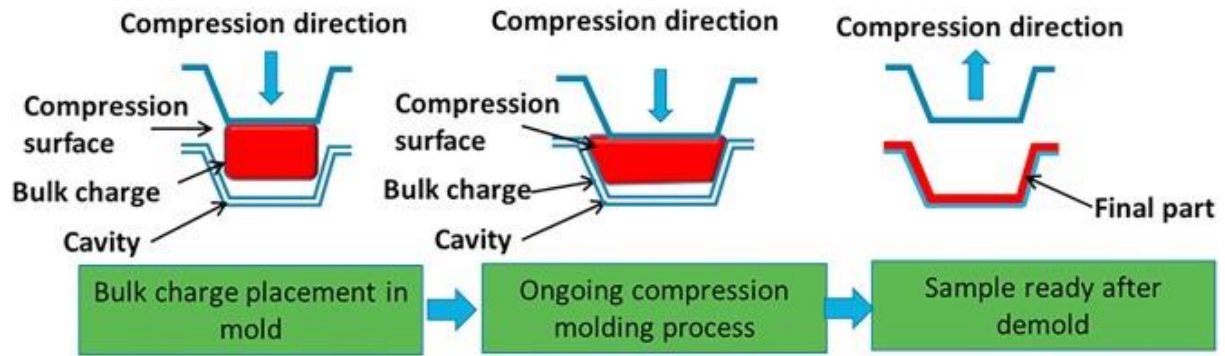


Figure 2.20. Compression molding process [34]

Resin transfer molding (RTM) or vacuum assisted resin transfer molding (VARTM) is utilized to produce two smooth surface composite parts. Dry reinforcement material is laid into mold, then resin mixture is transferred to fill mold cavity. Vacuum or pressure can be used to spread into resin uniformly. Then curing process, final part is removed from mold. Any composite part can be produced according to the mold cavity. This method is used to manufacture large composite parts so impregnation operation is significant to prevent resulting very expensive scraps [27]. Resin transfer molding is shown in Figure 2.21.

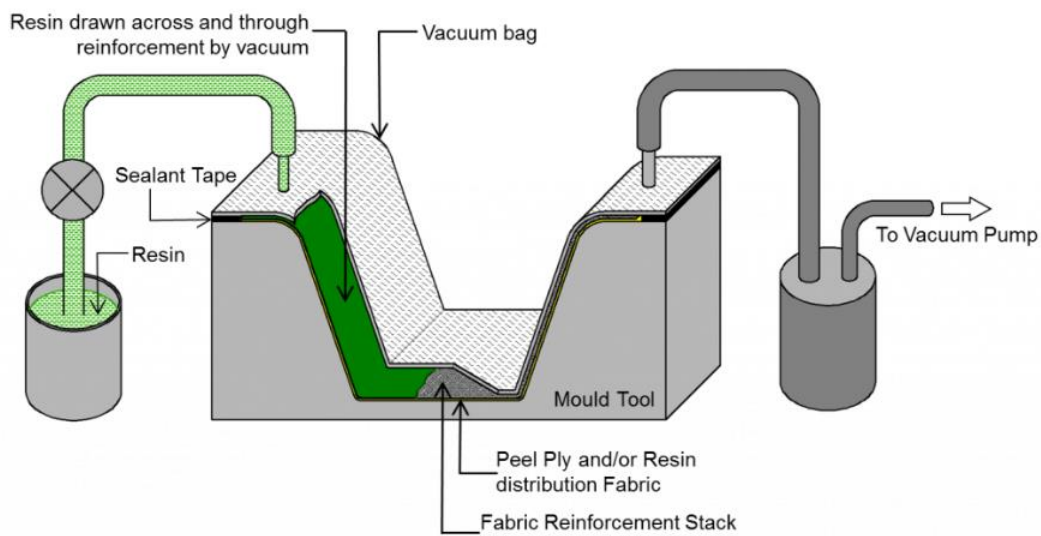


Figure 2.21. Resin transfer molding (Source: <https://l24.im/HU1qwKy>)

Pultrusion is an efficient and continuous process of manufacturing constant-form composite parts. This process are divided into six steps that are pulling fibers, collecting fibers,

thermoset resin bath for impregnation fibers, shaping fibers, application heat and curing, cutting of final product. The process has several advantages which are high efficient, easy changeable parameters, automatic production, less manpower, good surface quality, stability of product dimension [27]. The process steps are shown in Figure 2.22.

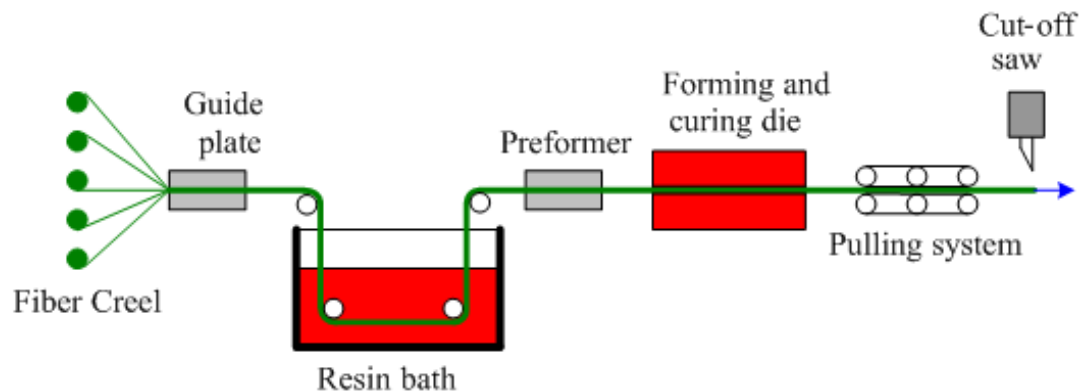


Figure 2.22. Pultrusion process (Source: <https://l24.im/5kKA>)

Filament or fiber winding (FW) method is utilized for fabricating composite cylindrical structures. This manufacturing method has positive sides as a high automated product fabrication, low cost required less manpower, and continuous production. But spinning speed and variation of product are limited and curing application may be difficult. In this method, the fiber resin formation is continuously wound onto the mandrel. This method is an inexpensive and automated method for positioning fibers in a precise pattern that adapts to the tension path, allowing efficient use of high-strength fibers for improved structural efficiency. The process takes place as follow stages, a mandrel is rotating and fiber resin is wound on it. While the mandrel is rotating, a carriage arm moves horizontally. The arm distributes pre-impregnated fibers. The exact direction of pre-impregnated fibers is determined by the transport and the rotational speed of the mandrel. Firstly, the fibers are impregnated with the resin, then wound onto the mandrel, and then solidified with the fiber. After the fiber overwrap is finished, the whole part is placed in the oven to be heated for curing. When the composite resin is completely cured, the mandrel is removed and the composite structure remains [27], [35], [36]. Fiber winding method is shown in Figure 2.23.

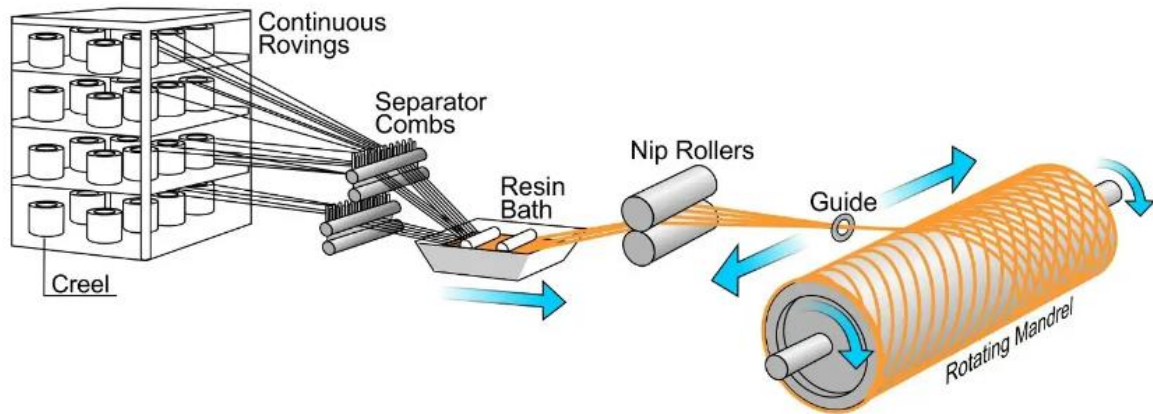


Figure 2.23. Fiber winding method [35]

2.4 Hydrogen Storage Methods

There are mainly four alternatives for hydrogen storage metal-hydrate, liquid storage, cryo-compressed storage, and compressed gas storage. Metal hydrides can store hydrogen with absorb and release hydrogen properties. The release or absorption of hydrogen relates to a change in the temperature of the metal hydride. For absorption of hydrogen, metal hydride starts to produce heat, and the temperature can be reached 2500 C°. On the other hand, it needs 120-200 C° temperature application to desorb hydrogen. Hydrogen absorption and desorption are presented in Figure 2.24. The storage method has many positive sides following as high hydrogen density and storage capacity, high safety, and good reversible cycle properties. But, it is not ideal for hydrogen storage due to be heavy, certain filling-discharge capacity, requiring temperature application for release or absorb hydrogen, and rare element usage [10], [37].

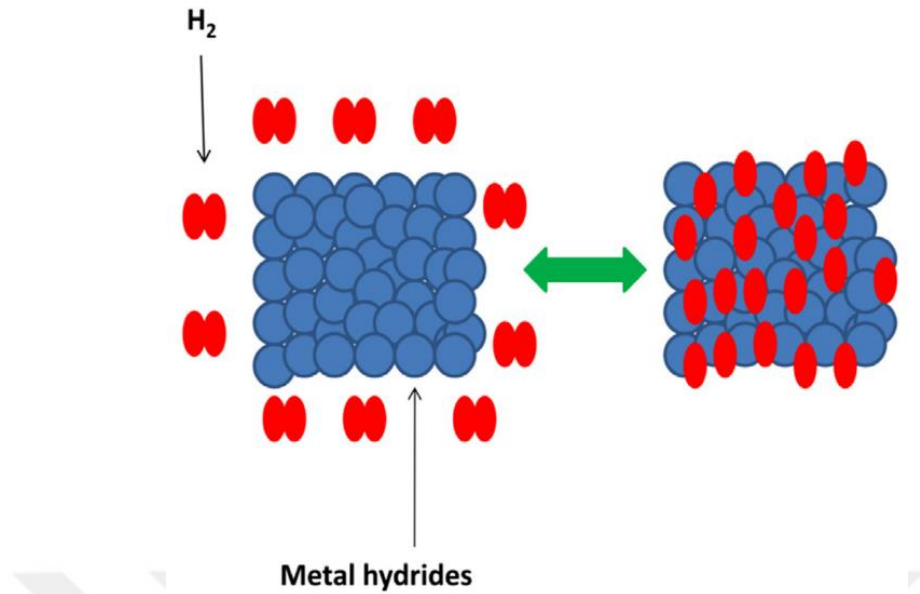


Figure 2.24. Hydrogen absorption and desorption process on metal hydride [10]

Another advanced storage of hydrogen method is liquid storage (cryogenic) form at $-253\text{ }^{\circ}\text{C}$ or 20 K . Liquid form hydrogen storage requires keeping at $-253\text{ }^{\circ}\text{C}$ to store it in cryogenic form. So, hydrogen density is more immense compared to gas storage. Therefore, lower-pressure storage and smaller cryogenic tanks are counted as advantages of this storage. On the other hand, insulation, maintaining store at low temperature, high energy loss (about 40%), time consuming are important challenge subjects. The other hydrogen storage technique is known as the cryo-compressed storage method that is a combination of both gas storage and cryogenic storage. Cryo-compressed hydrogen is a supercritical cryogenic gas. Hydrogen is compressed and stored in gas form and it is kept at about $-233\text{ }^{\circ}\text{C}$ temperature conditions [10], [38]. Compressed hydrogen storage is more economical and easy compared to other techniques. To store hydrogen in gas form, pressure is applied between 350 and 700 bar [39]. There are five distinct pressure vessel types and classified as type-I, II, III, IV, and V [40]. Different tank types with varied geometries can be seen in Figure 2.25. The properties of these tanks are also shown in Figure 2.26. Type I pressure vessel is composed of only metal which is generally made from steel or aluminum. Of the other pressure vessel types, this type is the cheapest however it is also the heaviest. It can withstand up to 50 MPa operation pressure, but it is used to store hydrogen at between 20 and 30 MPa pressure ranges. Also, it is used for industrial and stationary applications [38], [41]. Type II pressure vessel made from steel, and it is covered by fiber-resin materials in hoop direction. Thanks to the composite

layers of the tank, the tank can withstand high pressure. The type-II tank manufacturing costs are about 50% higher as regards type-I pressure tanks. However cost of a type II tank is higher, and it can have less weight 30-40% than type I tanks [38]. Type III pressure vessels have a metal liner, and it is covered with fully fiber-resin material. The composite layer decreases the metal liner thickness of type III pressure vessel, therefore it leads to considerable weight savings. Moreover, the layers serve to share strength of body between 75% to 90% ratio. For types I, II, and III pressure vessel, steel is not proposed. Because, gaseous hydrogen can degrade mechanical properties such as steels, carbon steels, low alloy steels, and stainless steels. When hydrogen is used in steel pressure vessel, it reduces fracture toughness of steel material. The phenomenon is known as hydrogen embrittlement [42]. Type IV pressure vessels have polymeric liners and the liner is covered with fiber-resin materials. Most structural load of the body is carried with composite layers. The type IV pressure vessel is lighter compared to metal liner tanks, but the cost of it is higher than type III tanks. Type V pressure vessels consist of only composite layers, so there is no liner. Linerless design decreases its weight by about 20% as regards type IV tanks. But, it did not withstand as high pressure as the operating pressure of type III and IV tanks [38]. The ideal material characteristics for the high-pressure vessel are listed follow as high tensile strength, light design, and not reacting with hydrogen or allowing it to diffuse from the body pressure vessel [10]. Among these tanks, type III and IV tanks are preferred due to their mature technologies for fuel cell vehicles. In addition, type IV and V tanks are more expensive because they contain more composite layers than type III tanks [43]. When tanks are evaluated in lightness and economy, type III tanks are more suitable for fuel cell vehicles.



Figure 2.25. Different pressure tank types (Source: <https://124.im/O97F4w>)

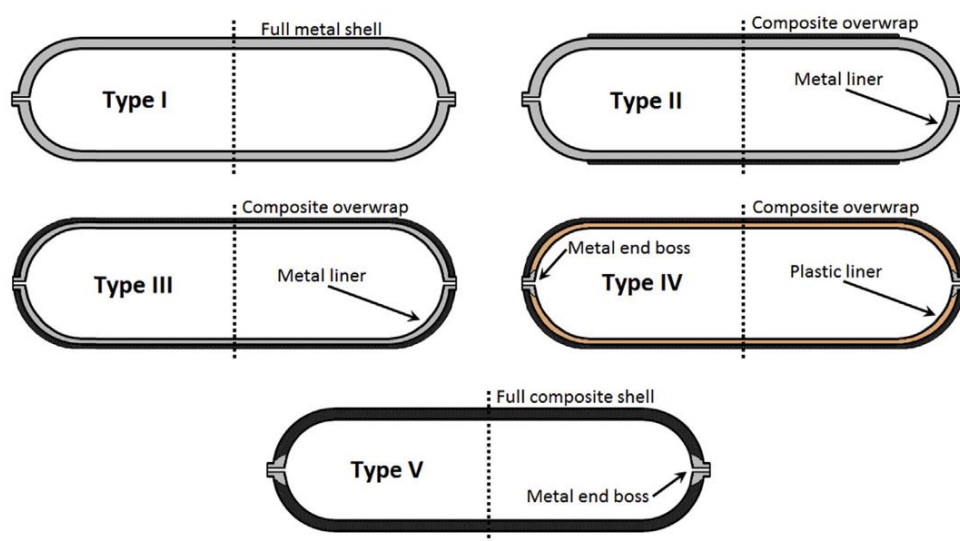


Figure 2.26. Properties of the different type pressure tanks [43]

For characterizing the dissimilar requirements for the design, manufacture, and testing of tanks, standards such as GB/T 35544, ISO 19881, CSA/ANSI HGV2, and GB/T 42612 sorts tanks into different types. In GB/T 35544, tanks are classified A and B according to their nominal working pressure. In ISO19881 and CSA/ANSI HGV2, cylinders are classified A, B, and C according to their intended use. GB/T42612 divides cylinders into four categories, A1, A2, B1, and B2. A1 and A2 cylinders have a nominal working pressure of 35 MPa, while B1 and B2 cylinders have a nominal working pressure of 70 MPa. Only passenger cars with at least four wheels, a maximum length of 8 m, and a maximum number of 19 seats can use A1 and B1 cylinders. They are designed, manufactured, and tested to more strict requirements than A2 and B2 cylinders. The detail classification of the tanks is shown in Figure 2.27.



Figure 2.27. Storage tank classification [40]

In production stages, metal liners or cylinders of type I-III tanks are subsequently manufactured by deep-drawing, and hot-spinning processes [36]. Polymer liners can be manufactured by roto-molding, blow-molding process [44]. Type III or IV composite tanks are manufactured with a liner wrapped with continuous fibers, as shown in Figure 2.28. The first step is to fabricate an inner liner from metal or polymer and then inspect the surface in case of for any defects. Next, the fibers are wrapped, and the external surface polished. The last step is the final product inspection after it has passed the hydrostatic pressure test [45]. Filament or fiber winding machine is shown in Figure 2.29.

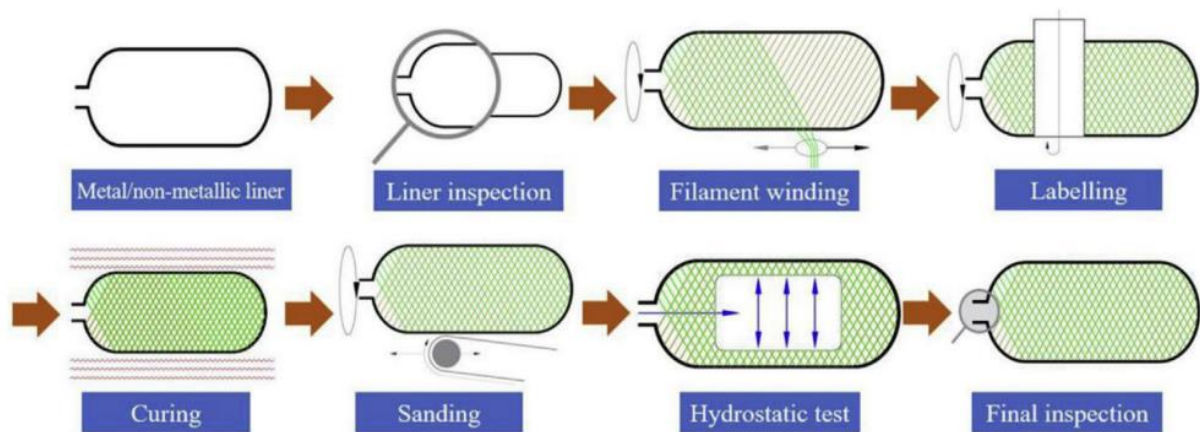


Figure 2.28. Composite pressure tank manufacturing steps [45]



Figure 2.29. Fiber winding machine (Source: <https://l24.im/TVe0m>)

Hydrogen storage of tanks requires additional measures for the safety of the tank. For this purpose, tests such as strength, fracture toughness, leakage, impact, and fire are carried out to ensure the tank is safe. Hydrogen in an unsafe tank can be very dangerous. Figure 2.30 shows how severe the explosion can be in a fire test. The explosion test was carried out with a fire explosion test of a 165-liter type III aluminum liner tank with a nominal pressure of 35 MPa and a maximum storage pressure of 43.75 MPa. When it reached 44 MPa pressure, it exploded. In another experiment, type III and type IV tanks placed under the SUV vehicle were placed separately and the composite pressure tanks were subjected to a fire test. In the first test, the 72.4 liter Type IV pressure tank was set to 34.3 MPa before the test, and in the other test, the 88 liter Type III tank was set to 31.8 MPa before the test and the experiments were carried out. Type IV tank failed at 35.7 MPa pressure. The type III pressure tank

exploded later than the type IV tank. Explosion images before and after the experiment are shown in Figure 2.31.



Figure 2.30. Fire explosion test of a type III tank [46]

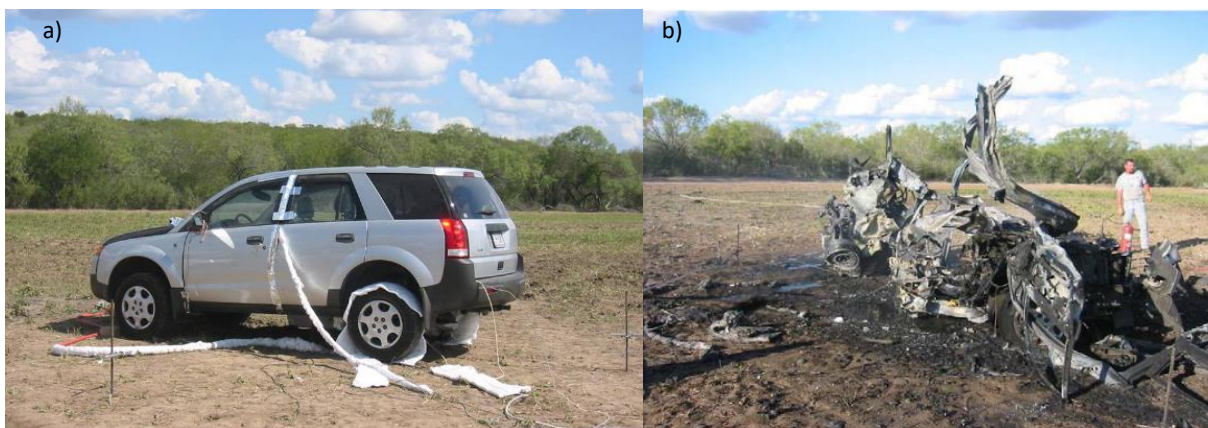


Figure 2.31. Fire explosion test of a composite pressure tanks: a) before explosion, b) after explosion [47], (source: <https://l24.im/k32iReg>)

2.5 Investigating the Mechanical Properties of Pipes and Storage Tanks

The growing population and the desire to achieve better living conditions have been increasing energy requirement day by day. The fact that more than 80% of energy needs are met from fossil fuels has led to both the concern of depletion of fossil fuels and the increase in greenhouse gases and global warming due to the use of fossil fuels. This condition has led to the search for alternative energy which has clean, cheap, and sustainable properties. In alternative energy resources, hydrogen is an element that is abundant in nature and does not produce harmful gases so it is clean. It can be generated from renewable resources such as solar or wind, and non-renewable sources. In addition, hydrogen can be used in power generation systems or transportation technology as fuel. Therefore, hydrogen is regarded as the new clean energy carrier for the next century. There are different ways to store hydrogen, such as liquid storage tanks, metal hydrides, and gaseous high-pressure storage tanks. Nowadays, high-pressure gas storage of hydrogen is a more mature technology compared to the other storage methods [10], [48], [49], [50].

Composite pressure tanks, which are superior to metal tanks, are formed with layers wrapped with filament to withstand high pressures. Therefore It is preferred an option where there is a need for storage of gas at high pressure, and they are used in all areas as well as used in fuel cell vehicles. Having a lightweight design, resistance to high pressure, high capacity gas storage, and superior mechanical properties are significant and desirable for fuel cell vehicles. Therefore, it is preferred in fuel cell vehicles because it provides safety and commercial conditions for hydrogen storage [51], [52], [53]. Basically, storage tanks are classified into 4 different types. Of these types, Type I consists only of the seamless metal liner. Another type II is made by wrapping the metal liner with fibre resin composite material. Type III is fully wrapped with fibre resin composite material on the metal liner. Type IV has a polymer liner and is fully wrapped with fibre resin composite. Type III and IV composite pressure vessels are chosen for hydrogen storage due to their advantages such as high strength/stiffness to weight ratio. In addition to these 4 types of tanks, there is a new type V composite tank, and both the liner and the layers of this tank are made entirely of fibre resin composite material. Type V tanks have been produced by some composite companies and have been successfully

tested. However, there have not been many comprehensive studies on this type of tank [36], [51], [54], [55].

Among these different types of pressure vessels, type III pressure vessels are strong candidates for storing hydrogen at high pressure levels of 700 bar. To safely operate high-pressure tanks it is necessary to determine the characteristic strength properties of the tank and the corresponding working range. If high-pressure tanks do not have sufficient strength, there is a risk that they will explode. This requires knowledge of the mechanical properties of the tank in order to determine the safe operating ranges of the tanks [52], [53]. For hydrogen storage, many experimental and numerical studies have been carried out to improve the safety and reliability of high-pressure tanks, with numerical studies dominating. Son and Chang [52] investigated the stress distributions of Type III hydrogen pressure vessels with 5 mm aluminium liner and 45 mm composite laminate. They used three different modelling approaches, which are the laminate-based modelling, the hybrid modelling and the full ply-based modelling. The study indicated that laminate and hybrid modelling resulted in under- and overestimation of the stress distribution of composite overwrapped pressure vessel (COPV), respectively. However, the stress distribution was more accurately estimated by the other model, full ply-based modelling. Therefore, they recommended the model for the estimation of the stress distribution of the COPV. Neto et al. [56] investigated behavior under burst pressure testing of a polymer liner that blends of low linear density polyethylene (LLDPE) and high density polyethylene (HDPE). The work primarily investigated liner burst pressure with experimental studies on both small-scale and full-scale. In addition, they analyzed the mechanical behavior of COPV using the von Mises and Tsai-Wu failure criterion to answer whether the liner withstands whether it can withstand approximately twice the working pressure using the finite element method. They reported that the bursting pressures of inner liners of different thicknesses were compared experimentally and numerically. Accordingly, the bursting pressures in the numerical models at the 13.9 mm thickness were very close to the actual bursting pressure, while the others gave erroneous results up to 18%. In addition, the behavior of the layers of a numerical model with 40° carbon fiber wrapped in a 15.3 mm thick inner liner was investigated with the Tsai- Wu criterion at an internal pressure of 40 MPa. As a result of this study, the safety factor of the second ply of the composite plate was critical with a value of 1.039. The maximum

elongation was 3.053 mm in the lower dome. Liao et al. [57] studied the effects of autofrettage on pressure vessels. In their numerical study, the inner liner and fibre stresses of two different models without and with autofrettage treatment were compared. It was observed that the fibre stresses decreased significantly after autofrettage treatment. When the internal pressure value reached 45 MPa, it was observed that the fibre tensions of the autofrettage treated tank and the untreated tank started to be the same. Autofrettage treatment was found to be effective at internal pressures below 45 MPa, while fibre tensions showed the same behaviour at internal pressures of 45 MPa or higher. The pressure changes of the liner were analysed when the internal pressure was 0 MPa and 20 MPa. It was observed that the autofrettage treated liner stresses were lower than the other tank at both pressures. They stated that matrix damage appears first in the helical layers, but fibre damage appears first in the hoop layers. Also, most matrix damage occurs in the helical layers, but fibre damage is more severe in the hoop layers than in the helical layers. In addition, the autofrettage process only has an effect on stress distribution when the internal pressure is lower than the autofrettage pressure. Therefore, the appropriate autofrettage pressure for the composite vessel plays an important role in maximizing the benefits of the tank. Błachut et al. [58] examined the properties, structure and functions of composite materials and emphasised the importance of systematic approaches to understanding these materials. It considered the influence of composites on various structures and the methods used to manufacture and test these structures. For example, the effects of different fibre tensions on the strength of a pressure vessel and the manufacturing challenges were analysed. Statistical analysis was used to quantify the effect of fibre tension on the mechanical properties and efficiency of high-pressure composite tanks. It was found that selecting a winding angle of 54 degrees was optimal for the manufacturing process, resulting in improved strength properties of the high-pressure composite tank. The use of increased fibre tension presented manufacturing challenges, including fibre abrasion and increased sensitivity to fibre positioning. Ghany et al. [59] carried out numerical and analytical studies to investigate the burst pressure of three distinct composite pipes which are E-glass fiber/epoxy, aramid fiber/epoxy, and carbon fiber/epoxy. The results specified $[\pm 55]$ winding angle orientation performed better as regards the other layer orientation. In addition, experimental datas were compared with E-glass fiber/epoxy, and the numerical and experimental results were verified. $[\pm 55]$ layer orientation reached higher burst pressure than the other angle orientations, and it concluded to confirm

the numerical results. Onder et al. [60] investigated experimentally and numerically that optimal angle-ply orientations for maximum burst pressure of E-glass composite pressure vessel, and the results of the study stated that the optimum winding angle for the composite pressure vessel is obtained as 55° for laminates. Kangal et al. [61] designed a type III glass and carbon filaments were overwrapped pressure vessel with $[\pm 11/90_2]_3$, and they compared burst pressure of glass fiber, and hybrid (glass/carbon fiber based) pressure vessel. They indicated that the results were close to each other for both experimental and numerical studies. Kartav et al. [62] Aluminum 6061-T6 carbon-epoxy overwrapped pressure vessels for high-pressure hydrogen storage were designed and modeled by the finite element method. In addition, they were manufactured with different $[\pm 14/90]$ layer orientations by filament winding technique and tested for burst pressure. They have produced pressure tanks that reach a burst pressure of 1480 bar.

Pipes or pressure vessels have a similarly cylindrical body. They are produced by winding with composite material for purposes at high-pressure usage. Composite pressure vessel or tank is named as COPV. Their safety generally is decided using stress based composite failure criterion. In case of cracks, porosity, or gaps in their type III or IV pressure vessels, the failure criteria may be inadequate. Therefore, investigation of fracture toughness comes into view as a necessity for more safety usage. Determining tensile stress and fracture toughness of pressure tank are important to design pipe or pressure vessel.

The tensile strength of a pipe or pressure tank can be determined by split disk tensile test (SDT) or ring hoop tension test (RHTT) methods. The two test methods focus on measuring hoop stress, but their specimens have different preparation processes. Also, the hoop stress of isotropic or orthotropic pressure tank materials can be evaluated by these methods. Jemii et al. [63] studied mechanical characteristics and the mechanical strength of industrial PVC pipes using the split disk tensile test method. They stated that the split disk tensile method showed a good correlation between both experimental and numerical results. Bobba et al. [64] investigated the mechanical properties of two different glass fiber reinforced plastic (GFRP) which are E-glass and S-glass fabric wound specimens using a split disk tensile test. The specimens were prepared with thickness and diameters selected in different sizes, and the results demonstrated S-glass was characterized as superior to E-glass as regards mechanical

properties. Barsoum and Ali [65] developed a ring hoop tension test method to characterize the mechanical properties of ring specimens. By using Al 6063-T5 specimens, two different experimental setups were created as a D-block ring test and a Roller needle bearing ring test with Amberglide PTFE lubricant. As a result, lubricating had a substantial effect, and numerical model results showed that the friction coefficient depends on the test methods. Finite element models demonstrated friction coefficients of the D-block ring test and Roller needle bearing ring test were found as $\mu=0.25$ and $\mu=0.13$, respectively. Kaynak et al. [66] investigated the effects of five different filament materials, their five different winding angles, and two distinct resins using split disk tensile test. The study showed that carbon fibers had higher mechanical performance than glass fibers as considered hoop tensile strength and hoop elastic modulus of five distinct materials. Moreover, they stated winding angle fibers had influenced both hoop tensile strength and hoop elasticity modulus of specimens. As the winding angle increases toward 90 degrees, all fiber materials' elasticity modulus and hoop tensile strength started to increase. With winding angle increases 0° to 90° , it was observed failure of fiber, matrix, or both of them. The failures were found as rupture of the matrix cracking, rupture of matrix phase, fiber-matrix debonding, delamination of layers, and fiber-matrix debonding at the 0° , 25° , 45° , 65° , and 90° winding angle specimens, respectively. In all experiments, there were no remarkable effects on mechanical properties as regards different epoxy resins. Also, the mechanical properties of epoxy resins could be neglected. Hwang et al. [67] proposed a new hoop ring test method to measure the fiber material properties of COPV. Hydraulic pressure was applied to the hoop specimen to reach up to burst pressure. Thus, the test method provides burst pressure and filament material properties measuring hoop strain. In addition, the study compared the hoop ring test method with the split disk method to demonstrate its validity. Walsh and Adams [68] developed a new design with reshaping split disk tensile test apparatus. The new design was named quadrant ring test method, and it built up with four pieces from one disk to overcome contact stress, friction between specimen and test fixture, and local bending deformations. In this way, they asserted that it can distribute the pressure to inner surface of specimen. But, experimental results were close to split disk tensile test. Additionally, both split disk and quadrant ring methods differ from flat panel testing when the results are compared. Saghir et al. [69] conducted a comprehensive experimental study of pipes tensile strength. It focused on hoop tensile strength of fiber reinforcement composite pipes enhanced with particulate and chop glass

reinforcements fiber-overwrapped pipes. The tensile strength of pipes was enhanced with the proportion of chopped glass in pipes increased. On the other hand, pipe stiffness was increased and pipe costs were reduced by increasing the amount of particulate reinforcement. However, the tensile strength of the pipes was fallen down. Kim et al. [70] investigated properties of filament-wound composite/aluminum ring specimens at cryogenic temperatures. The low temperature generates compressive thermal stress on the composite layers, besides the temperature conditions affected aluminum yield stress negatively. By using split disk tensile test for measuring hoop stress, they stated that the negative effects of cryogenic temperatures can be minimized by applying auto-frettage process. Kim et al. [71] performed tensile test using split disk tensile test for composite pressure tanks. They found that overwrapping 10.8% by weight of carbon nanotube (CNT) yarn over Al rings resulted in a 209% increase in hoop tensile properties compared to the uncoated Al ring. This findings show affects of fiber reinforcement of tank liner based on tensile strength. Azeem et al. [72] stated that the research findings have several practical implications for the design of composite pressure vessels. Studies have shown that factors such as winding angle, filament winding parameters, and multi-filament winding ply angles significantly influence the mechanical properties and strength of composite pressure vessels. In particular, fiber winding was found to provide the highest strength and stiffness, while different winding parameters affected the strength of the pressure vessels. In addition, the use of multi-filament winding ply angles and the determination of the optimum winding angle under internal pressure play a crucial role in the design and manufacture of composite pressure vessels. Srividya et al. [73] found that the orientation angle of natural fibers in composite pressure tanks significantly affects their strength and performance. Furthermore, the stress deflection values and the von Mises stress vary with different fiber orientation angles. Besides, increasing the number of plies reduces the stress level in the tanks, while reducing the number of plies increases the stress level. Furthermore, a comparison of synthetic and natural fiber pressure tanks at different angles of orientation shows that the deformation values decrease as the angle of orientation increases. The 90° plies effectively contribute to increasing the hoop strength of the pressure tanks. The study showed that the optimum orientation angle for minimum deformation varies depending on the material. In addition, the fiber orientation angle plays a critical role in determining the mechanical behavior, stress distribution, and overall strength

of composite pressure tanks. Optimizing the orientation angle can improve the performance and durability of pressure tanks, making it a key factor in their design and failure analysis.

There are different fracture toughness methods to measure mode-I, mode-II, or mode-III. But, different fracture methods are used to find fracture toughness for unidirectional mode-I loading conditions or mode-I interlaminar investigations. Mode-I of composite materials can be measured by compact tension specimen (CTS), Arcan specimen or single edge notch bend (SENB) specimens. By some arrangements, arcan or CTS methods are used to find different mode fracture toughness for different loading angle. Mode-I, mode-II and mixed mode loading fracture toughness measurement were performed for flat plate [74], [75], [76]. In addition, mode-I, mode-II and mixed mode interlaminar fracture toughness was performed by using Arcan specimen [77]. Besides arcan and CTS were used to predict fracture toughness of the three modes [78], [79]. To find fracture toughness in different modes, double cantilever beam (DCB) is used for mode-I, end-notched flexure (ENF) and end load split (ELS) are used for mode-II, mixed mode bending (MMB) is used for mixed-mode. [80], [81].

DCB is used for mode-I delamination and investigation of interlaminar fracture characterization. Rekbi et al. [82] focused on the experimental and numerical determination of the effect of the initial crack on the fracture behavior of DCB specimens during the initiation and, propagation of delamination. They stated that finite element analysis and experimental results are close. Makri and Baali [83] been carried out experiments to investigate the effect of winding angle and initial crack length for investigating delamination behavior of vinyl ester resin-fibreglass composites using DCB method. They prepared pipe specimens with layer orientation $\pm 45^\circ$, $\pm 55^\circ$ and $\pm 65^\circ$. After experiments, they reported that a winding angle of $\pm 65^\circ$ gives the best delamination resistance behavior compared to winding angles of $\pm 55^\circ$ and $\pm 45^\circ$. Sako et al. [84] studied ENF tests of curved beam specimens which are cut from tanks or cylinders. They compared the results of analytical and experimental studies, and concluded that could measure mode II fracture toughness accurately. Shariati et al. [85] designed a new specimen to carried out mode-I fatigue crack growth of metal alloys with experimentally and numerically. The paper stated that the new specimen was more successful to predict fatigue lifetime than compact tension method. Asghari et al. [86] cut specimens from a steel pipe to investigate relation between charpy impact energy (CVN). They estimated fracture toughness of specimen material by CVN. Also, the study showed to find in good

agreement with the real fracture toughness and fracture resistance values. Alizadeh and Dehestani [87] focused to find which cracks in the inner or outer edge of the pressure vessel were more critical with numerical study. Outer crack is more critical than inner crack at the same conditions. Besides, they applied CFRP layer on crack location, and stated that the layer can increase load bearing capacity of pressure vessel. Additionally, the works pointed out there is no important difference between elastic-plastic and elastic analyses. Jemii et al. [88] studied fracture characteristics of polymeric pipes with curved three point bending (CTPB) method. After investigation of fracture toughness experimental and numerical studies, they concluded that mode I stress intensity factor (K_I) and mode I strain energy release rate (G_I) increase with the aging temperature. However, if the depth of the initial crack increases, K_I and G_I decrease. Chen and Pan [89] investigated axial crack at inner surface of a composite compressed natural gas (CNG) tank. They compared empirical formula and numerical study for determining K_I and, declared that the equation can predict the K_I with 5 percent error. Damjanović et al. [90] researched on relation between SENB and pipe ring notched bend (PRNB) specimens which cut out from steel pipe. They obtained fracture toughness of the specimens using crack tip opening displacement (CTOD), and concluded that both SENB and PRNB specimens gave close results. Also, it is declared that PRNB method can be used to measure pipe fracture toughness. Musrati et al. [91] used PRNB specimens which cut out from seam and seamless pipe to measure fracture toughness. They stated that PRNB is a useful method to investigate fracture toughness for pipe material. Hsu [92] used two curved compact tension specimens together and named as X specimen. Zirconium Alloy (Zry-4) pipes were investigated mode-I fracture toughness at with various hydrogen concentrations at room temperature and 300 °C. Increasing concentration hydrogen resulted decline of fracture toughness of the alloy in room temperature. But, there was small differences fracture toughness of unhydrided and hydrided cladding X specimens at 300 °C. Cartie et al. [93] studied interlaminar fracture toughness of carbon/epoxy composite pressure vessels at different pressures as 4, 300, and 900 bars using mode-I and mode-II methods. The results of experiments indicated that mode-I fracture is more critical than mode-II. They also stated the pressure changes affected mode II crack propagation predominantly compared to mode I. Quino et al. [94] investigated affects on fracture toughness of material after wet aging process. Using compact tension method based on ASTM D5045. The process leaded detrimental effects on fracture toughness. Also they found the measured toughness can be

correlated to the water content in the neighborhood of the crack. Sajith et al. [95] utilized compact tension for predicting mode I, mode II, and mixed mode fatigue crack of aluminum 6061. After carrying out experimental and numerical studies, they stated that Irwin's model and one of Tanaka's models were successful in predicting the mixed mode fatigue life, and their results were close to the experimental data. Besides Irwin and Tanaka models, fatigue life estimation was performed satisfactorily with Richard, Yan, and Demir models separately. Jemblie et al. [96] presented the determination of fracture properties of stainless steel - X60/X65 carbon steel pipes with and without a Ni-interlayer using the compact tension method. The results showed Ni-interlayer improves fracture resistance compared to the non-Ni-interlayer pipes in hydrogen environment. Liu et al. [97] carried out for determining the intralaminar fracture toughness of high-strength carbon fiber composites used in aerostructures is presented and validated. The study proposes a novel approach that includes the use of a C-scan system to locate the crack tip, the use of compliance calibration and area methods to determine the fiber-dominated fracture toughness, the use of SEM investigations to understand the damage mechanisms and the validation of the measured toughness values by finite element modeling. The area and compliance calibration methods were used to assess the accuracy of the tensile strength values of one IMS60/epoxy laminate. The propagating toughness values calculated using both methods were very similar. Virtual Modified Compact Tension (MCT) tests were performed in Abaqus/Explicit using Fibre-Elongation-Tracking (FET) based fracture toughness values and Visible-Crack-Tracking (VCT) based fracture toughness values. A comparison of the load versus displacement curves showed that the damage model using the VCT-based fracture toughness values gave a better correlation with the experimental tests. This confirmed that the proposed measurement method is capable of providing precise fracture toughness data. Zheng et al. [98] investigated the constraint characterisation and fracture initiation analysis for quasi-elliptic surface cracks in a real large-scale reactor pressure vessel. It is emphasised how the crack depth and aspect ratio affect the overall level of restraint of the crack. It was noted that conventional fracture analyses are likely to be conservative for most cracks, and it was emphasised that the restraint effect should be taken into account in order to make more accurate fracture predictions for the RPV. Sung et al. [99] examine the effects of curvature on ductile fracture initiation in curved compact tension (CCT) specimens of hydrided irradiated Zr-2.5Nb materials with split circumferential hydrides. The study uses three-dimensional finite element analyses to

determine the effects of curvature on fracture initiation load, stress triaxiality, and plastic zone in the specimens. The findings showed that the fracture initiation load for unhydrided CCT specimens is slightly lower than those for unhydrided compact tension and pressure tube specimens. Wu et al. [100] focused on understanding the mechanical response near crack fronts, the energy balance of the system, and the influence of element size on simulation results. The study involved finite element analyses of crack propagation in curved compact tension specimens of irradiated and hydrided irradiated Zr-2.5Nb pressure tube materials. Key findings include successful simulation of crack extension, adoption of Hill's orthotropic yield function to characterize plastic behavior, agreement of simulation results with experimental data, calibration of cohesive energies for cohesive zone modeling, examination of the energy balance in the system, and investigation of cohesive element size effects.

2.6. Introduction to Fracture Mechanics

Fracture mechanics is a methodology used to determine critical loading and stress threshold values of a part in case of cracks or defects. It is accepted that there are no broken or defects in the materials and traditional strength tests are applied. This approach will be valid if there are no defects in the material. However, the materials may contain defects, cracks, porosity or voids during production or due to environmental conditions. This situation will cause to magnify the stress in the places where there are defects in the material so the material fails earlier than the conventionally calculated strength values. The stress applied to the part is greatly magnified at the crack tip due to the theoretical zero area. Therefore, it may fail more quickly than expected at lower stress values applied externally to the material. Materials are classified as ductile or brittle. During fracture, ductile materials absorb more energy, while brittle materials absorb very little energy. However, ductile materials show obvious signs while fracture occurs, brittle materials may fail suddenly with showing too few symptoms. One of the known example for fracture is Liberty ships [101], [102]. The fracture failure of Liberty ship is shown in Figure 2.32. Another example fracture failure of pressure vessel is presented in Figure 2.33.



Figure 2.32. Fracture failure of Liberty ship [101]



Figure 2.33. Fracture failure of a pressure vessel (Source: <https://l24.im/sxS0mTw>)

2.6.1. Stress concentration factor (K_t)

Kirsch (1898) used a mathematical method to determine the stress concentration around a circular hole in an infinite plate subjected to tensile stress. The relations are given in the following Equations. Stresses around a hole are displayed in Figure 2.34. Similarly, Inglis (1913) had a study of the elastic stress distribution for an elliptical hole. Kirsch studied stress around a hole when a uniaxial load applied to the infinite plate [103]. Where σ_{rr} is radial stress, $\sigma_{\theta\theta}$ is hoop stress, $\tau_{r\theta}$ is shear, σ_{∞} is remote stress, R_h is radius of hole, and r radial coordinate.

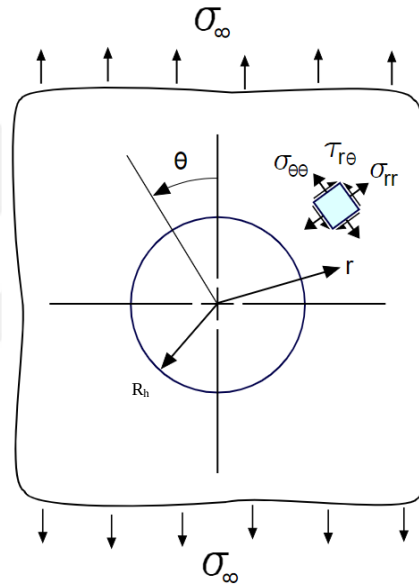


Figure 2.34. Stresses around a hole (Source: <https://l24.im/M1tRvAh>)

Kirsch's linear elastic solution for stresses around a hole is stated as: R_h

$$\sigma_{rr} = \frac{\sigma_{\infty}}{2} \left(1 - 2 \left(\frac{a}{r} \right)^2 \right) + \frac{\sigma_{\infty}}{2} \left(1 - 4 \left(\frac{a}{r} \right)^2 + 3 \left(\frac{a}{r} \right)^4 \right) \cos 2\theta \quad (2.1)$$

$$\sigma_{\theta\theta} = \frac{\sigma_{\infty}}{2} \left(1 + \left(\frac{a}{r} \right)^2 \right) - \frac{\sigma_{\infty}}{2} \left(1 + 3 \left(\frac{a}{r} \right)^4 \right) \cos 2\theta \quad (2.2)$$

$$\sigma_{r\theta} = -\frac{\sigma_{\infty}}{2} \left(\left(1 + 2 \left(\frac{a}{r} \right)^2 \right) - 3 \left(\frac{a}{r} \right)^4 \right) \sin 2\theta \quad (2.3)$$

When $r = \infty$, a/r terms go to zero, so equations transform as:

$$\sigma_{rr} = \frac{\sigma_{\infty}}{2} + \frac{\sigma_{\infty}}{2} \cos 2\theta \quad (2.4)$$

$$\sigma_{\theta\theta} = \frac{\sigma_{\infty}}{2} - \frac{\sigma_{\infty}}{2} \cos 2\theta \quad (2.5)$$

$$\sigma_{r\theta} = -\frac{\sigma_{\infty}}{2} \sin 2\theta \quad (2.6)$$

When $r = a$, $a/r=1$ the equations transform as:

$$\sigma_{rr} = 0 \quad (2.7)$$

$$\sigma_{\theta\theta} = \sigma_{\infty}(1 - 2\cos 2\theta) \quad (2.8)$$

$$\sigma_{r\theta} = 0 \quad (2.9)$$

In case of being fracture or flaws in the loads acting on the part, the stress intensity will be different in this region. Stress concentration changes around a hole for infinite plate, it increases as close to the hole vicinity of the hole. When stress is maximum at hole border, and concentration factor is $K_t = 3$, it can be found using the Equation (2.10). But, stress decreases to applied stress value provided that enough remote distance from the hole. The representation is shown in Figure 2.35. Stress concentration factor is stated as in the following Equation. Where σ_{max} refers maximum stress at hole border, and $\sigma_{applied}$ is normal applied stress. But, if there is a crack on the body, stress concentration factor is useless due to infinity magnitude of stress at the stress at crack tip.

$$K_t = \frac{\sigma_{max}}{\sigma_{applied}} \quad (2.10)$$

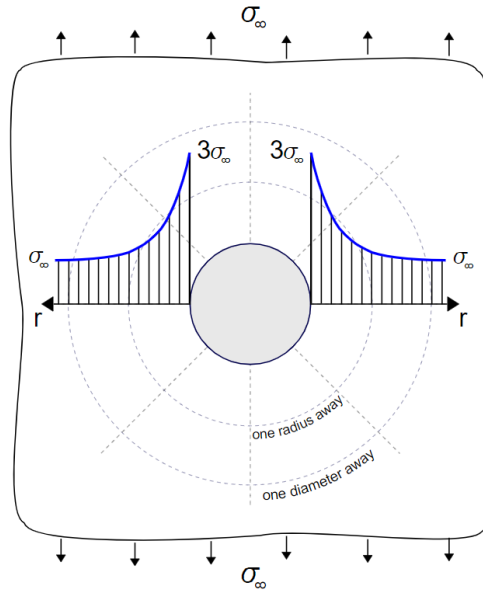


Figure 2.35. Infinite plate stresses around a hole (Source: <https://l24.im/M1tRvAh>)

Biaxial stress is the same stress in the x and y axes. By superposing the Kirsch solution, which is allowed because it is linear, the effect on the stress state in a hole can be determined. It can be seen in Figure 2.36 that the stress concentration in a hole is equal to twice the stress acting in both directions. It can be found using the Equation (2.8) for $\theta = 0$ and $\theta = 90$ degree.

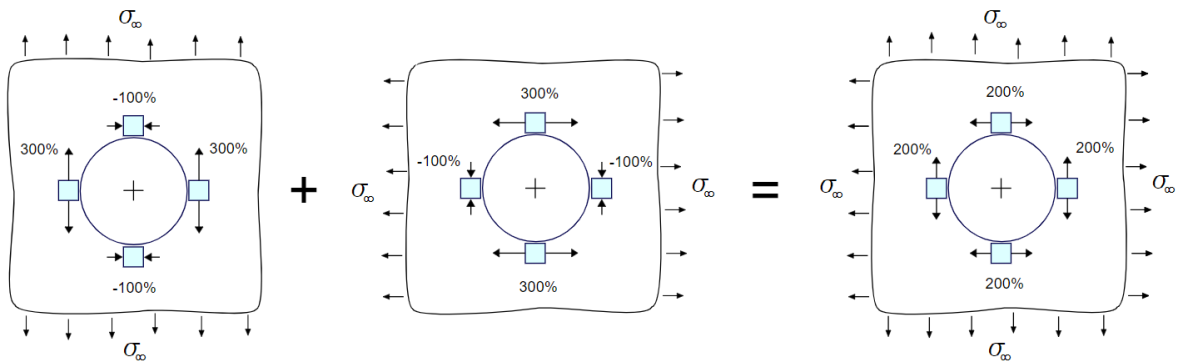


Figure 2.36. Equibiaxial loading and stresses around a hole

(Source: <https://l24.im/M1tRvAh>)

Similarly, Saint Venant's principle stated that as moving away from the hole, the stress concentration begins to be uniform [104]. After a certain distance from the hole, the stress distribution becomes completely stable that can be seen in Figure 2.37.

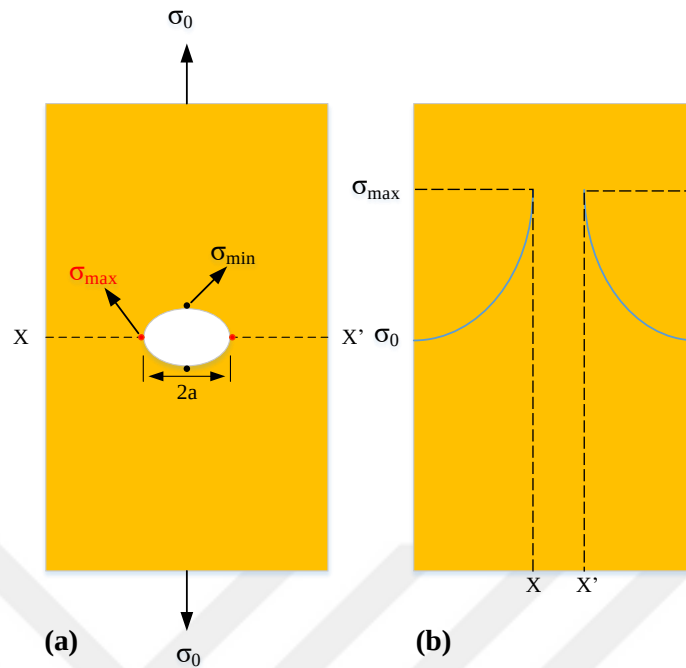


Figure 2.37. Saint Venant's principle

2.6.2. Basics of fracture mechanics

It is important to know that the geometry fails or not when an applied load to specimen. In case of being cracks or flaws in the specimen the tip of flaw will be more critical significant to provide safety. A. A. Griffith submitted linear elastic theory of crack elongation. He investigated the difference of strength between normal and multi crack materials. He noticed that the same materials fail before their theoretical strength based on brittle materials. Thus he developed an energy balance to determine strength of material that has flaws or cracks. Griffith's approach is based on the balance of internal surface energy and strain energy required to form new surfaces during crack propagation. So, the required energy to begin crack is named as fracture toughness. It depends on the magnitude of the acting stresses, the geometry, shape and size of crack, and propagation of crack-like defects [103], [105], [106]. While fracture surface formation begins in a body, they consume energy as fracture surfaces are created. In addition, surfaces are exposed to more energy than the body. Whether the fracture is stable or unstable depends on the fracture energy being equal to or exceeding this amount. Conservation of energy are stated as following Equations. Where, work performed per unit time ($\dot{W}$), rates of change of the internal elastic energy ($\dot{U}_E$), plastic energy ($\dot{U}_P$),

kinetic energy ($\dot{K}$), and the energy per unit time ($\dot{\Gamma}$) for increasing crack area. Crack formation is shown in Figure 2.38 [107].

$$\dot{W} = \dot{U}_E + \dot{U}_P + \dot{K} + \dot{\Gamma} \quad (2.11)$$

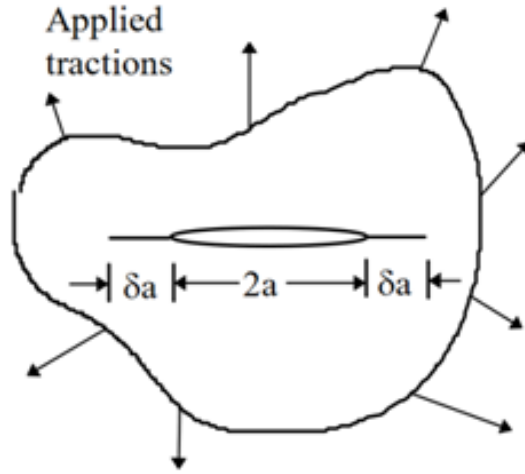


Figure 2.38. A schematic representation of cracked system [107]

If the crack propagates slowly, $\dot{K}$ is negligible and can be rearranged in the energy balance equation. Where A represents the crack area, $\dot{A}$ is the crack surface area growth rate per unit time.

$$\frac{\partial}{\partial t} = \frac{\partial}{\partial A} \frac{\partial A}{\partial t} = \dot{A} \frac{\partial}{\partial A} \quad (2.12)$$

Potential energy of the system,

$$\Pi = U_E - W \quad (2.13)$$

After rewriting the equation, the Equation (16) denotes that the potential energy decline is equal to the plastic work dissipation energy and surface creation energy.

$$-\frac{\partial \Pi}{\partial A} = \frac{\partial U_P}{\partial A} + \frac{\partial \Gamma}{\partial A} \quad (2.14)$$

Griffith concentrated on calculation fracture energy of brittle material. Therefore plastic energy is assumed negligible. By rewriting the equation in new form,

$$-\frac{\partial \Pi}{\partial A} = \frac{\partial \Gamma}{\partial A} = 2\gamma \quad (2.15)$$

where γ refers the energy required to for creating new surface area. The factor 2 represents two new creating area during crack propagation. The balance equation means that there must be sufficient potential energy in the system to overcome the surface energy of the material. It is possible to define a crack extension force per unit of width of the crack front as:

$$G = -\frac{\partial \Pi}{\partial A} \quad (2.16)$$

Irwin (1948) stated that the strain energy stored in ductile materials is dispensed for both creating new surfaces and energy required for plastic deformation, and he defined the critical strain energy release rate G_C for a crack growth criterion. Similarly, G_C represents the total strain energy released belong to crack propagation. Irwin (1957) introduced three different modes of fracture in the region of crack tips: mode I (opening mode), mode II (slip mode) and mode III (tear mode). Irwin studied the stress state around the crack tip when LEFM dominated. He defined the magnitude of the local stress around this area as the stress intensity factor. Irwin concentrated on stating the crack tip of the plastic zone. By considering the material is elastic, he proposed a tensile stress equation for vicinity crack tip that is given in Equation (2.17). Typically the mode I stress intensity factor (K_I) is a function of the applied stress (σ), crack length (a), and geometry.

$$\sigma = \frac{K_I}{\sqrt{2\pi a}} \quad (2.17)$$

K zone is equal to inverse square-root singular stresses. Irwin's K -based fracture criterion differs from Griffith's free surface energy criterion. Because, K based fracture concentrates on the response of stresses near the crack tip. To decide fracture failure with stress intensity factor Irwin's criterion can be expressed as: $K_I = K_{IC}$ which means that the applied stress increases proportionally K_I . When K_I is equal to K_{IC} , fracture failure occurs [106]. The

notation r is distance from crack tip, K_I is mode-I stress intensity factor, and σ is tensile stress, K_{IC} is critical mode-I stress intensity factor. As r is too small distance, the stress goes to infinity near the crack tip.

2.6.3. Approaches of fracture mechanics

There are generally two approaches to fracture mechanics that are linear elastic fracture mechanics (LEFM) and elastic-plastic fracture mechanics (EPFM). In addition to these, high temperature time dependent fracture mechanics (HTTDFM) approach can be listed. According to the material properties, the classification given in Figure 2.39 can be taken as a basis. If the material has brittle or less ductile behavior, LEFM approach can be used, if it shows completely ductile properties, EPFM approach can be preferred, and HTTDFM approach can be utilized for fracture behavior due to high temperature fatigue.

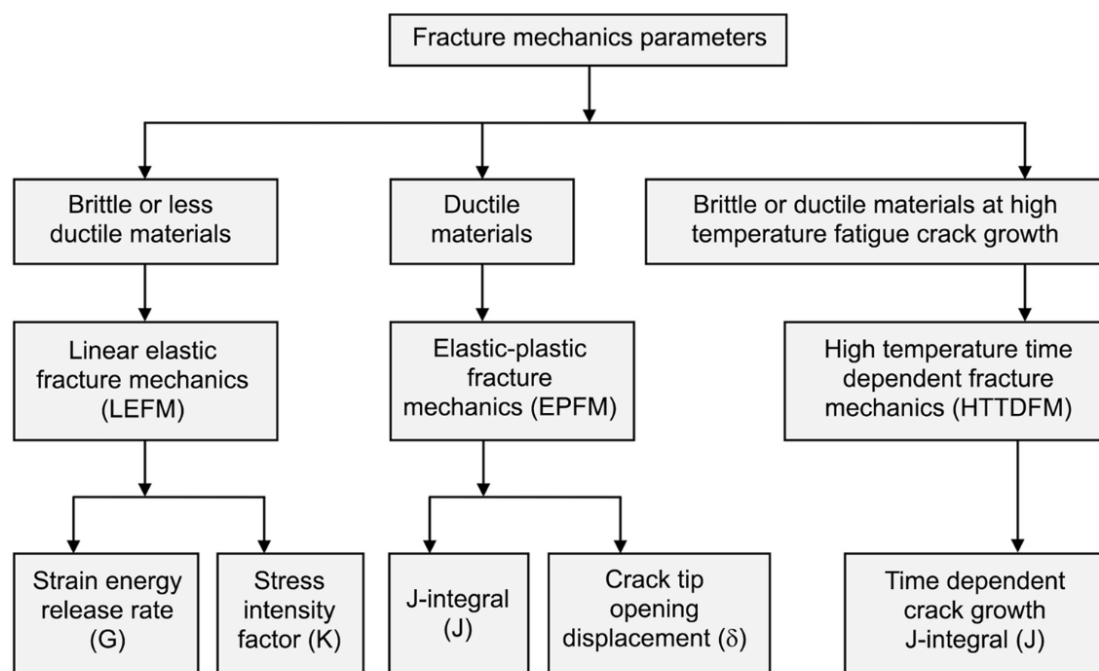


Figure 2.39. Fracture mechanics approaches [108]

2.6.4. Linear elastic fracture mechanics (LEFM)

Linear elastic fracture mechanics (LEFM) based on stress intensity factor and strain energy release rate. It is assumed that the crack is linear, elastic, and small plastic deformations are neglected at the crack tip [1, 4]. This approach provides determination of materials crack resistance. Irwin developed the definition that is stress intensity factor (K). It is an important factor due to defining severity of the stress distribution around the crack tip [109]. Griffith improved energy balanced approach that focuses on changing elastic strain energy and the energy released while cracking. The strain energy difference between before cracking and after cracking states that strain energy release rate (G) [110]. As seen in Figure 2.40, elastic (linear) and plastic zones (non-linear) represent K dominated area, core region, respectively. In LEFM approach, plastic zone can be neglected due to core region is too small as regards to elastic zone [106], [111].

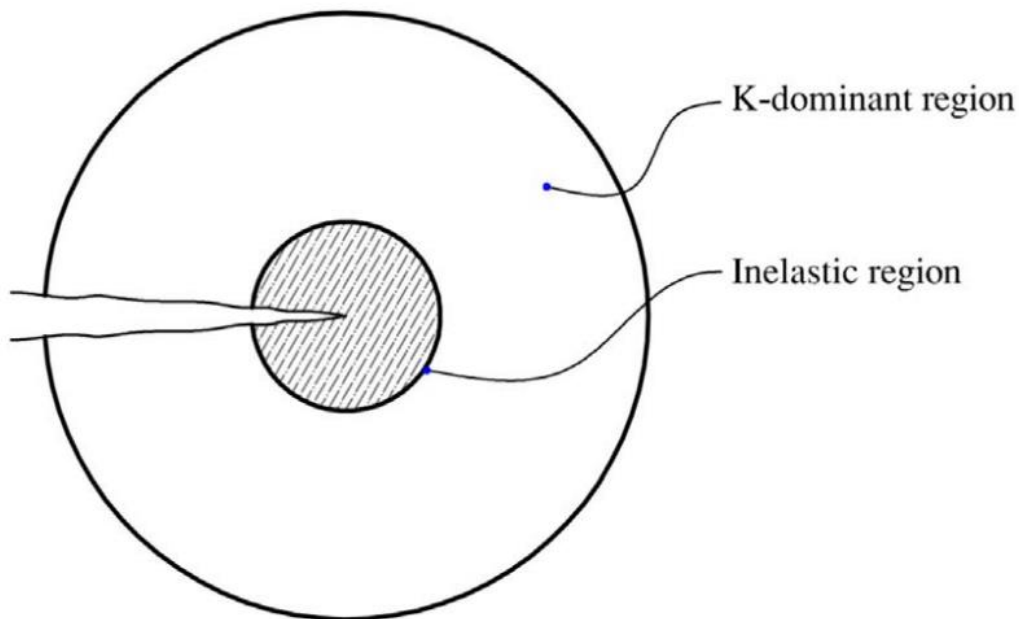


Figure 2.40. Elastic and plastic zone of a crack [87]

The other approach to investigate fracture of materials is Elastic-Plastic Fracture Mechanics (EPFM). The intensity singularity in the vicinity of a crack tip can be calculated by using a path-independent integral. The J-integral method is used to evaluate potential energy stored

before and after crack growth in the material. Also, the method states a combination of non-linear energy release rate and stress intensity factor [112]. Crack tip opening displacement approach is used to investigate fracture toughness while plastic deformation formation [113]. In summary, stress intensity factor and strain energy release rate are used for measuring linear elastic deformation at crack vicinity in small changes. If there are large plastic deformation at crack tip, J-integral and crack tip opening displacement are more convenient to gain fracture toughness of materials [114]. In this study, stress intensity factor and strain energy release rate were studied to investigate fracture toughness of a type III composite tank material.

2.6.5. Elastic-plastic fracture mechanics (EPFM)

J integral is a method to define characterization of crack resistance property. It is also known as elastic-plastic fracture mechanics test method, but it is applicable to materials which are linear, non linear and elastic-plastic behaviors [115]. As seen in Figure 2.41, linear, non-linear, and elastic-plastic materials behaviors with relationship stress and strain.

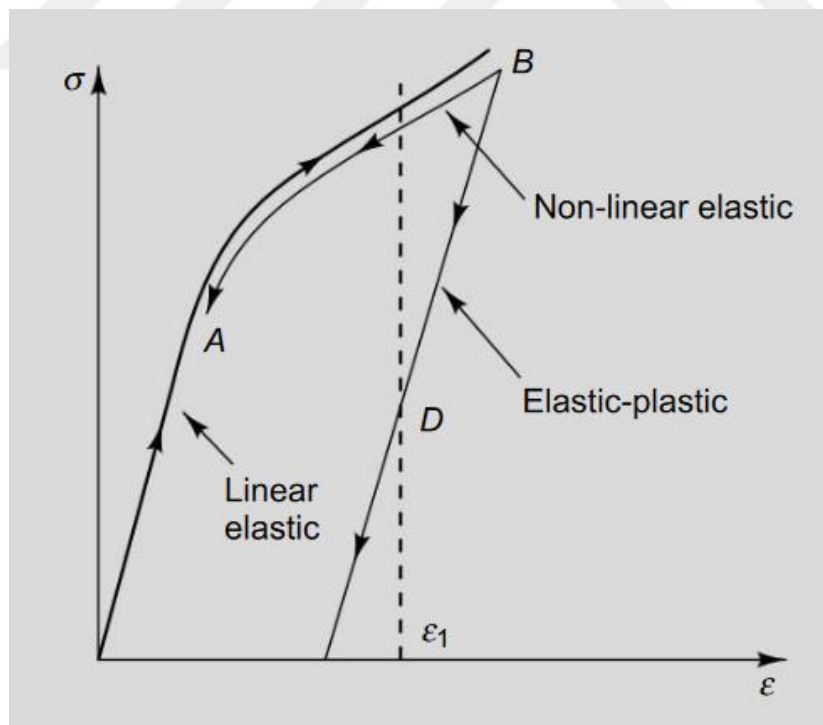


Figure 2.41. Different material behavior [115]

J-integral method was introduced by Rice in 1968 for plane surfaces. The relations are defined for 2D plane as:

$$J = -\frac{\partial U_p}{\partial a} \text{ (Release of potential energy per unit extension)} \quad (2.18)$$

$$J = \int_{\Gamma} \left(w dx_2 - T_i \frac{\partial u_i}{\partial x_1} ds \right) \quad (2.19)$$

$$w = \int (\sigma_{ij} d\varepsilon_{ij}) \quad (2.20)$$

$$w = \int_0^{\varepsilon_{11}} (\sigma_{11} d\varepsilon_{11}) + \int_0^{\varepsilon_{12}} (\sigma_{12} d\varepsilon_{12}) + \int_0^{\varepsilon_{21}} (\sigma_{21} d\varepsilon_{21}) + \int_0^{\varepsilon_{22}} (\sigma_{22} d\varepsilon_{22}) \quad (2.21)$$

Where T_i = traction vector at a point on the path Γ , u_i = displacement vector at a point on the path, ds = an increment of the contour path, Γ = The integral path near crack, w = strain energy per unit volume due to loading, $T_i \frac{\partial u_i}{\partial x_1}$ is stress work input rate. Path Γ around the crack tip is shown in Figure 2.42.

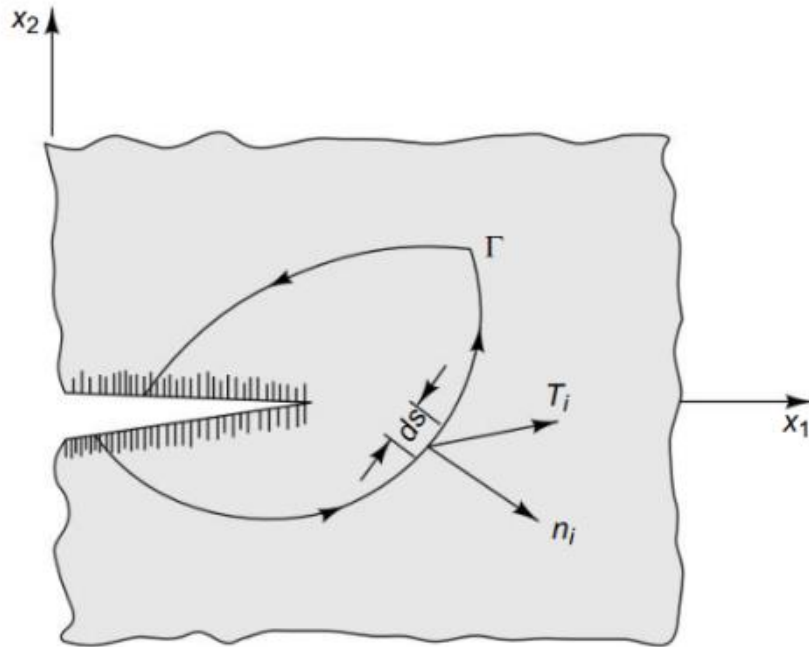


Figure 2.42. Path Γ around the crack tip with outward normal n_i and traction T_i

There are relation for J-integral with other fracture energy parameters G , K , and CTOD for isotropic material at mode I loading conditions which are given in the following Equations.

$$G = J = \frac{K_I^2}{\bar{E}} \quad (2.22)$$

$\bar{E} = E$ for plane stress assumption, $\bar{E} = \frac{E}{(1-\nu^2)}$ for plane strain assumption

$$CTOD = \frac{K_I^2}{E\sigma_y} = \frac{G_I}{\sigma_y} \quad \text{CTOD relation with } K \text{ and } G \quad (2.23)$$

$$CTOD = \frac{J}{\sigma_y} \quad \text{CTOD and J-integral relation} \quad (2.24)$$

Crack tip opening displacement is another calculation method of fracture energy. It was introduced by Wells and Cottrell for crack initiation and propagation in ductile materials. Similarly, CTOD is used to measure fracture energy which materials capable of plastic deformation. In addition, this method can be applicable for both LEFM and EPFM. Accurate measurement of crack opening displacement is one of the essentials of testing [103], [115]. The CTOD method is shown in Figure 2.43.

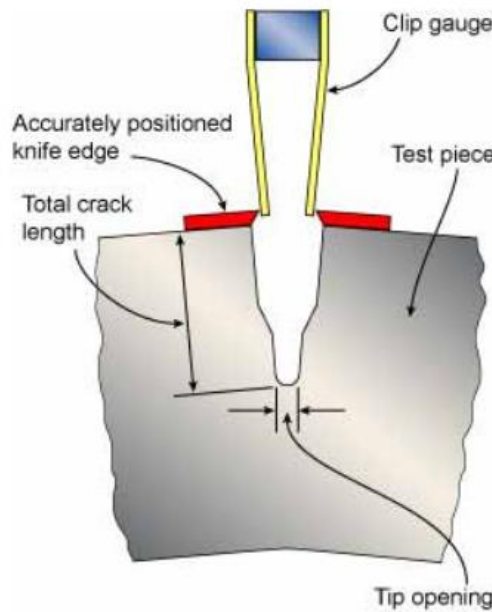


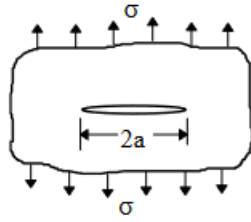
Figure 2.43. CTOD method and displacement measurement (Source: <https://l24.im/bZcyY>)

2.6.6. Fracture stress and toughness using LEFM approach

Stress intensity factor is a useful expression to define materials fracture toughness. The general equation of stress intensity factor is expressed as Equation 2.27. This characteristic property depends on applied stress, crack size, and the geometry or correction factor is shown in Figure 2.44 with example geometries. The notations are stated as $f\left(\frac{a}{w}\right)$ is correction (geometry) factor, a is crack length, σ is applied stress. Geometry factor value is different, and it changes with shape of material specimen. It depends on ratio of crack length and width [107].

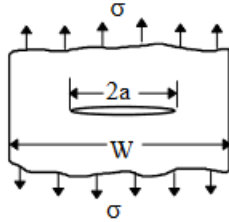


1. Crack in an infinite body



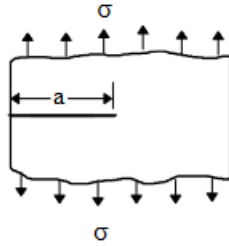
$$K_I = \sigma\sqrt{\pi a}$$

2. Centre crack in a strip of finite width



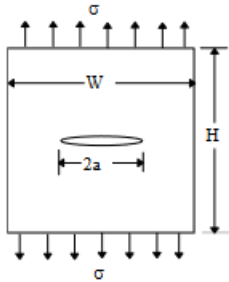
$$K_I = \sqrt{\sec \frac{\pi a}{W}} \sigma \sqrt{\pi a}$$

3. Edge crack in a semi-infinite body



$$K_I = 1.12 \sigma \sqrt{\pi a}$$

4. Edge crack in a finite width strip



$$K_I = f\left(\frac{a}{W}\right) \sigma \sqrt{\pi a}$$

Figure 2.44. Stress intensity factor relation with geometry [107]

The stress components in a crack tip point can be rewritten using stress intensity factor for cartesian coordinate system. The relationship stress and strain energy release rate are given in the following Equations. Where crack direction stress (σ_x), normal direction stress (σ_y), shear stress (τ_{xy}), K_I is the mode I stress intensity factor, E is modulus of elasticity and ν is Poisson's ratio, x is the crack direction, y is the normal direction and r and θ are the polar coordinates of crack plane.

$$\sigma_x = \frac{K_I}{\sqrt{\pi r}} \cos \frac{\theta}{2} \left(1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right) \quad (2.25)$$

$$\sigma_y = \frac{K_I}{\sqrt{\pi r}} \cos \frac{\theta}{2} \left(1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right) \quad (2.26)$$

$$\sigma_z = \frac{K_I}{\sqrt{\pi r}} 2\nu \cos \frac{\theta}{2} (E\varepsilon) \quad (2.27)$$

$$\tau_{xy} = \frac{K_I}{\sqrt{\pi r}} \cos \frac{\theta}{2} \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \quad (2.28)$$

To calculate stress at crack tip, the angle (θ) will be zero. By rearranging the Equation (2.25), the mode I stress intensity factor (K_I) is obtained as Equation (2.29). The geometry and crack length affect the stress intensity factor so the Equation can be written with correction factor as Equation (2.30) [116], [117], [118]. Stress components around a crack tip is illustrated as in Figure 2.45.

$$\sigma_x = \frac{K_I}{\sqrt{\pi a}} \quad (2.29)$$

$$K_I = \sigma \sqrt{\pi a} f_I \left(\frac{a}{w} \right) \quad (2.30)$$

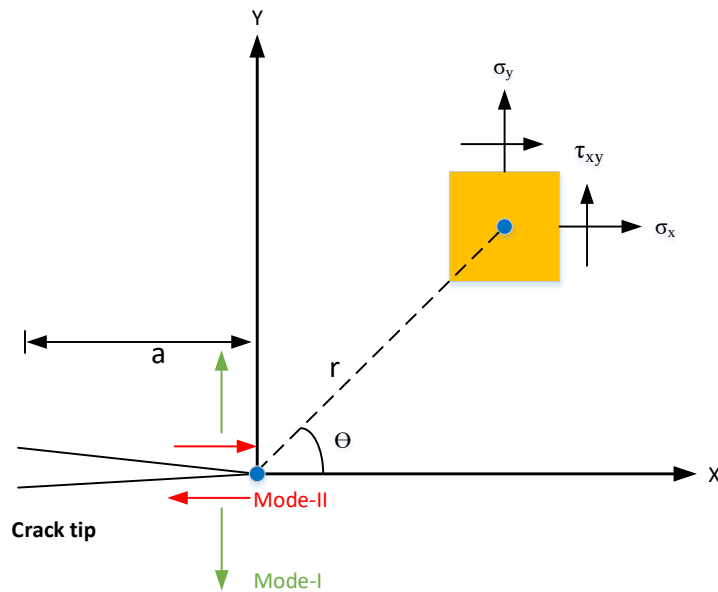


Figure 2.45. Stress components around the crack tip

Stress intensity factor and strain energy release rate are related to each other, the relationship is denoted using the following Equations and it is shown in Figure 2.46. The factor 2 denotes two opposite crack surfaces. [107], [119]. Where G_I is mode I strain energy release rate, G_{II} is mode II strain energy release rate, G_{III} is mode III strain energy release rate, G_T is total strain energy release rate, K_I is mode I stress intensity factor, K_{II} is mode II stress intensity factor, K_{III} is mode III stress intensity factor.

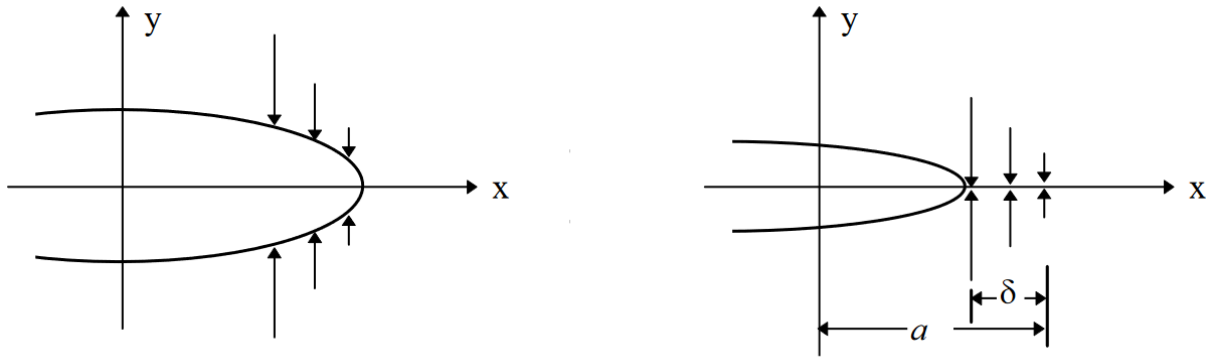


Figure 2.46. Strain energy release rate calculation [107]

$$\delta U_E = 2B \int_0^\delta \frac{1}{2} \sigma u dx = 2B \int_{a-\delta}^a \frac{1}{2} \sigma u dx \quad (2.31)$$

$$G = \lim_{\delta \rightarrow \infty} \left(\frac{2K_I^2}{\pi E \delta} \right) \int_0^\delta \sqrt{\frac{\delta-r}{r}} dr = \frac{2K_I^2}{\pi E} \int_0^{\frac{\pi}{2}} \sqrt{\frac{\cos^2 \theta}{\sin^2 \theta}} 2\delta \sin \theta \cos \theta d\theta \quad (2.32)$$

For plane stress conditions, the relationship can be shown for mode-I, II, and III.

$$G_I = \frac{K_I^2}{E} \quad G_{II} = \frac{K_{II}^2}{E} \quad G_{III} = \frac{K_{III}^2}{E} \quad (2.33)$$

When assuming plane strain conditions, the relationship K and G is shared as the following equations for mode-I, II, and III.

$$G_I = (1 - \nu^2) \frac{K_I^2}{E} \quad G_{II} = (1 - \nu^2) \frac{K_{II}^2}{E} \quad G_{III} = (1 - \nu^2) \frac{K_{III}^2}{E} \quad (2.34)$$

Total strain energy is summation of the three modes strain energy release rates.

$$G_T = G_I + G_{II} + G_{III} \quad (2.35)$$

2.6.7. Plane stress and plane strain conditions

The Hooke's law is an efficient mathematical expression to explain stress and strain formation when a load applied on a material. There are 6 different stress notations and the component of stress tensor is shown in Figure 2.47 [120]. The stress tensor matrix is given in Equation 2.36.

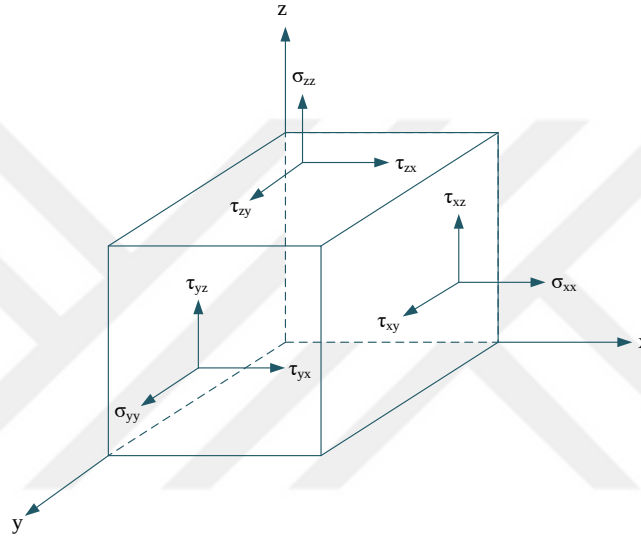


Figure 2.47. The components of the stress tensor

$$\sigma = \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix} \quad (2.36)$$

Stress and strain relationship is stated as Generalized Hooke's Law that is given in Equation 2.37. There are six stresses and six strains that are given in Equation with 6x6 matrix. The stress expressions ($\tau_{xy} = \tau_{yx}$, $\tau_{xz} = \tau_{zx}$, $\tau_{zy} = \tau_{yz}$) are equal to each other so they are written in the equation one of them to express stress acting on one direction. The strain expressions ($\gamma_{xy} = \gamma_{yx}$, $\gamma_{xz} = \gamma_{zx}$, $\gamma_{zy} = \gamma_{yz}$) are equal to each other so they are written in the equation one of them to express stress acting on one direction. Additionally, Equation 2.37 can be written strain matrix and it is given in Equation 2.38 [26]. The notations of the terms of the nonzero entries C_{ij} are the stiffness matrix and the nonzero entries S_{ij} are the compliance matrix.

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{zy} \\ \tau_{zx} \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{zy} \\ \gamma_{zx} \\ \gamma_{xy} \end{bmatrix} \quad (2.37)$$

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{zy} \\ \gamma_{zx} \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} \\ S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} \\ S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{zy} \\ \tau_{zx} \\ \tau_{xy} \end{bmatrix} \quad (2.38)$$

Furthermore, there is a useful mathematical simplicity relation between stiffness and inverse of compliance matrix that is given in Equation 2.39. The generalized Hooke's law can be written for isotropic material with six strain components and six stress components [121]. The relation between stress and strain is given in Equations 2.40 and 2.41, respectively.

$$C = [S]^{-1} \quad (2.39)$$

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{zy} \\ \tau_{zx} \\ \tau_{xy} \end{bmatrix} = \alpha \begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0 \\ \nu & 1-\nu & \nu & 0 & 0 & 0 \\ \nu & \nu & 1-\nu & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-2\nu & 0 & 0 \\ 0 & 0 & 0 & 0 & 1-2\nu & 0 \\ 0 & 0 & 0 & 0 & 0 & 1-2\nu \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{zy} \\ \gamma_{zx} \\ \gamma_{xy} \end{bmatrix}$$

$$\alpha = E/[(1+\nu)(1-2\nu)] \quad (2.40)$$

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{zy} \\ \gamma_{zx} \\ \gamma_{xy} \end{bmatrix} = \frac{1}{E} \begin{bmatrix} 1 & -\nu & -\nu & 0 & 0 & 0 \\ -\nu & 1 & -\nu & 0 & 0 & 0 \\ -\nu & -\nu & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(1+\nu) & 0 & 0 \\ 0 & 0 & 0 & 0 & 2(1+\nu) & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(1+\nu) \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{zy} \\ \tau_{zx} \\ \tau_{xy} \end{bmatrix} \quad (2.41)$$

Fracture toughness basically depends on material thickness [106]. While the material thickness increases, fracture toughness K_{IC} starts to decrease. But, the material thickness

reaches in plane strain conditions, K_{IC} value starts to not change. This characteristic value is known as fracture toughness of material. When a stress is applied to the material, K_I value increases up to K_{IC} . This condition is critical for propagating the crack, subsequently the fracture failure occur. Effect of thickness on fracture toughness is presented in Figure 2.48.

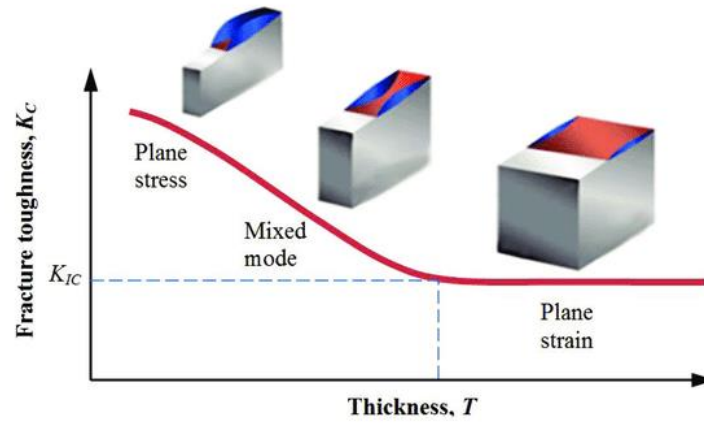


Figure 2.48. Critical stress intensity factor and thickness effects on fracture toughness [122]

If the material is thin and there is no load at z direction, plane stress approach is useful to obtain the changes stress and strain. Also, the plane stress approach transforms 3-Dimensional tensor to 2-Dimensional matrix. The conditions are given in Equation 2.42. By rearranging Equation 2.40 for plane stress, new form of matrix is obtained that is given in Equation 2.43. The strain and stress relation is given in Equation 2.44. Furthermore, the strain in z -direction is given in Equation 2.45 [121]. Plane stress and plane strain conditions are given in Figure 2.49.

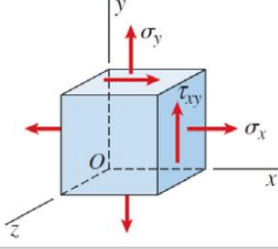
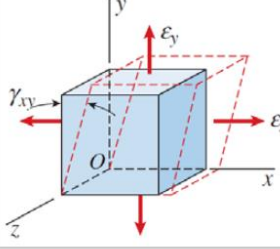
	Plane stress	Plane strain
		
Stresses	$\sigma_z = 0$ $\tau_{xz} = 0$ $\tau_{yz} = 0$ σ_x , σ_y , and τ_{xy} may have nonzero values	$\tau_{xz} = 0$ $\tau_{yz} = 0$ σ_x , σ_y , σ_z , and τ_{xy} may have nonzero values
Strains	$\gamma_{xz} = 0$ $\gamma_{yz} = 0$ ϵ_x , ϵ_y , ϵ_z , and γ_{xy} may have nonzero values	$\epsilon_z = 0$ $\gamma_{xz} = 0$ $\gamma_{yz} = 0$ ϵ_x , ϵ_y , and γ_{xy} may have nonzero values

Figure 2.49. Plane stress and plane strain conditions (Source: <https://l24.im/geOohtq>)

$$\sigma_z = \tau_{zx} = \tau_{zy} = 0 \quad (2.42)$$

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \frac{E}{(1-\nu^2)} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{(1-\nu)}{2} \end{bmatrix} \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{bmatrix} \quad (2.43)$$

$$\begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{bmatrix} = \frac{1}{E} \begin{bmatrix} 1 & -\nu & 0 \\ -\nu & 1 & 0 \\ 0 & 0 & 2(1+\nu) \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} \quad (2.44)$$

$$\epsilon_z = \frac{-\nu}{E} (\sigma_x + \sigma_y) = \frac{-\nu}{1-\nu} (\epsilon_x + \epsilon_y) \quad (2.45)$$

If the material is thick and there is no strain at z direction, plane strain approach is used to obtain the changes stress and strain. Also, the plane strain approach transforms 3-Dimensional tensor to 2-Dimensional matrix. The conditions are given in Equation 2.46. By rearranging Equation 2.40 for plane strain, new form of matrix is obtained that is given in Equation 2.47. The strain and stress relation is given in Equation 2.48. Additionally, the stress in z-direction is given in Equation 2.49 [121].

$$\varepsilon_z = \gamma_{zx} = \gamma_{zy} = 0 \quad (2.46)$$

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & 0 \\ \nu & 1-\nu & 0 \\ 0 & 0 & \frac{1}{2}-\nu \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \quad (2.47)$$

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \frac{1+\nu}{E} \begin{bmatrix} 1-\nu & -\nu & 0 \\ -\nu & 1-\nu & 0 \\ 0 & 0 & 2 \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} \quad (2.48)$$

$$\sigma_z = \frac{E\nu}{(1+\nu)(1-2\nu)} (\varepsilon_x + \varepsilon_y) = \nu(\sigma_x + \sigma_y) \quad (2.49)$$

To obtain stress intensity factor and strain energy release rate for orthotropic materials, the Equation 2.37 is rearranged and the constants are given in Equation 2.50.

$$\begin{aligned} S_{11} &= \frac{1}{E_x}; S_{22} = \frac{1}{E_y}; S_{33} = \frac{1}{E_z}; S_{44} = \frac{1}{G_{yz}}; S_{55} = \frac{1}{G_{xz}}; S_{66} = \frac{1}{G_{xy}}; S_{12} = S_{21} = -\frac{\nu_{xy}}{E_x} = -\frac{\nu_{yx}}{E_y}; \\ S_{13} &= S_{31} = -\frac{\nu_{xz}}{E_x} = -\frac{\nu_{zx}}{E_z}; S_{23} = S_{32} = -\frac{\nu_{yz}}{E_y} = -\frac{\nu_{zy}}{E_z} \end{aligned} \quad (2.50)$$

For plane strain condition $\varepsilon_z = \gamma_{yz} = \gamma_{xz} = 0$, the strain-stress relation turns into following Equations. Where the constants b_{ij} are defined in terms of S_{ij} of the compliance matrix.

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{pmatrix} = \begin{pmatrix} b_{11} & b_{12} & b_{16} \\ b_{12} & b_{22} & b_{26} \\ b_{16} & b_{26} & b_{66} \end{pmatrix} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix} \quad (2.51)$$

$$b_{ij} = S_{ij} - \frac{S_{i3}S_{j3}}{S_{33}} \quad (i, j=1, 2, 4, 5, 6) \quad (2.52)$$

$$S_{16} = S_{26} = S_{36} = S_{45} = 0, b_{16} = b_{26} = 0,$$

$$b_{11} = \frac{S_{11}S_{33} - S_{13}^2}{S_{33}}, b_{12} = \frac{S_{12}S_{33} - S_{13}S_{23}}{S_{33}}, b_{22} = \frac{S_{22}S_{33} - S_{23}^2}{S_{33}}, b_{66} = \frac{S_{66}S_{33} - S_{36}^2}{S_{33}} \quad (2.53)$$

Stress intensity factors (K_I , K_{II}) are stated in Equation (2.54) and strain energy release rates (G_I , G_{II}) for linear elastic isotropic material is given in Equations (2.55) and (2.56), respectively.

$$K_I = \frac{P_c \sqrt{\pi a}}{wt} f_I(a/w) \quad K_{II} = \frac{P_c \sqrt{\pi a}}{wt} f_{II}(a/w) \quad (2.54)$$

$$G_I = \frac{K_I^2}{E} \quad G_{II} = \frac{K_{II}^2}{E} \quad (\text{for plane stress}) \quad (2.55)$$

$$G_I = \frac{K_I^2}{\bar{E}} \quad G_{II} = \frac{K_{II}^2}{\bar{E}} \quad \bar{E} = \frac{1}{1-\nu^2} \quad (\text{for plane strain}) \quad (2.56)$$

Strain energy release rates (G_I , G_{II}) for orthotropic linear elastic material is given in the Equations (2.57), (2.58) and (2.59), respectively [123]. Where E_I , E_{II} are modulus of elasticity for mode I, II, respectively.

$$G_I = \frac{K_I^2}{E_I} \quad G_{II} = \frac{K_{II}^2}{E_{II}} \quad (2.57)$$

$$E_I = \sqrt{\frac{2}{S_{11}S_{22}}} \frac{1}{\sqrt{\left(\sqrt{\frac{S_{22}}{S_{11}}} + \frac{2S_{12}+S_{66}}{2S_{11}}\right)}}, \quad E_{II} = \frac{\sqrt{2}}{S_{11}} \frac{1}{\sqrt{\left(\sqrt{\frac{S_{22}}{S_{11}}} + \frac{2S_{12}+S_{66}}{2S_{11}}\right)}} \quad (\text{plane stress condition}) \quad (2.58)$$

$$E_I = \sqrt{\frac{2}{b_{11}b_{22}}} \frac{1}{\sqrt{\left(\sqrt{\frac{b_{22}}{b_{11}}} + \frac{2b_{12}+b_{66}}{2b_{11}}\right)}}, \quad E_{II} = \frac{\sqrt{2}}{b_{11}} \frac{1}{\sqrt{\left(\sqrt{\frac{b_{22}}{b_{11}}} + \frac{2b_{12}+b_{66}}{2b_{11}}\right)}} \quad (\text{plane strain condition}) \quad (2.59)$$

To determine if the calculated K_C value is acceptable to the plane strain fracture toughness criteria, which K_C is the critical fracture toughness of the material and it is independent of specimen thickness by using the following Equations [124]. Where a is crack length, t is thickness, σ_Y is yield stress of the material.

$$t, a > 2.5 \left(\frac{K_C}{\sigma_Y} \right)^2 \quad (2.60)$$

$$0.45 < \frac{a}{w} < 0.55 \quad (2.61)$$

2.6.8. Composite faults and failures

Composite materials are used in a wide range of industries because of their high strength-to-weight ratio and durability. However, these materials are not invulnerable to failure. There are several types of composite failure that can occur, including delamination, fiber breakage, matrix cracking, and debonding. Delamination refers to the separation of layers in a composite material, which can result from insufficient bonding between layers or stress-induced cracking. Fiber breakage occurs when the reinforcing fibers within the composite material fracture, reducing the overall strength and stiffness of the material. Matrix cracking refers to the formation of small cracks within the matrix material surrounding the reinforcing fibers. Debonding is the failure of the bond between the reinforcing fibers and the matrix material. These failures can be caused by a variety of factors, including excessive loads, environmental conditions, manufacturing defects, and improper design. It is important to note that composite failures can be complex and interconnected, with multiple failure modes occurring simultaneously or leading to secondary failures. All failures in composite material are illustrated in Figure 2.50. Apart from these defects, other faults that may occur during production are shown in Figure 2.51. When constructing a laminated composite, it is important to remove wrinkles as new layers are added. Wrinkles can cause air entrapment and resin layering. They can weaken the composite and make the design unusable. Air entrapment, sometimes called voids, between fiber layers. Voids can occur because air is trapped between layers during the lamination process. Blistering occurs in the outermost layers. Voids and bubbles weaken the composite and can also cause other damage forms. In addition, foreign objects trapped between plies will reduce the strength of the composite [125], [126].

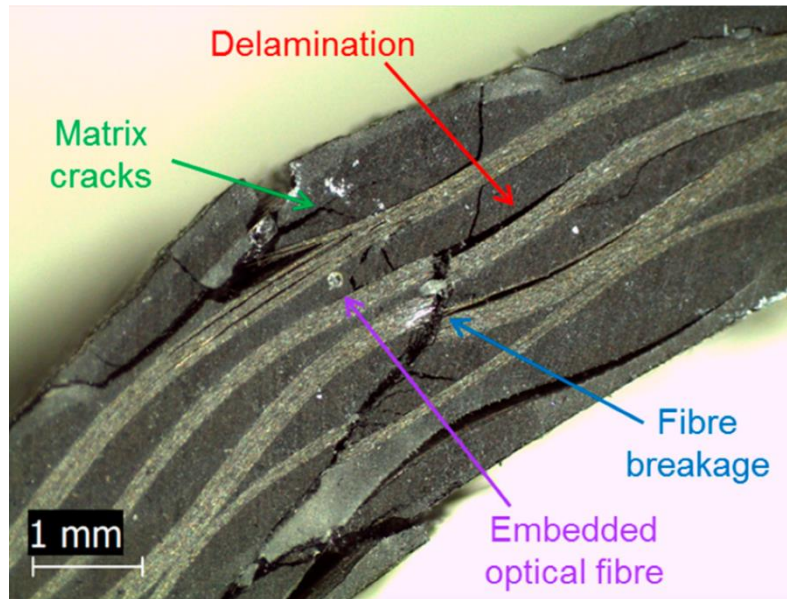


Figure 2.50. Composite fault types [127]

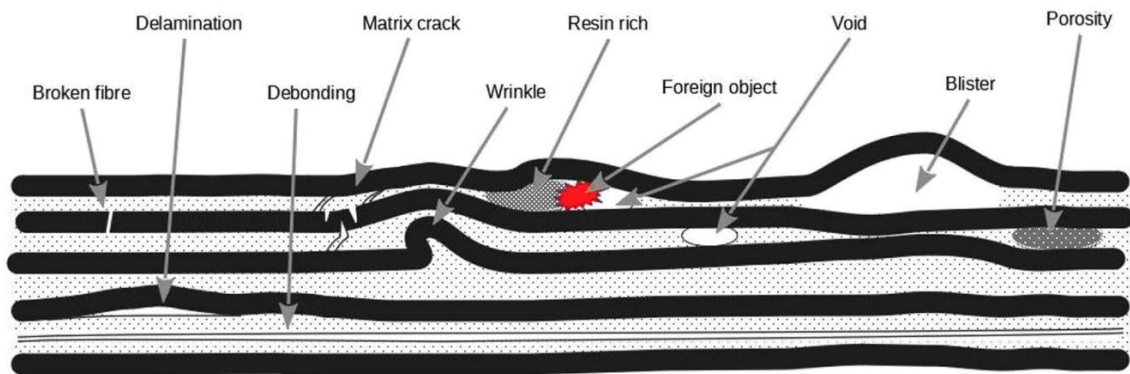


Figure 2.51. Composite fault types [128]

2.6.9 Fracture failure modes

There are several modes in which composite materials fail, and they are all interrelated, depending on the loading, material structure, and component geometry conditions. These failure modes can be grouped into three classes: translaminar, interlaminar, and intralaminar, as shown in Figure 2.52. Translaminar failure includes modes such as fiber cleavage, buckling, and shear, and involves failure of the reinforcing fibers. The other two types of failure don't comprise any important fiber breakage; interlaminar (delamination) failure includes breakage between plies, whilst intralaminar failure includes breakage through the thickness between fibers. Modes such as fiber-to-matrix delamination, matrix cleavage,

cohesive failure, and shear of either the matrix or the fiber-to-matrix interface fall into these two classes [129].

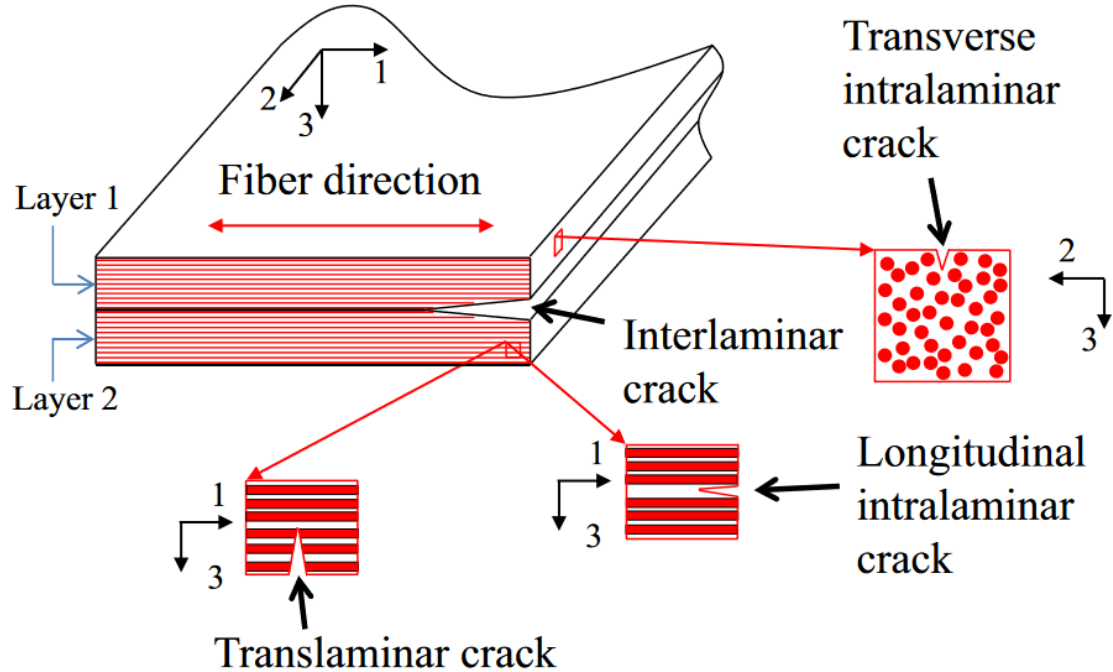


Figure 2.52. Fracture failure modes unidirectional in a composite laminate. [130]

2.6.10. Fracture Modes

Basically, there are 3 different fracture modes that are mode I (opening), mode II (shearing), and mode III (tearing). For mode- I, the employed forces direction is perpendicular to crack propagation and it is named mode-I or opening mode cracks. The mode is critical for brittle material due to weak resistance to tension force. The other fracture mode II is sliding or shearing mode. Load forces and crack extension direction are parallel to the crack plane. Mode III is also known as plane shearing or tearing mode. Load force is applied perpendicular to the plane, so a crack propagates parallel to the front line of the crack. If there are multiple cracks in different direction, they named as mixed mode which is a combination of two or all fracture modes. All materials have different mechanical properties, so they can have different fracture toughness values for each mode. When different loads are applied to the material, different methods are used to determine fracture toughness in each mode or combination of the fracture modes [131], [132], [103]. The fracture modes are illustrated in Figure 2.53.

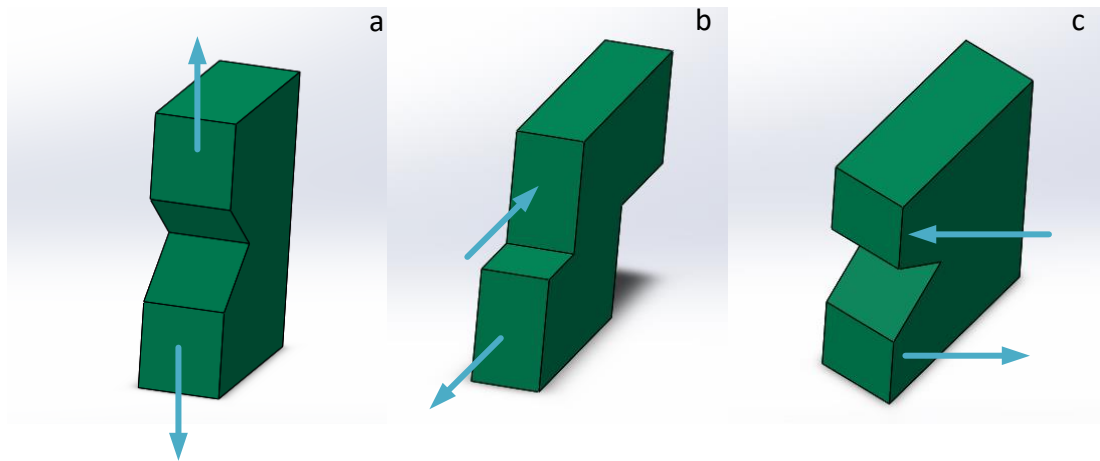


Figure 2.53. Fracture modes: (a) mode I, (b) mode II, (c) mode III

2.6.11. Fracture toughness measurement methods for mode I, II, III

There are several methods to measure fracture toughness of materials for opening (mode I), shearing (mode II), and tearing (mode III) modes. For each mode, measuring fracture toughness requires different experimental setup. Therefore, there are distinct measurement methods were proposed that are shown in Figure 2.54. Some of them are special to measure fracture toughness of material only one mode, but some methods have ability to determine more one mode. Mode I fracture toughness measurement methods basically are listed as compact tension specimen (CTS), single edge notched bending (SENB), middle tension specimen (MT), extended compact tension (ECT), double edge notched tension (DENT), single edge notched tension (SENT), four-point bend specimen (FPB), disk-shaped compact tension (DSCT), arc-shaped tension specimen (AST), Semi-circular bend (SCB), double cantilever beam (DCB), pipe ring notch bend specimen (PRNB), and curved compact tension specimen (CCT) are shown in the following Figures 2.55-2.62 [133], [134], [135], [136].

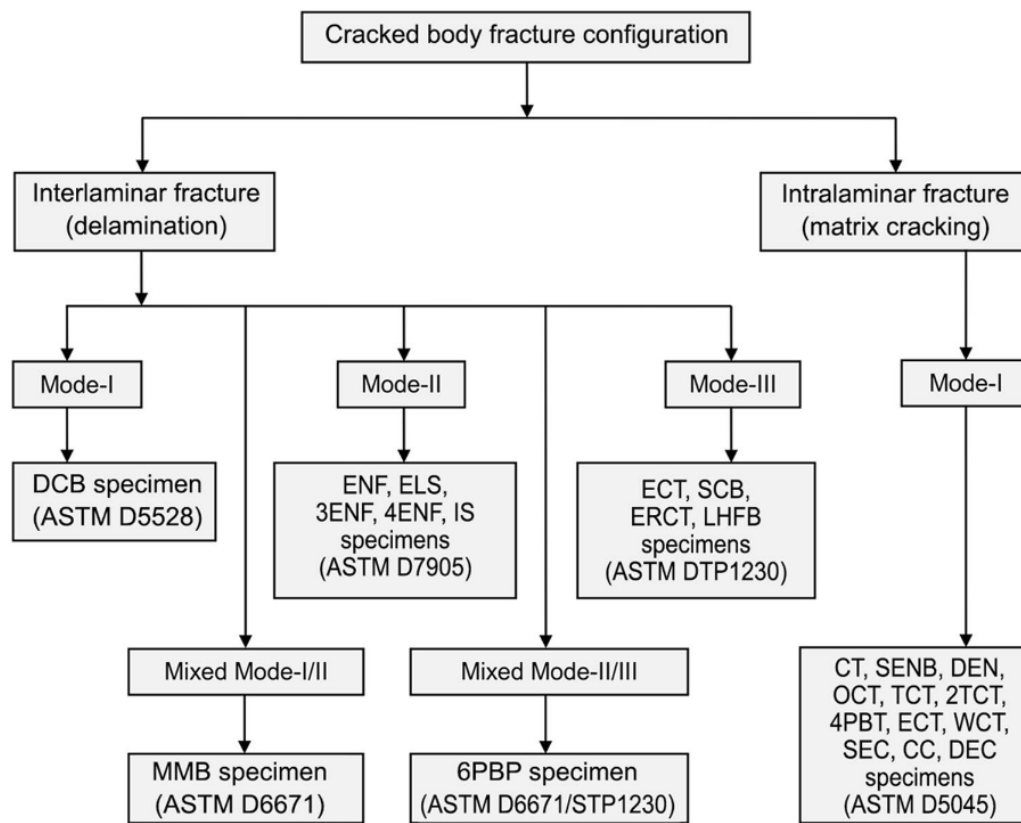


Figure 2.54. Fracture toughness measurement methods [108]

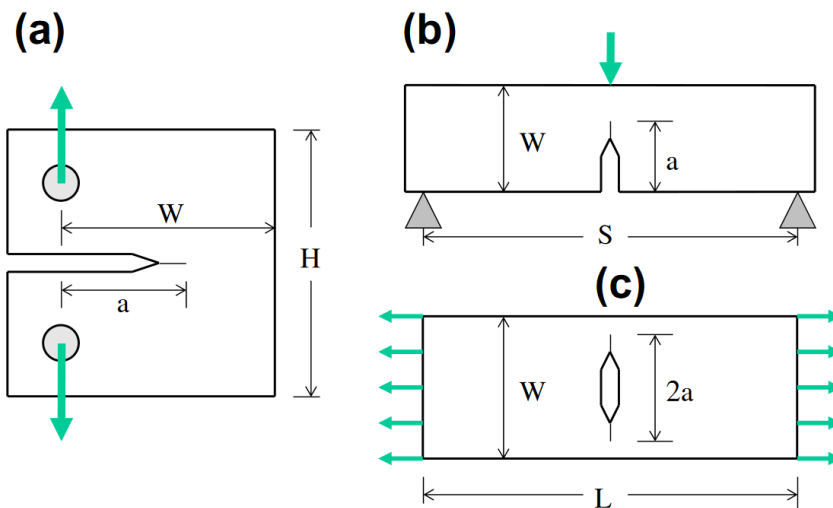


Figure 2.55. Mode I fracture toughness measurement methods part I: (a) CTS, (b) SENB, (c) middle tension (MT) specimen [134]

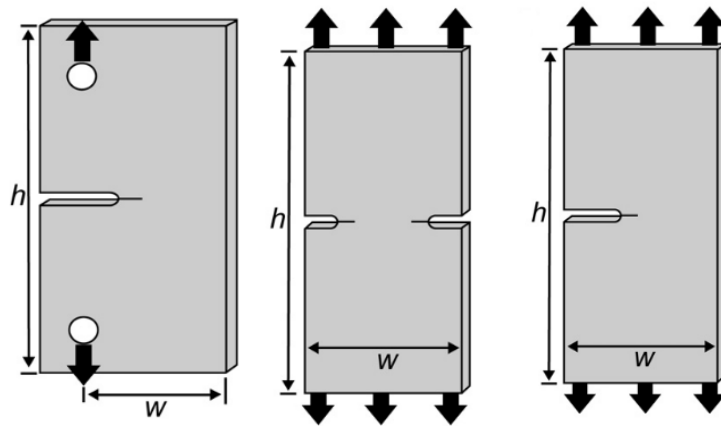


Figure 2.56. Mode I fracture toughness measurement methods part II: (a) extended compact tension, (b) double edge notched tension, (c) single edge notched tension [133]

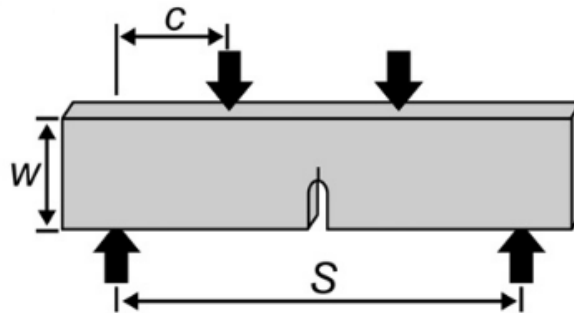


Figure 2.57. Mode I fracture toughness measurement methods part III: four-point bend specimen [133].

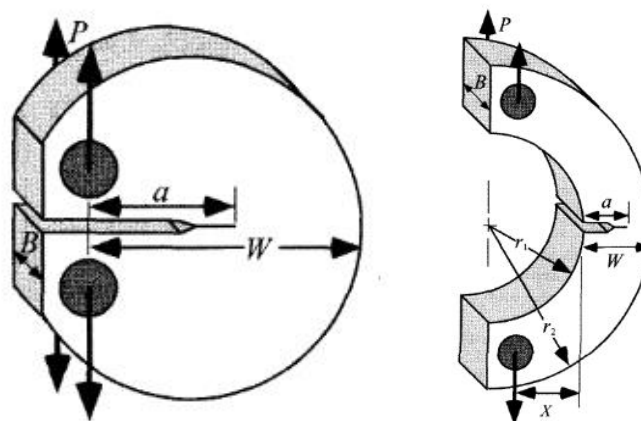


Figure 2.58. Mode I fracture toughness measurement methods part IV: (a) disk-shaped compact tension specimen, (b) arcshaped tension specimen [137]

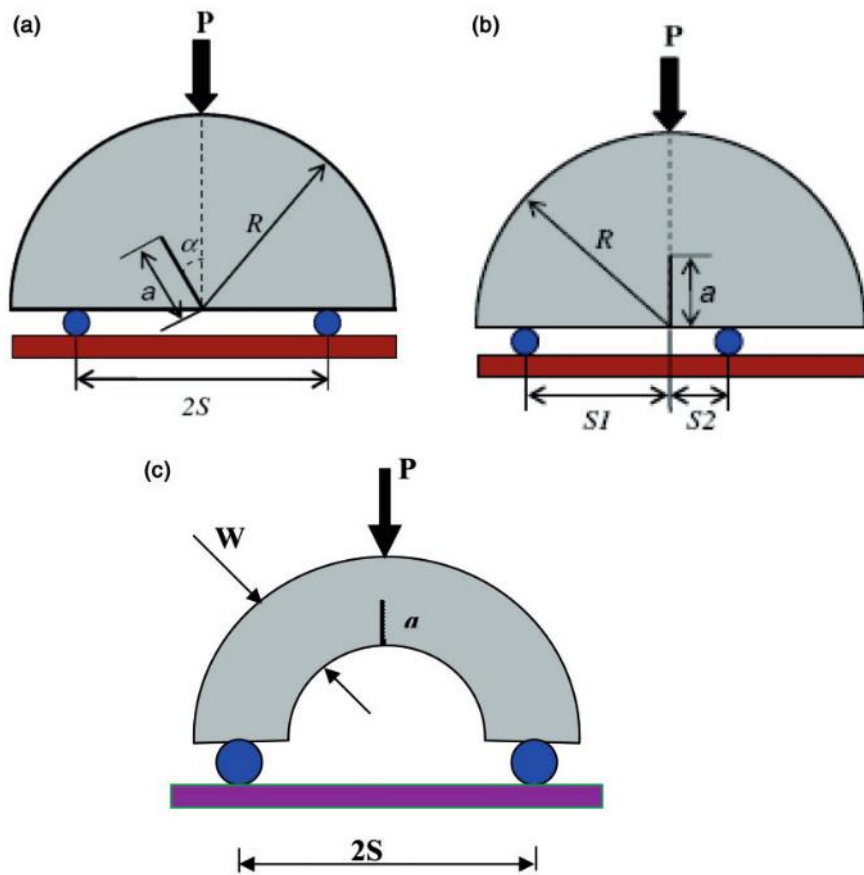


Figure 2.59. Mode I fracture toughness measurement methods part V: Semi-circular bend (SCB) specimen under three-point bend loading (a) with inclined crack (b) asymmetrical loading (c) semi-circular arc type bend specimen [138]

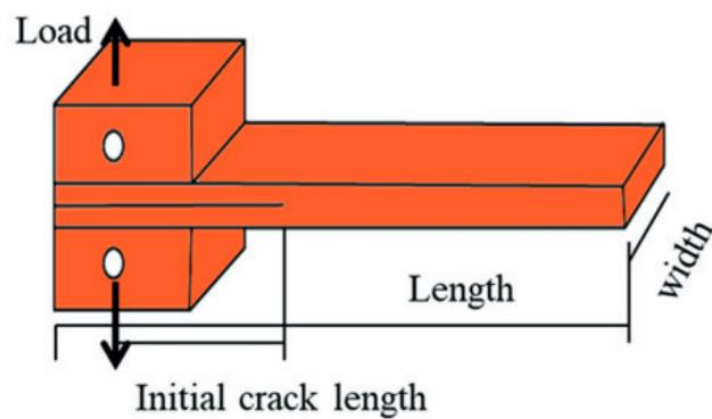


Figure 2.60. Mode I fracture toughness measurement methods part VI: double cantilever beam [139]

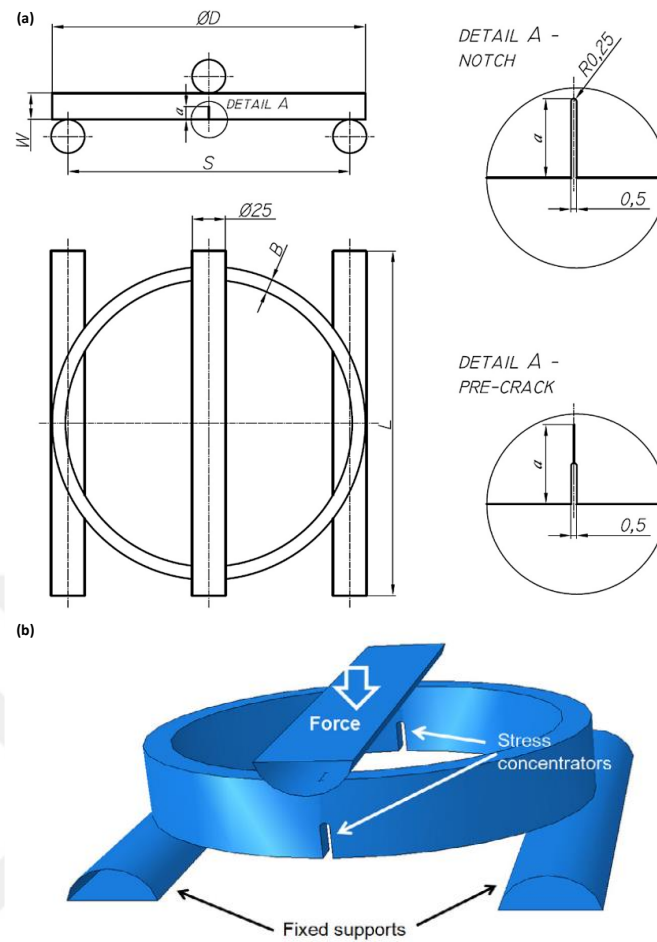


Figure 2.61. Mode I fracture toughness measurement methods part VII: pipe ring notch bend specimen (PRNB) (a) specimen dimensions and (b) testing scheme [140]

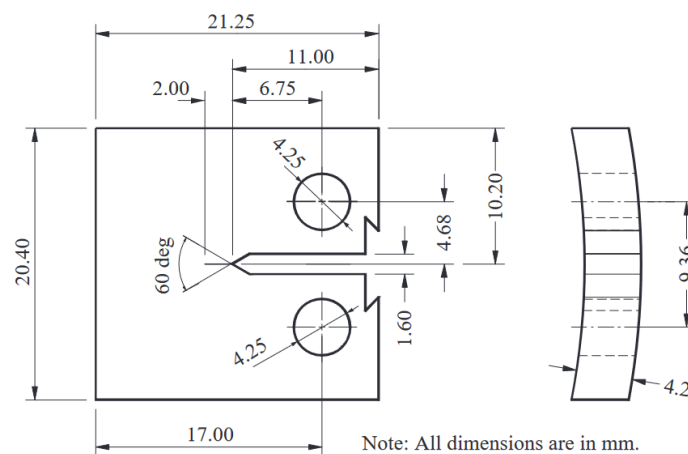


Figure 2.62. Mode I fracture toughness measurement methods part VIII: curved compact tension specimen [100]

End notched flexure (ENF) or three-point bend end-notched flexure (3ENF), end load split (ELS) specimens are fracture toughness test methods which generally to determine fracture toughness of material in mode II loading condions [135], [136], [141], [142], [143], [108], [144]. The methods are presented in Figures 2.63-2.64.

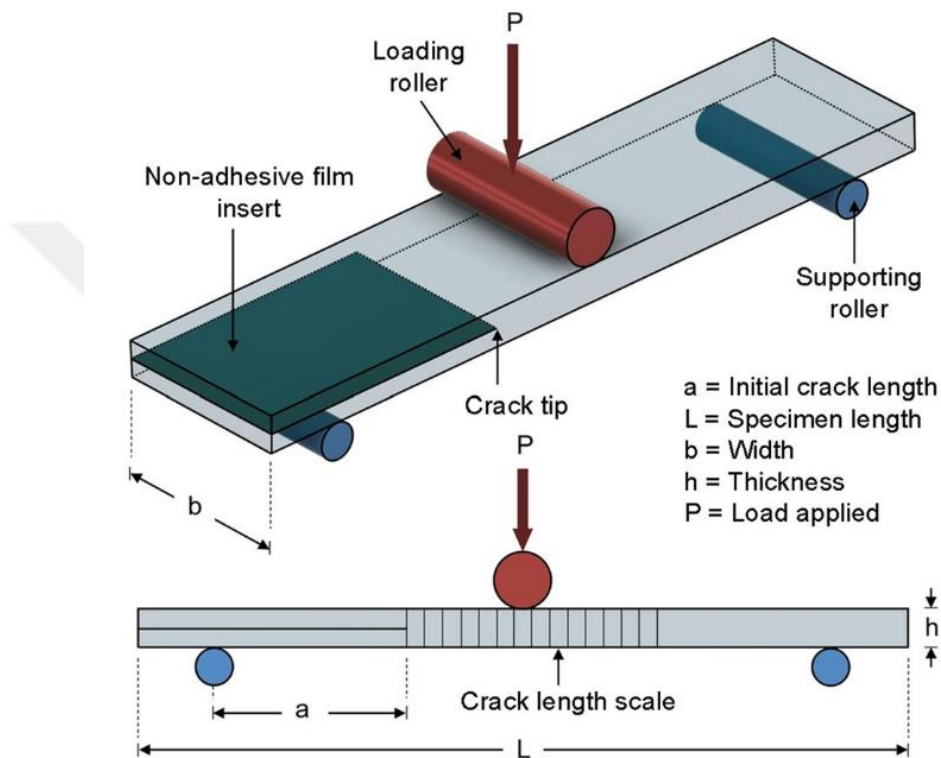


Figure 2.63. Mode-II interlaminar fracture toughness test setup (ENF specimen) [108]

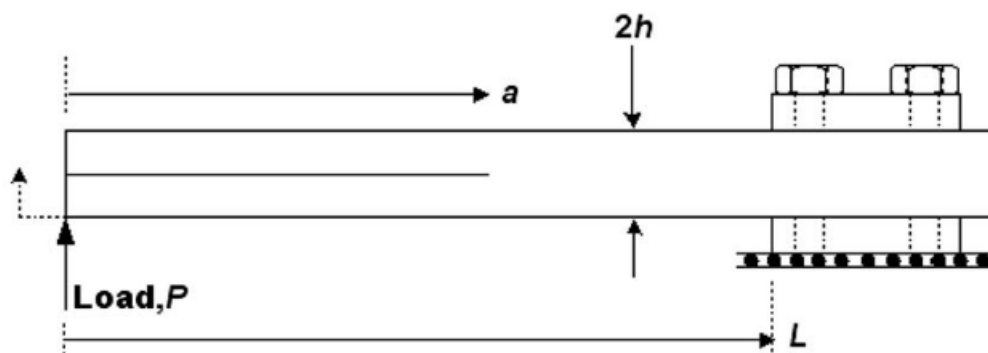


Figure 2.64. End loaded split (ELS) method [144]

There are mixed mode fracture toughness methods which are ability to pure two modes or combination of them. Measurement fracture toughness of mixed modes is attracted as a practical approach for defining fracture toughness of two or more desired modes. Therefore, methods are developed to allow testing for different modes with a single test method. Example methods for mixed modes are shown in Figures 2.65-2.68 [108], [145], [146], [147].

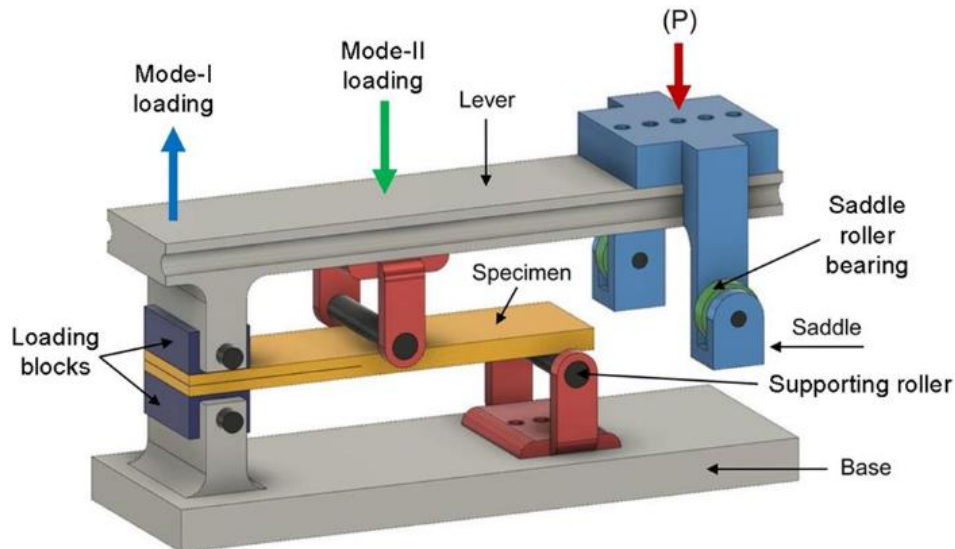


Figure 2.65. Mixed mode bending specimen (MMB) [108]

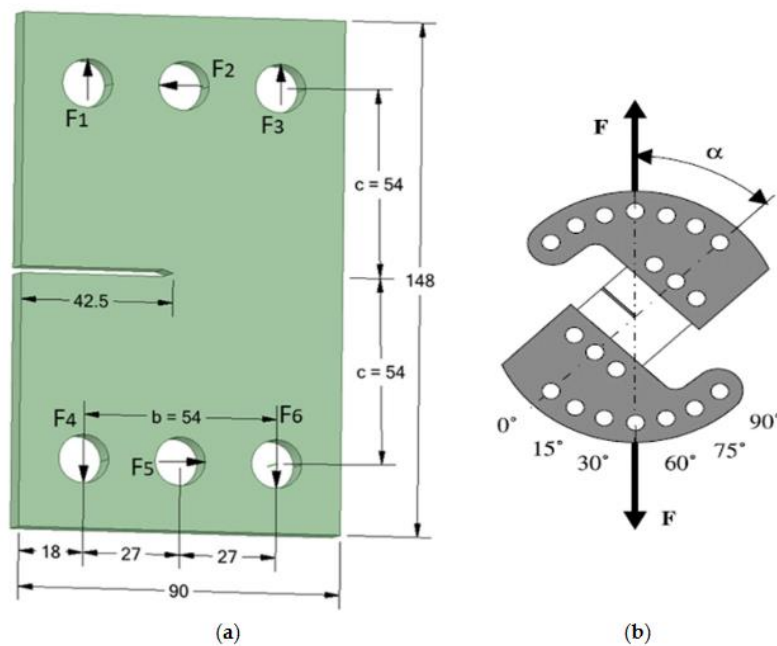


Figure 2.66. Mode I, II fracture toughness: (a) geometry of CTS, (b) loading angles [145]

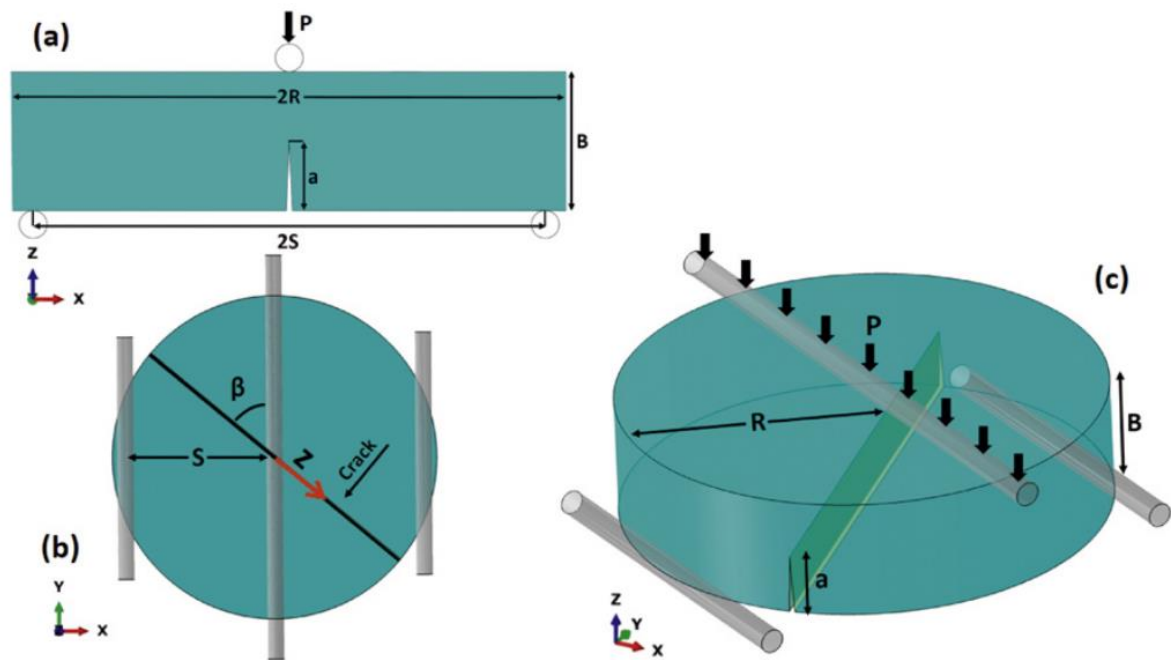


Figure 2.67. Mode I, III fracture toughness fixture: Edge Notched Disc Bend (ENDB) [146]

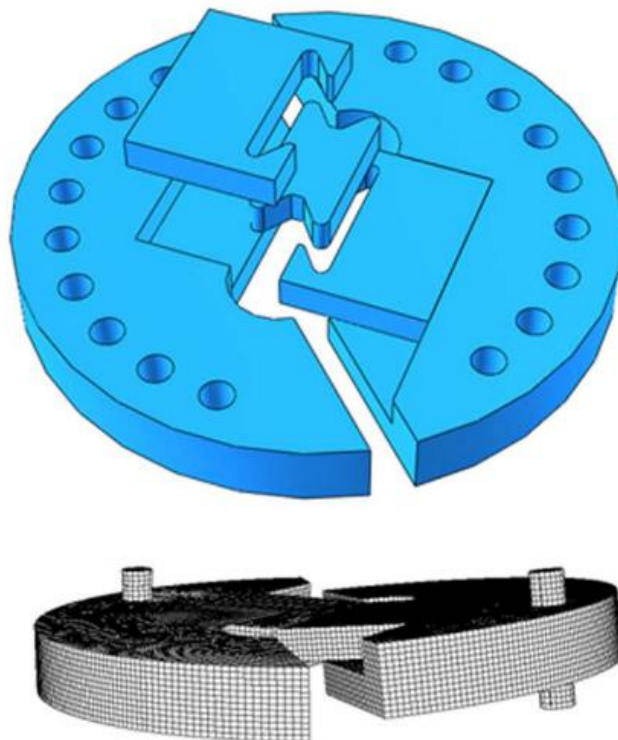


Figure 2.68. Mode I, II fracture toughness measurement methods: Arcan specimen [147]

There are many different methods for measuring mode III fracture toughness. In this method, fracture toughness is determined by exposing the specimen to tearing motion. Edge Crack Torsion (ECT), anti-plane four-point bend specimen, anti-plane punch-through shear specimen, torsional circumferentially notched cylinder, edge ring crack torsion test (ERCT), edge crack torsion test method (ECT), longitudinal half fixed beam (LHFB), crack rail shear (CRS) methods can be utilized for determining pure mode III fracture toughness. Pure mode III test methods are shown in Figures 2.69-2.74.

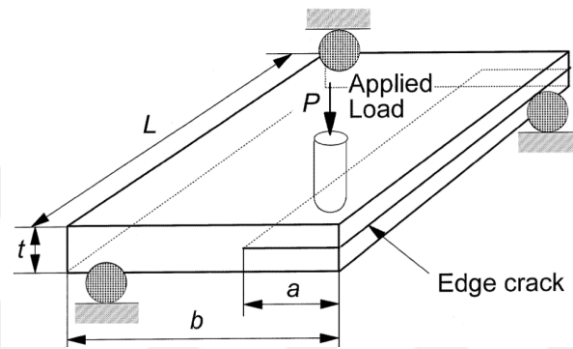


Figure 2.69. Edge crack torsion (ECT) specimen for Mode III delamination test [148]

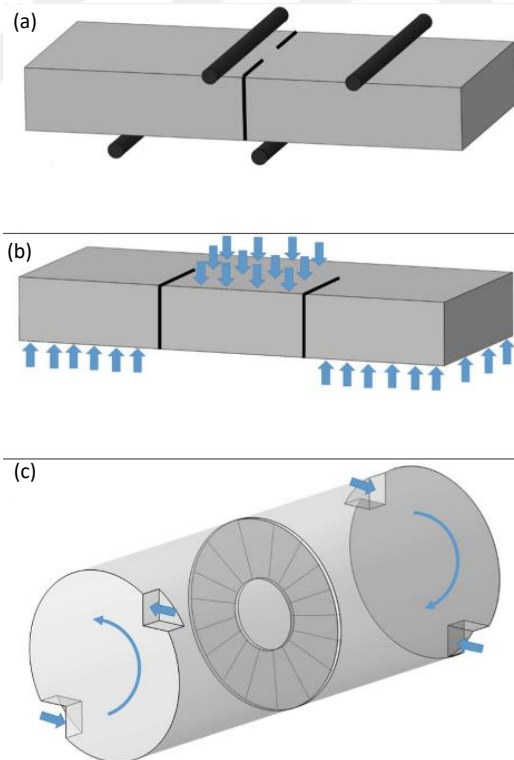


Figure 2.70. Pure mode III measurement methods: (a) anti-plane four-point bend specimen,

(b) anti-plane punch-through shear specimen, (c) torsional circumferentially notched cylinder
[149]

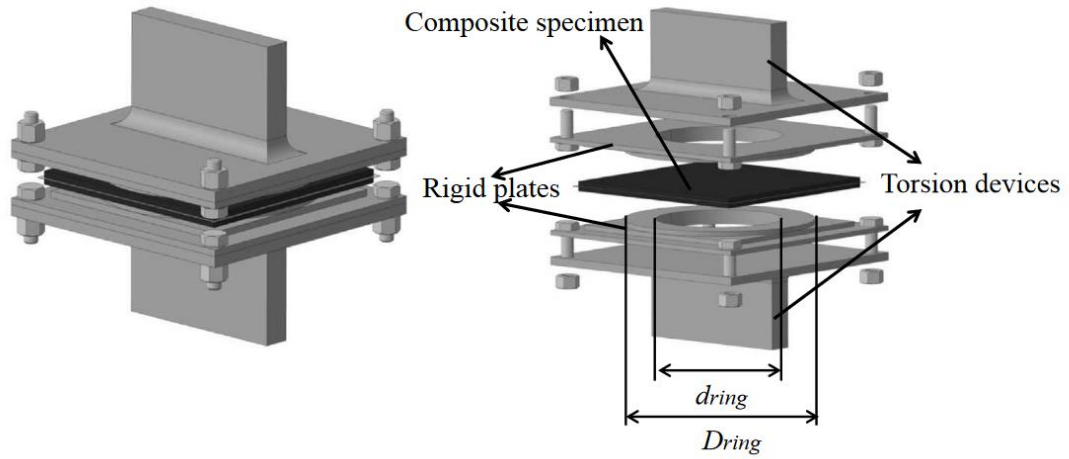


Figure 2.71. Edge Ring Crack Torsion test device (ERCT) [150]

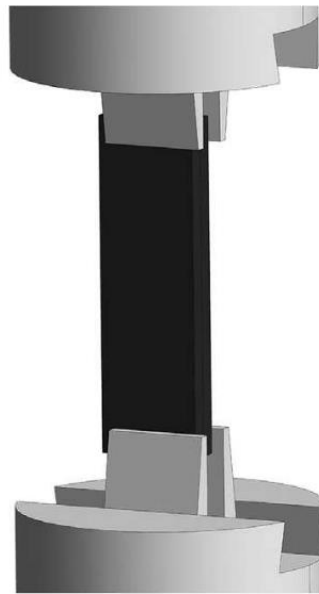


Figure 2.72. Edge Crack Torsion test method 2 (ECT) [150]

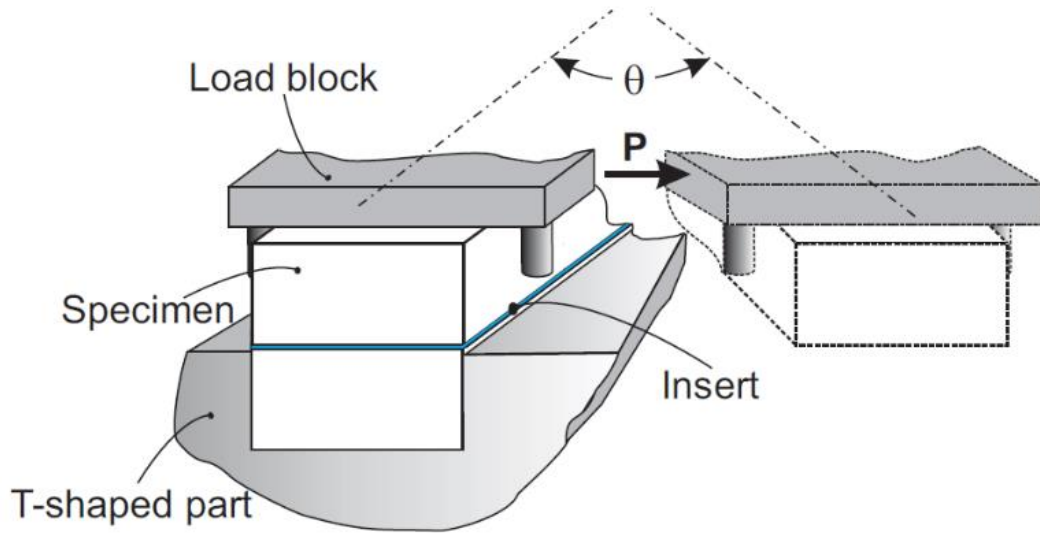


Figure 2.73. LHFB method for pure mode III [151]

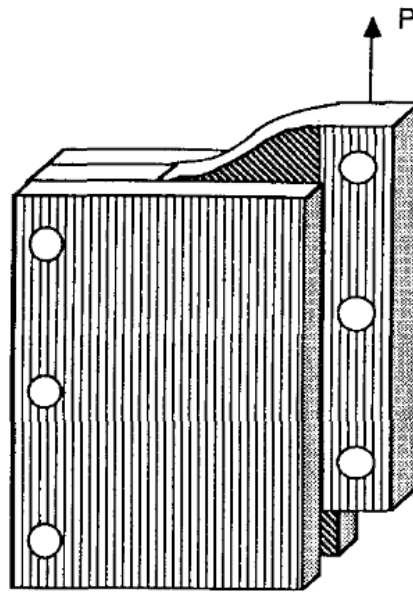


Figure 2.74. CRS method for pure mode III [152]

There are many methods to determine mixed mode-I-II-III fracture toughness of materials which are ability to pure three modes or combination of them. For example arcan and CT methods gives possibility to measure fracture modes which are mode I, II, III and combination of them [131], [147]. One another method is Compact Tension Shear Rotation (CTSR) specimen is also named all fracture mode (AFM) specimen which enable to mode I,

mode II and mode III [153]. The most important feature of these methods is that the values of mixed modes can be determined without using separate test methods for each mode. The Arcan method provides to measure fracture toughness values of material in each mode with additional arrangements. Also, Arcan specimen test methods rearranged for enabling for measuring mode I, II, III toughness of material [154]. Furthermore, a new modified compact tension specimen was developed. By using CT and additional apparatus together that gives the possibility of measuring toughness values of mixed-mode in mode I, II, III [155], [156]. The full mixed mode fracture toughness methods are shown in Figures 2.75-2.77.

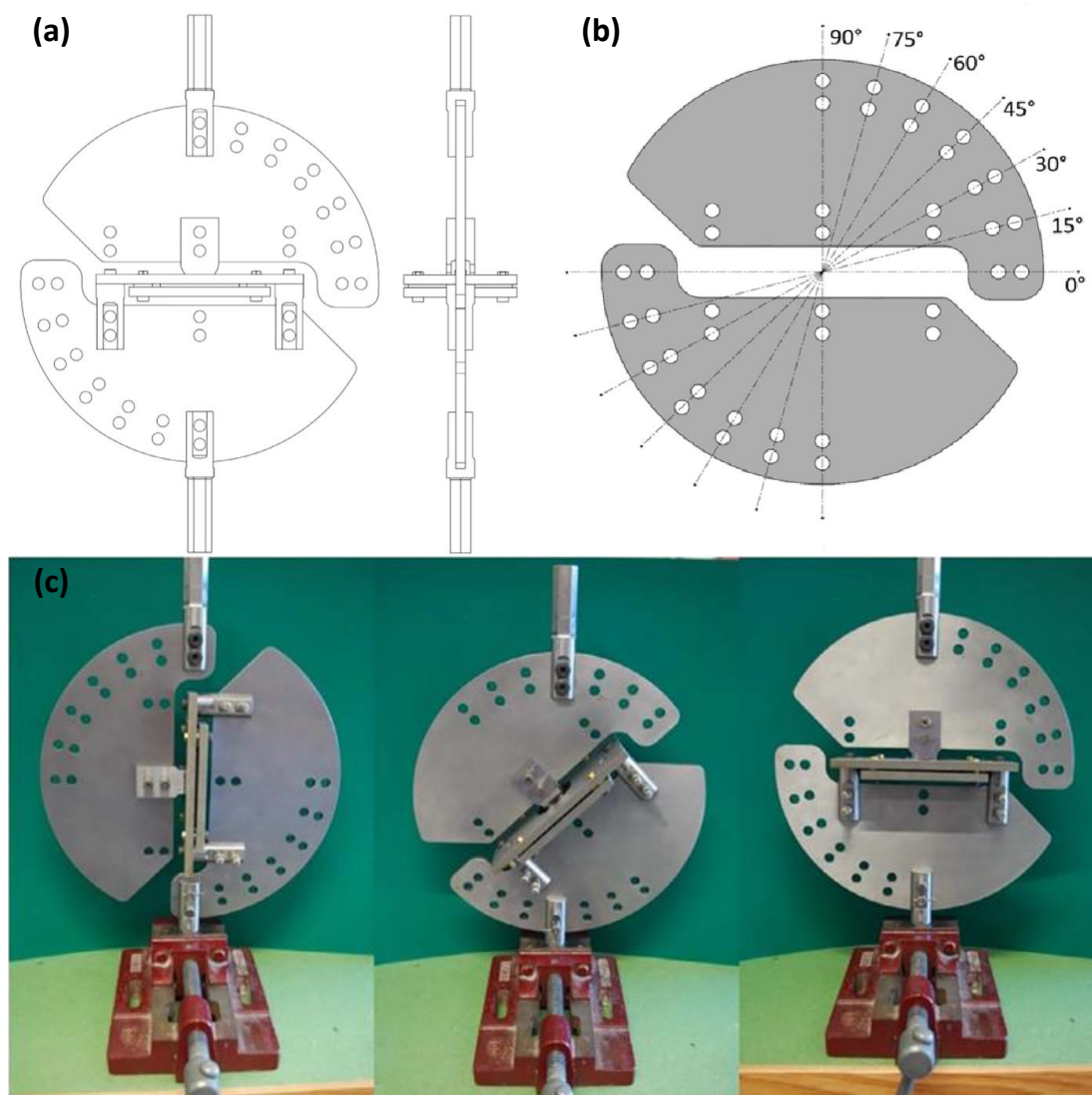


Figure 2.75. Mixed modes fracture toughness measurement methods: Arcan specimen (a) Arcan test geometry ,(b) Arcan plate loading directions, (c) experimental loading conditions [157]

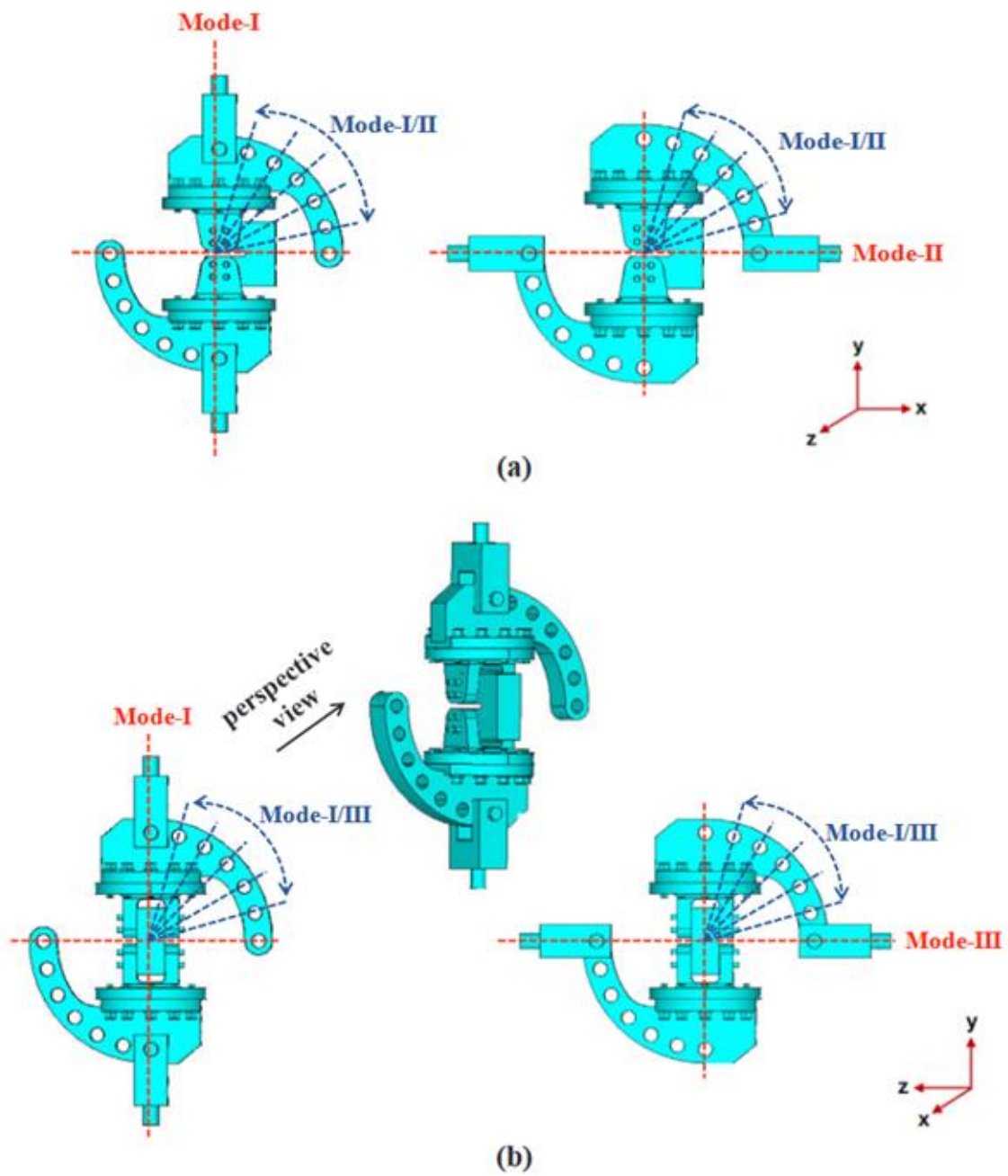


Figure 2.76. Overall views of the initial version of the test assembly for different mixed mode loading conditions (a) Mode-I/II, (b) Mode-I/III [79]

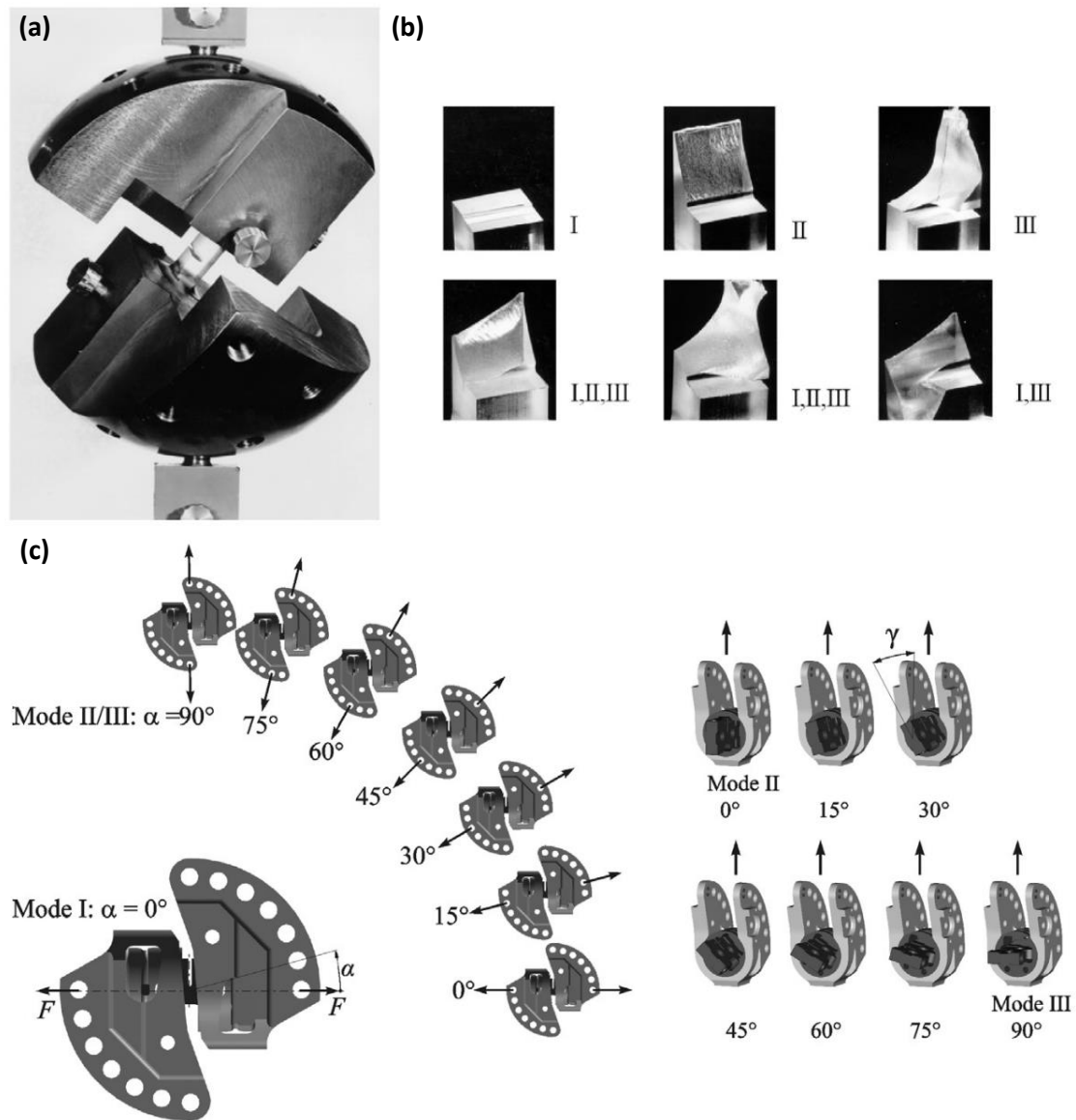


Figure 2.77. (a) Loading device for All fracture mode (AFM) specimen. (b) AFM-specimen, broken under different Modes, (c) Loading device: Adjustment of the ratio of Mode I to Mode II/Mode III [158]

There are many methods to determine the fracture toughness of a material. However, most of these methods are not useful when the body has curvature such as pipes or pressurised tanks. According to the literature review, curved compact tension (CCT) and pipe ring notched bending (PRNB) measurement methods were found to be more suitable for curved surfaces among the methods. In this study, these methods were preferred to determine the fracture toughness of a type III pressure tank.

3. METHODOLOGY

3.1 Materials

In this thesis, a type III high-pressure composite tank was used to investigate its tensile and fracture properties. The pressure tank has an actual volume of 6.8 liters, actual weight is 4.1 kg, a length of 537 mm, an outer diameter of 157 mm, working pressure of 300 bar, but the tank was tested with 500 bar hydraulic test pressure. The tank and its dimension are shown in Figure 3.1.



Figure 3.1. Type III composite pressure tank and its geometry

The manufacturing stages of the tank include punching, drawing, heat treatment, CNC flow forming spinning, and inner surface treatment, and fiber overwrapping with high precision. As seen in Figure 3.2, the main body consists of an aluminum 6061 alloy liner. The thickness of the tank is 10 mm, which consists of 1.6 mm aluminum liner and 8.4 mm composite layers. This liner was overwrapped with carbon and glass fibers with resin at different winding angles. These composite layers make it stronger than metal tanks or type I tanks. So, carbon and glass fibers improve tensile and fracture properties of the tank positively. Both the liner and fiber material's elastic properties are given in Table 3.1. Where E is the modulus of elasticity, ν is the Poisson's ratio and G is the shear modulus in the x , y , and z direction.



Figure 3.2. The type III composite tank: (a) the inlet port, (b) overview of the tank, (c) the inner of the tank, (d) the magnified view of the liner and composite layers

Table 3.1. Liner and fiber elastic properties of the composite pressure tank

Material	E_1 [GPa]	E_2 [GPa]	E_3 [GPa]	G_{12} [GPa]	G_{13} [GPa]	G_{23} [GPa]	ν_{12}	ν_{13}	ν_{23}
<i>Aluminum6061</i> [62]	57.55	57.55	57.55	21.62	21.62	21.62	0.33	0.33	0.33
<i>Carbon-epoxy</i> [61]	141.00	11.40	11.40	5.00	5.00	3.08	0.28	0.28	0.40
<i>Glass-epoxy</i> [61]	38.500	16.500	16.500	4.700	4.700	4.700	0.27	0.27	0.40

The tank liner was strengthened with fibers by wrapping different angles that are named hoop and helical winding. Hoop winding was termed a high-angle helical winding wound at a 90°

angle, usually 85° to 90° degrees. On the other hand, helical winding is the value of α lies in the range of 0° to less than 90° , or between 5° and 85° angles. Helical and hoop winding participate in carrying axial and radial loads of pressure vessel, respectively [159], [160]. The carbon-epoxy laminate was built using angle-ply layers with fibers oriented at positive, negative, and hoop directions. Ply layers and ply angle orientation of composite tank with liner and fiber layer are illustrated in Figure 3.3.

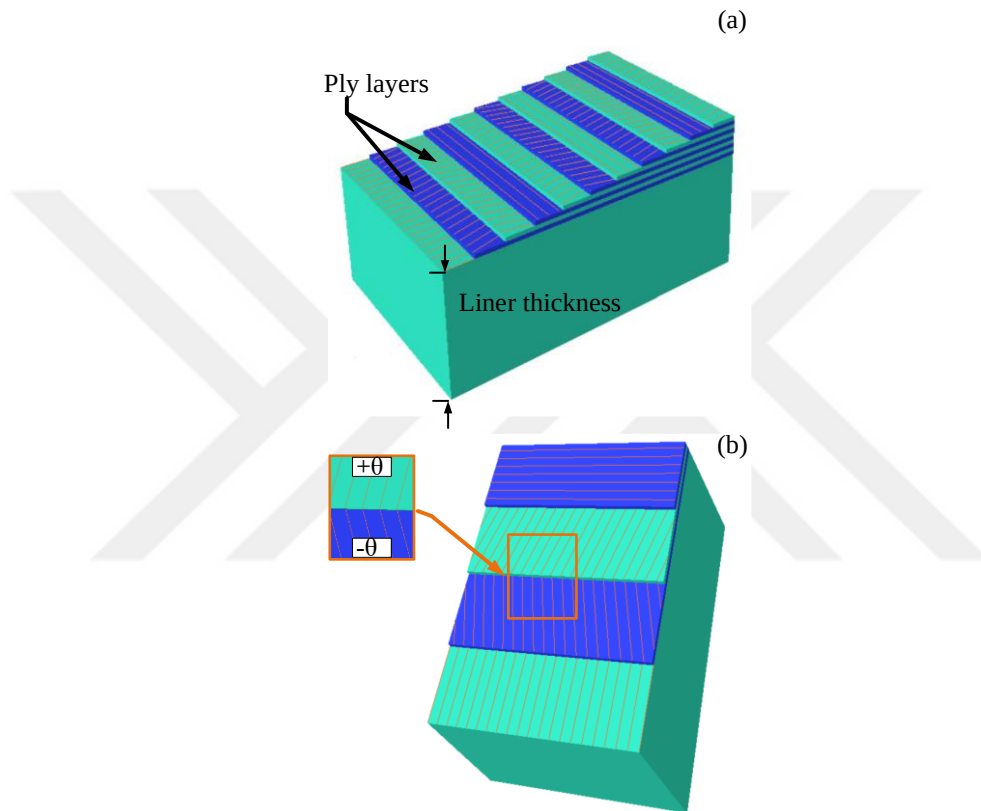


Figure 3.3. (a) Laminated composite plate, (b) ply angle orientation

The composite tank body consists of 42 fiber layer with 1.6 mm aluminum 6061 liner. The layer orientation is $[45/-45]_{19}$ with T700 carbon fiber and the last four layers were used glass fiber with $[90]_4$ winding orientation, and it is illustrated in Figure 3.4.

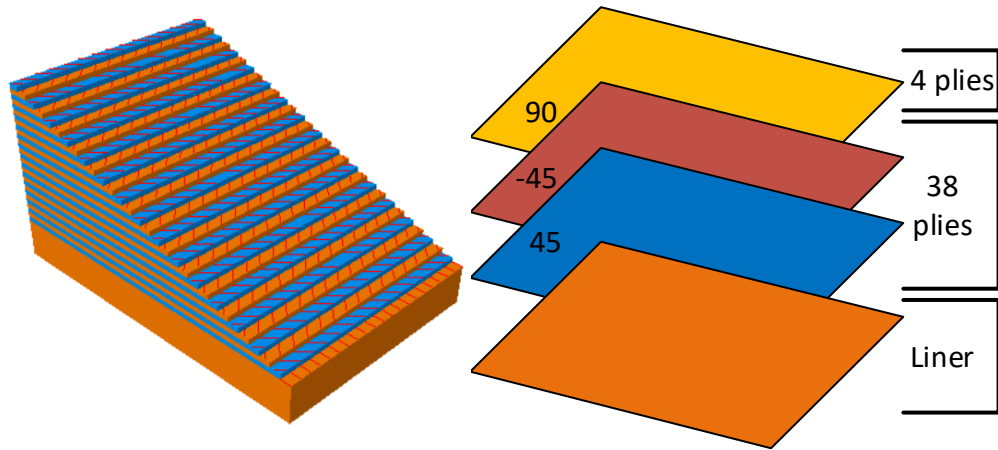


Figure 3.4. Layer orientation of type III pressure vessel

3.2 Universal Tensile Test Machine

Universal tensile test machines are used to determine material properties with experimental studies, and tensile and compression tests can be performed. The Shimadzu AGS-X tensile test machine is able to apply up to 100 kN force as tensile or compression form. The machine comprises basically stroke limiter, a load cell, two common joints, two jigs (Jaws), a main operation panel, and an emergency stop button. Stroke limiter permits to adjust stroke range of crosshead. The load cell measures test force with $\pm 0.5\%$ accuracy. Common joints allow the load to be transferred to the specimen. The jaws can be easily changed to perform tensile and compression tests. Two jaws are used to grip the specimen. The main panel enables control of the movements of jaws upward and downward direction, besides allowing storing the test data and changing specimens without a computer connection. The emergency stop button cuts the power supply. In an emergency, this stops the movement of the crosshead immediately. The universal test machine and its parts are illustrated in Figure 3.5. To implement the SDT method, the machine was used to create tensile force. In addition, the machine has the capability to carry out fracture toughness tests using appropriate apparatus. Therefore, the universal tensile machine would be used for carrying out fracture toughness experimental studies.

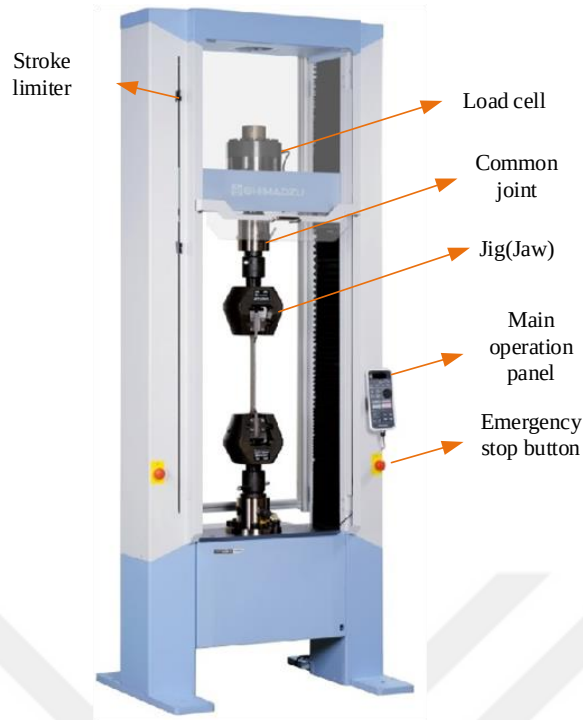


Figure 3.5. Universal tensile test machine

3.3 SDT Specimen

The tensile test is generally used to determine and characterize the tensile properties of flat materials, but the test method is not useful for circular shapes. The split disk tensile method (SDT) is proposed to determine mechanical properties of circular shape material [161]. The SDT was used to investigate the hoop tensile stress of the tank. This method was utilized by preparing ring specimens from the tank using ASTM D 2290 test method instructions. According to the standards, the specimen should be full diameter and full thickness and have narrowed two radius areas symmetrically or a reduced (gage) area. The geometry of ring specimen and determined dimensions of cross-sectional ring specimen are shown in Figures 3.6 and 3.7, respectively.

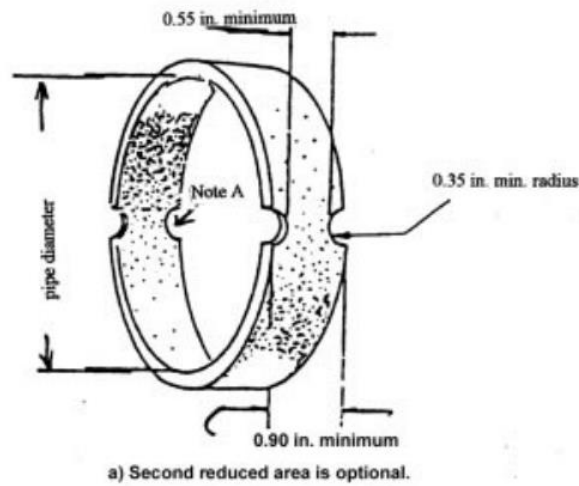


Figure 3.6. ASTM D 2290 standards of ring specimen [162]

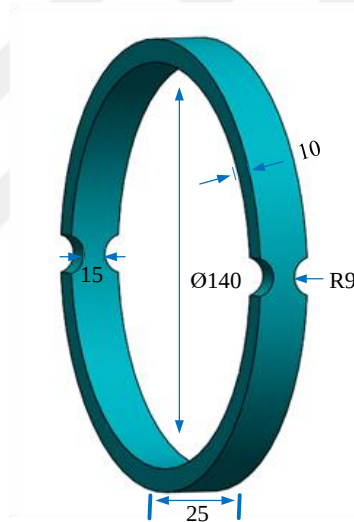


Figure 3.7. 3D model of ring specimen

Hoop tensile stress was calculated using load force and load application area relation which is given in following equation. As seen in Figure 3.8, the hoop tensile stress can be determined using the ratio of load force and cross-sectional area. The reduced area stress is given in Equation 3.1. Where F is load force, t is thickness, w is width, and A is two cross-sectional area, in mm^2 [63]. Three ring specimen would be prepared by cutting off from the pressure tank is illustrated in Figure 3.9.

$$\sigma = \frac{F}{2 \cdot \text{Area}} \quad (3.1)$$

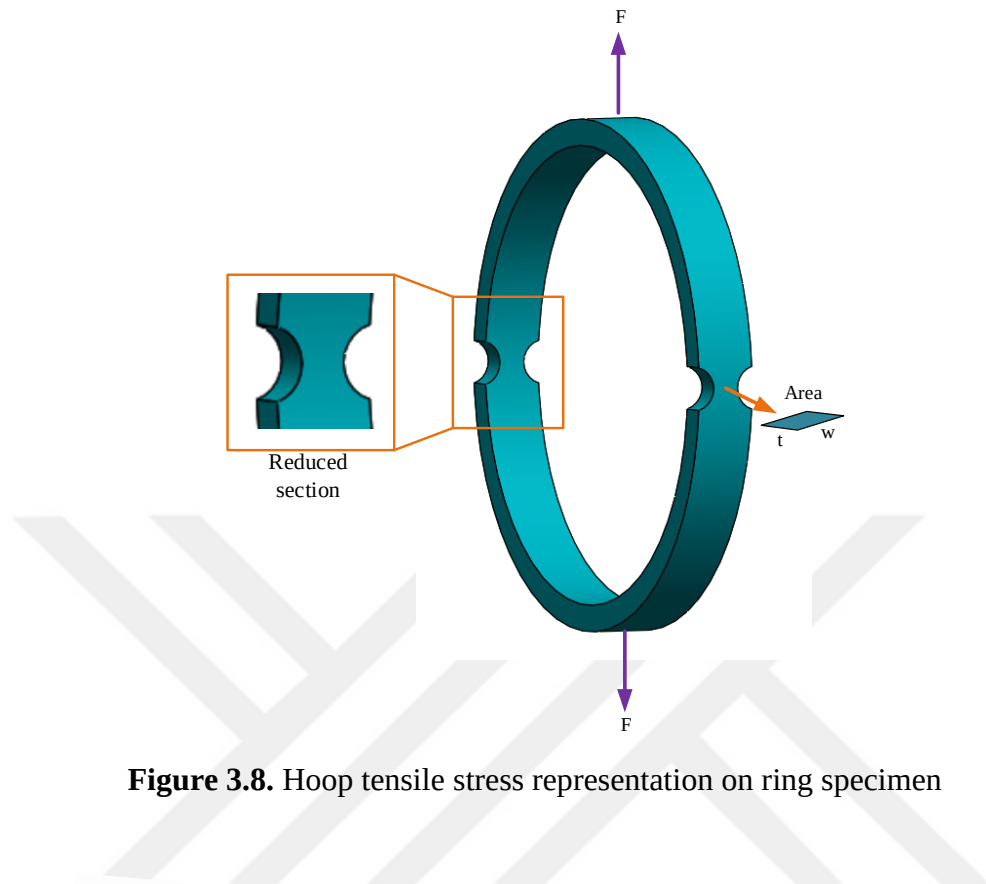


Figure 3.8. Hoop tensile stress representation on ring specimen

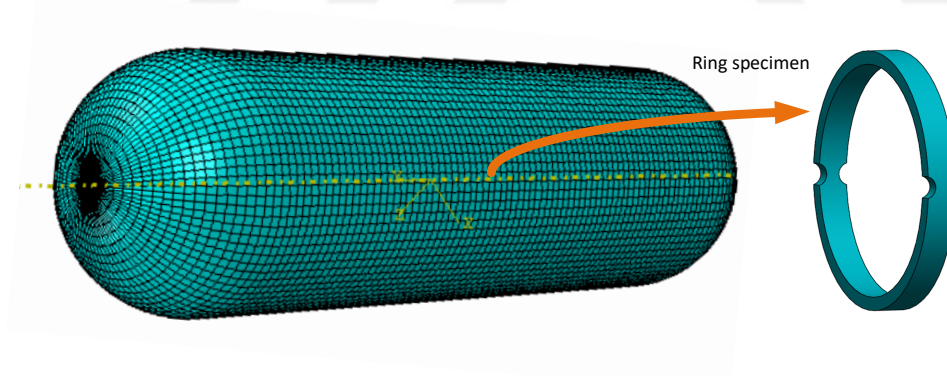


Figure 3.9. Cutting off ring specimen from the pressure tank

The ring specimens were prepared considering the ASTM D2290 standard. The parting operation with lathe is shown in Figure 3.10. The reduced areas were created with CNC machine with a 9 mm diameter tool. Three ring specimens were cut from the pressure tank for experimental studies, and the specimens are displayed in Figure 3.11.

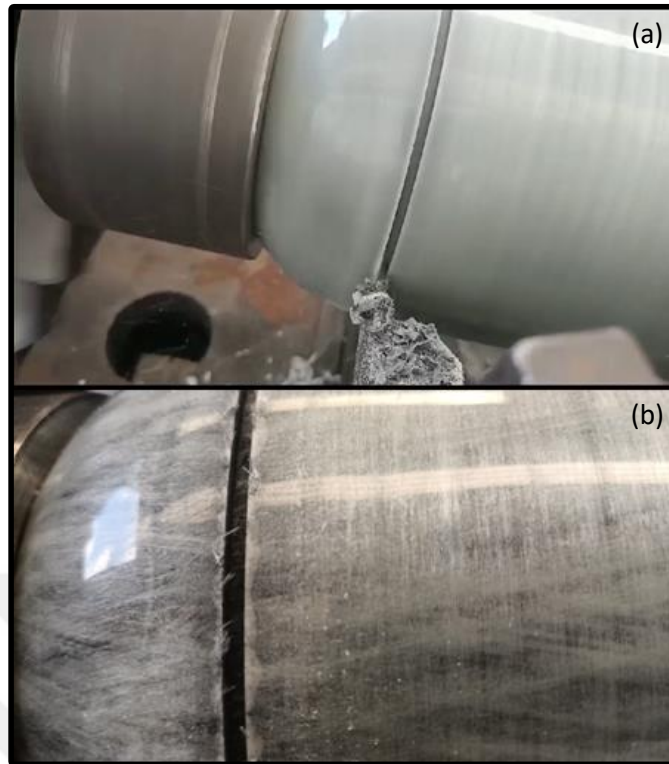


Figure 3.10. Parting and cutting operation for ring specimen



Figure 3.11. SDT specimen or ring specimen

After lathe and CNC operations, the final form of ring specimen was produced in accordance with the standard is shown in Figure 3.12.



Figure 3.12. Ring specimen

3.4 SDT Fixture

The SDT fixture shown in 3D Figure 3.13 was designed with Solidworks in order to connect the tensile test specimens to the universal tensile machine in a suitable way and to carry out the experiments. SDT fixture mainly consists of five parts: upper tensile loading link, lower tensile loading link, two split rigid disks, and SDT specimen. Upper and lower tensile loading links are used for implementing tensile force on the body. Split disks allow the ring specimen to be subjected to force and break away from the reduced area on the specimen. Thus, the stress of the SDT specimen in the hoop direction is determined. 4140 reclaimed steel was used in the production of the fixture. The mechanical properties of 4140 steel are given in Table 3.2 [163]. Figure 3.13 shows the picture of the designed SDT fixture. The SDT fixture was manufactured based on the ASTM D2290 standard for experimental study. The specimen was placed in an SDT fixture. Reduced areas and horizontal split lines are the same route. These areas are where the break occurs due to maximum stress [164].

Table 3.2. Mechanical properties of AISI4140 steel

Material Properties	
Density ($\times 1000 \text{ kg/m}^3$)	7.7-8.03
Poisson ratio	0.27-0.30
Elastic modulus (GPa)	190-210
Ultimate strength (MPa)	655.0
Yield strength (MPa)	417.1
Elongation (%)	25.7
Reduction in area (%)	56.9

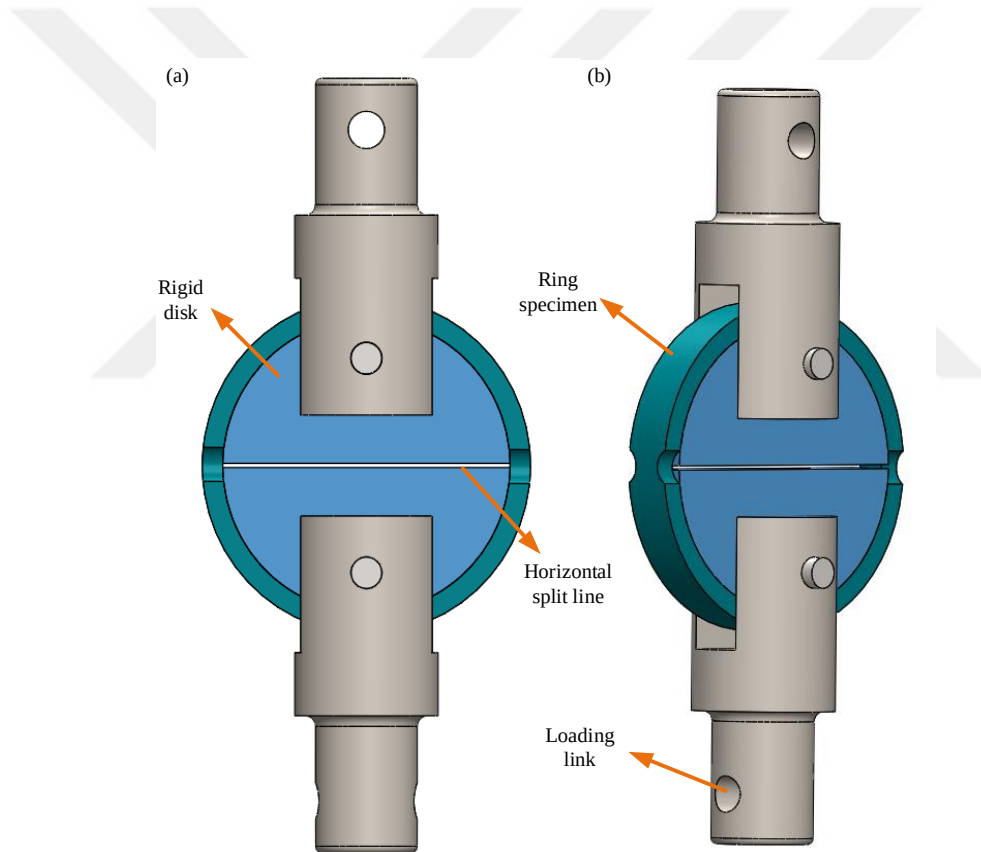


Figure 3.13. SDT fixture: (a) SDT specimen, (b) the fixture loading conditions

3.5 Fracture Methods

In this study, CTT, CT, and PRNB methods were used to determine the mode I fracture toughness of the type III composite pressure tank. Since the CT method is a common and accepted method and can be used to determine the fracture toughness of both flat plates and curved surfaces, therefore the first experimental studies were carried out with the CCT method based on ASTM D5045. The results obtained were compared with CT modeled as a flat plate to see the effect of curvature on the results. Subsequently, experimental studies were carried out with the PRNB method. PRNB is usually designed to measure fracture toughness with ASTM E 1820 using the CTOD approach. Unlike the classical PRNB method was prepared using the linear elastic fracture mechanics approach in this study. With the numerical model of this method, the crack size and internal pressure variation in the body of the type III composite pressure tank were also investigated. Thus, despite the inadequate definition of ASTM e 1820 standard for pipes or pressure tanks, the fracture toughness of the pressure vessel was determined and the criticality of the crack length for the pressure vessel was evaluated by numerical studies.

3.6 CCT Preparation

Compact tension specimen (CTS) method is a useful method for measuring fracture toughness value of a material. The CTS is a well-known method and it is used to characterize the fracture behaviors of various materials [165]. Specimen of CTS were designed and configured based on ASTM D5045 standards. The specimen can be cut off in flat or curved form and it stated that these shape forms do not affect experiment results [166]. As seen in Figure 3.14, there are two holes and a notch on the specimen. The holes are loading point that utilized to apply unidirectional load to the specimen. The notch is used to determine the crack length-width ratio. In designed CCT, a is determined as 30 mm, W is scaled as 60 mm. The specimen has a curvature radius of 70 mm. The specified dimensions of CTT are shown in Figure 3.15 in detail.

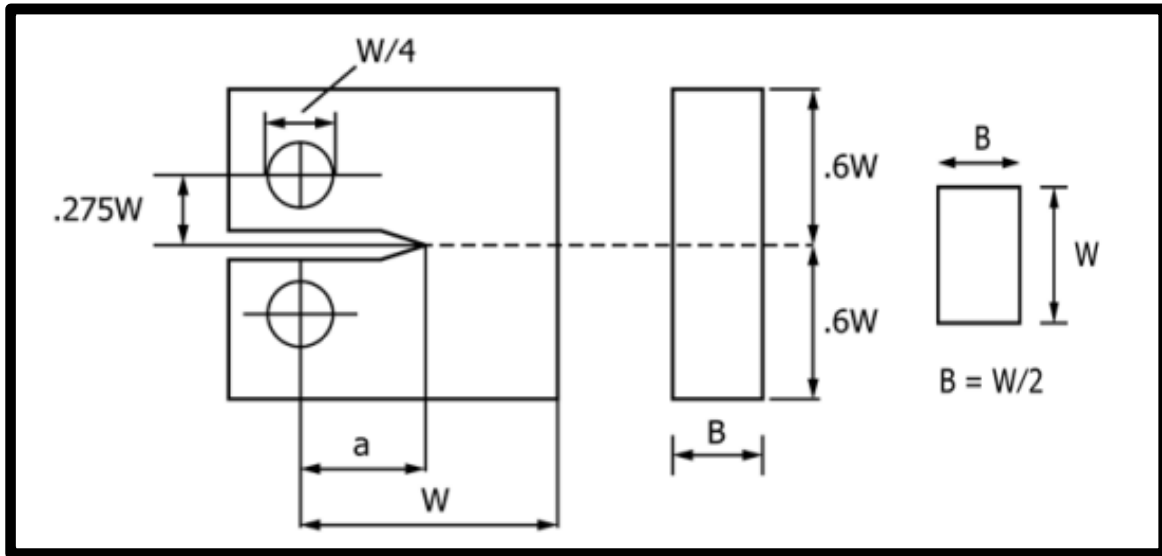


Figure 3.14. Curved compact tension configuration based on ASTM D5045 standards

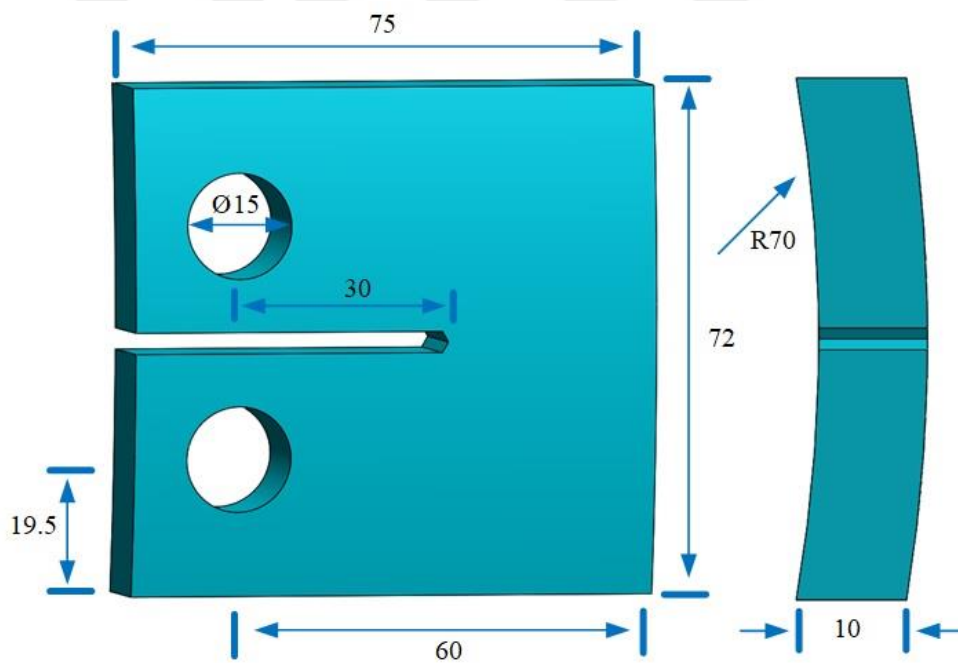


Figure 3.15. CCT 3D model

Hoop and axial stresses occur in the body of a tank due to internal pressure. Since the hoop stresses are higher in the tank, mode I crack is more critical. Therefore, the direction of fracture sampling is important when taking specimens from the tank. To investigate the opening mode behavior, specimens were taken as shown in Figure 3.16.

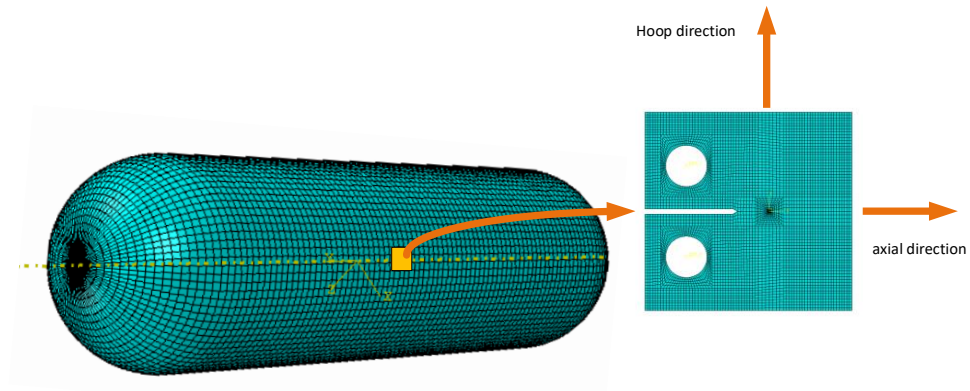


Figure 3.16. Preparing CCT specimen from the pressure tank

There are three different modes to characterize the fracture behavior of a specimen. By using an appropriate fixture, the fracture modes can be measured with CCT. However, this study focused on determination of critical mode I, known as opening mode. To evaluate mode-I fracture toughness of the material, unidirectional force is applied from both sides of the specimen using the CCT method. Load application is illustrated is shown in Figure 3.17.

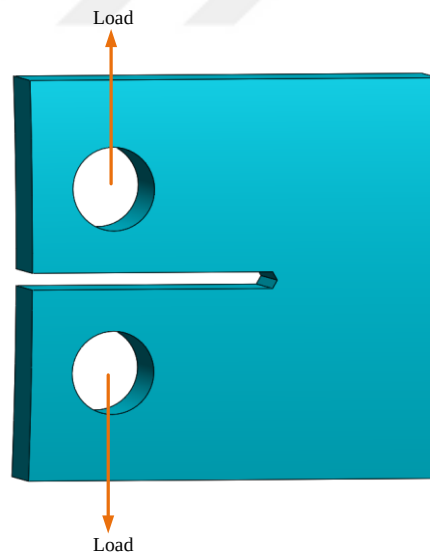


Figure 3.17. CCT 3D model (Opening mode)

After determining the dimensions of the CCT specimen and fixture, production processes were started. The sample was cut based on the standards of the CNC machine and hole drilling operations were performed with a milling cutter. A picture from the specimen

manufacturing stage is shown in Figure 3.18. The final form of the specimen prepared for the experiment is shown in Figure 3.19.



Figure 3.18. CCT specimen preparation using milling machine

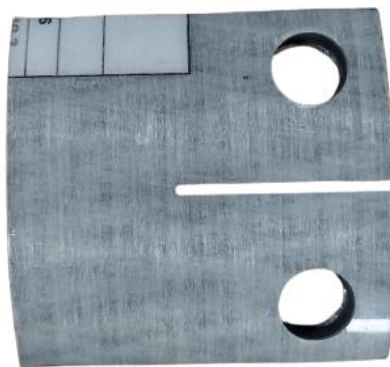


Figure 3.19. CCT specimen

3.7 CCT Fixture

The CCT fixture consists of three main parts, the top load link, the bottom load link, two connecting pins, and the specimen. Figure 3.20 shows the specimen mounted on the fixture. When the unidirectional load is applied using the loading links, the load is transferred to the specimen and it enforces the specimen to reveal the Mode I failure behavior. Figure 3.21 shows the final form of CCT specimen with its fixture. It was manufactured based on ASTM D5045 standards. Before experiments, the specimen The CCT was attached to the fixture via pins.

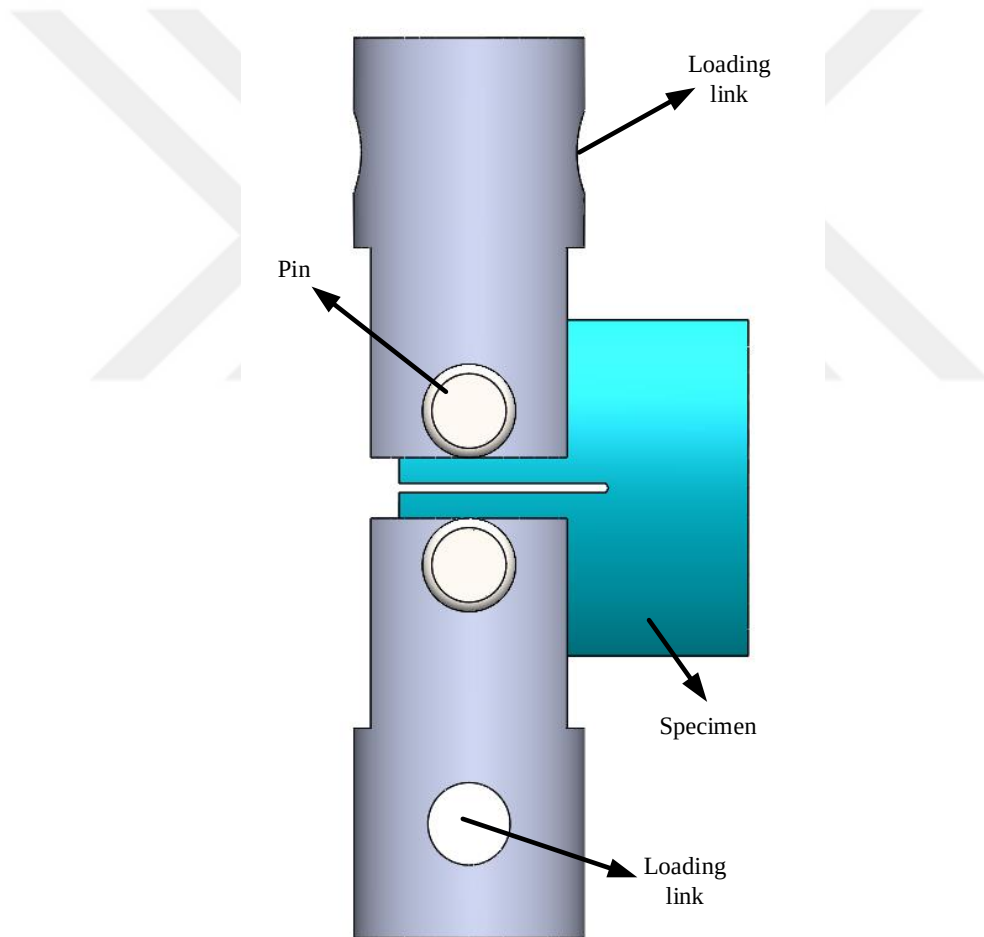


Figure 3.20. 3D draft of CCT fixture with the specimen



Figure 3.21. Curved compact tension with its fixture

3.8 Fracture Energy Calculation

The fracture energy of a material can be calculated using the following equations by plane strain assumptions for orthotropic material. Where, P is the applied load, a is the crack length, w is the width, t is the thickness, and $f_I(a/w)$ is the correction factor of the CTS under mode-I loading conditions. Equations (3.2) and (3.4) could be used to calculate the mode-I stress intensity factor and strain energy release rate for the orthotropic material under plane strain conditions, respectively.

$$K_I = \frac{P\sqrt{\pi a}}{wt} f_I(a/w) \quad (3.2)$$

General form of correction factor $f_I(a/w)$ was defined in Equation (3.3) for CTS method [94]. Where x is ratio of crack and width ($\frac{a}{w}$). E_I is the effective elastic modulus of the pressure tank along the x-axis of the high-pressure tank.

$$f_I(x) = \left(\frac{2+x}{1-x^{3/2}}\right)[0.886 + 4.64x - 13.32x^2 + 14.72x^3 - 5.64x^4] \quad (3.3)$$

$$G_I = \frac{K_I^2}{E_I} \quad (3.4)$$

The tank was considered as an orthotropic linear elastic material and the composite plate stiffness equations were used to calculate the E_I values [31]. Figure 3.22 shows a schematic cross-section of a Type III high-pressure tank structure. In this notation, N is the number of lamina, t is the total thickness of the body, and Z_i is the distance of the i -th lamina from the center plate. The first layer is referred to as the metal liner, while the following layers correspond to the fiber-reinforced resin layers in various directions. Each lamina is in a state of planar stress due to the small thickness of the lamina compared to the in-plane dimensions of the plate and the stress conditions in high-pressure vessels. Consequently, following Equations (3.9), (3.10) can be used to calculate mode I and II elastic modulus of a composite structure.

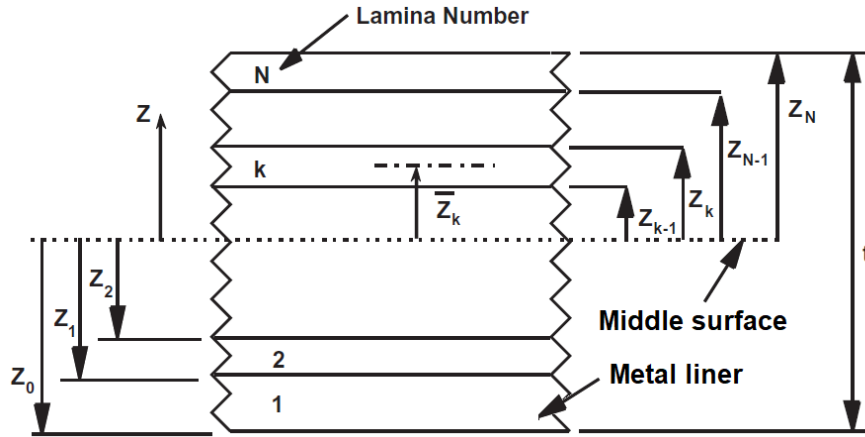


Figure 3.22. Cross-section of the of type III pressure tank [31].

Using composite plate stiffness equations for computing E_I [27]. Where N is reactant forces, M is reactant moment, A is plane stiffness matrix, D is bending stiffness matrix, B is bending-extension coupling matrix, ε is strain, K is curvature, N_x , N_y , and N_{xy} are the tensile and shear forces [N], and M_x , M_y , and M_{xy} are the moments [N/m]. The superscript k indicates the lamina number.

$$\begin{pmatrix} N \\ M \end{pmatrix} = \begin{pmatrix} A & B \\ B & D \end{pmatrix} \begin{pmatrix} \varepsilon \\ K \end{pmatrix} \quad (3.5)$$

$$\begin{pmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{21} & A_{22} & A_{26} & B_{21} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{21} & B_{22} & B_{26} & D_{21} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{pmatrix} \begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \\ K_x \\ K_y \\ K_{xy} \end{pmatrix} \quad (3.6)$$

$$\begin{aligned} A_{ij} &= \sum_{k=1}^N (\bar{Q}_{ij})_k (z_k - z_{k-1}) = \sum_{k=1}^N (\bar{Q}_{ij})_k t_k ; i, j = 1, 2, 6 \\ B_{ij} &= -\frac{1}{2} \sum_{k=1}^N (\bar{Q}_{ij})_k (z_k^2 - z_{k-1}^2) = -\sum_{k=1}^N (\bar{Q}_{ij})_k t_k \bar{z}_k ; i, j = 1, 2, 6 \\ D_{ij} &= \frac{1}{3} \sum_{k=1}^N (\bar{Q}_{ij})_k (z_k^3 - z_{k-1}^3) = -\sum_{k=1}^N (\bar{Q}_{ij})_k t_k \bar{z}_k^2 + t_k^3/12 ; i, j = 1, 2, 6 \end{aligned} \quad (3.7)$$

Reduced stiffness matrix Q in lamina coordinates 1, 2, 3.

$$Q = \begin{bmatrix} E_I/\Delta & v_{12}E_{II}/\Delta & 0 \\ v_{12}E_{II}/\Delta & E_{II}/\Delta & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \quad (3.8)$$

Reduced stiffness matrix in laminate coordinates X, Y, Z. The transfer matrix is stated as:

$$[\bar{Q}] = [T(\theta)]^{-1}[Q][T(\theta)]^{-T} = [T(-\theta)][Q][T(-\theta)]^T$$

Where Δ is denoted as $\Delta = 1 - v_{12}v_{21} = 1 - v_{12}^2 \frac{E_{II}}{E_I}$

where Q is the reduced stiffness matrix, $\bar{Q}$ is the transfer matrix of Q for the laminate oriented at an angle θ with respect to the axis I. Provided that the axes of orthotropy coincide with the coordinates (x, y, z) of the laminate, the equivalent moduli of the laminate is given in the following Equation for mode-I and II.

$$E_I = \frac{A_{11}A_{22} - A_{12}^2}{tA_{22}} \quad (3.9)$$

$$E_{II} = \frac{A_{11}A_{22} - A_{12}^2}{tA_{II}} \quad (3.10)$$

$$V_{xy} = \frac{A_{12}}{A_{22}} \quad (3.11)$$

3.9 PRNB Specimen Preparation

The PRNB method is generally used to evaluate the mode-I fracture toughness of circular-shaped material. It is a more useful method when it is difficult to sample circular materials. Two cracks are present in the specimen to generate mode-I fracture behavior. The PRNB specimen and the experimental configuration are shown in Figure 3.23.

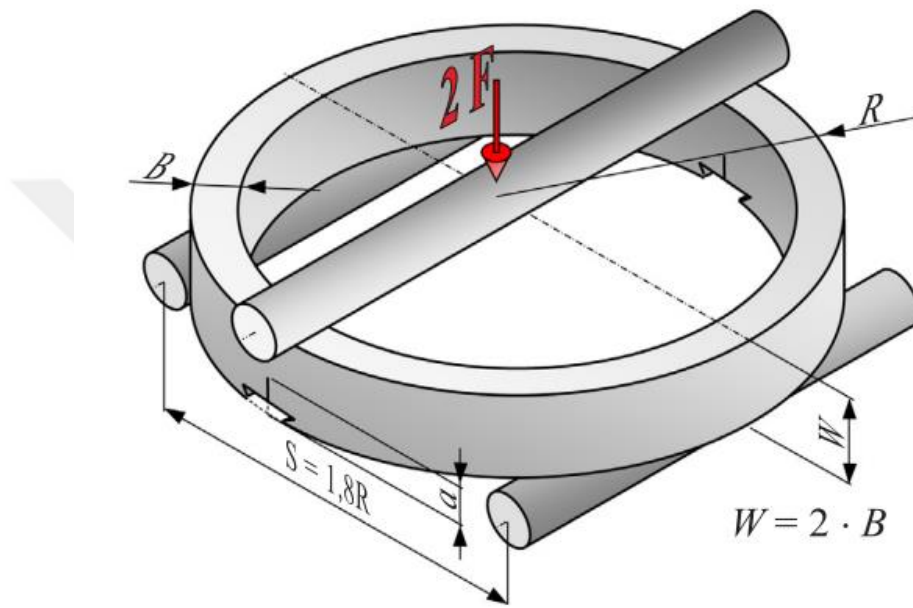


Figure 3.23. PRNB configuration based on ASTM standards [167]

For PRNB specimen preparation, the dimension of the specimen was determined and cut off from the tank in accordance with the ASTM standards. Firstly, ring-shaped specimens are cut from the tank and then two notches at 180 degree angle are formed on the specimen to be used in fracture toughness measurement. The mentioned preparation process is basically illustrated in Figure 3.24. The specimens to be used in the experimental studies are shown in Figure 3.26.

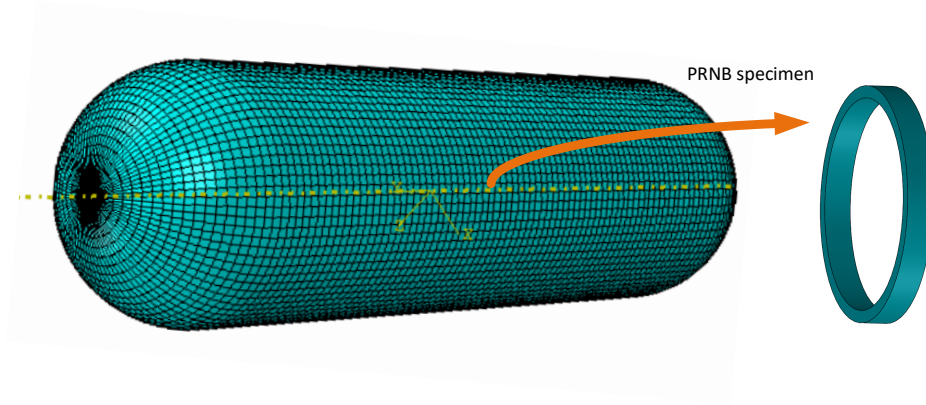


Figure 3.24. A schema of PRNB cutting off from the pressure tank

After PRNB specimen cut off from the tank, mode I fracture conditions are created by applying force to the crack point on the specimen. This force enforces the specimen to start crack propagation. Crack and loading points on the specimen are shown in Figure 3.25.

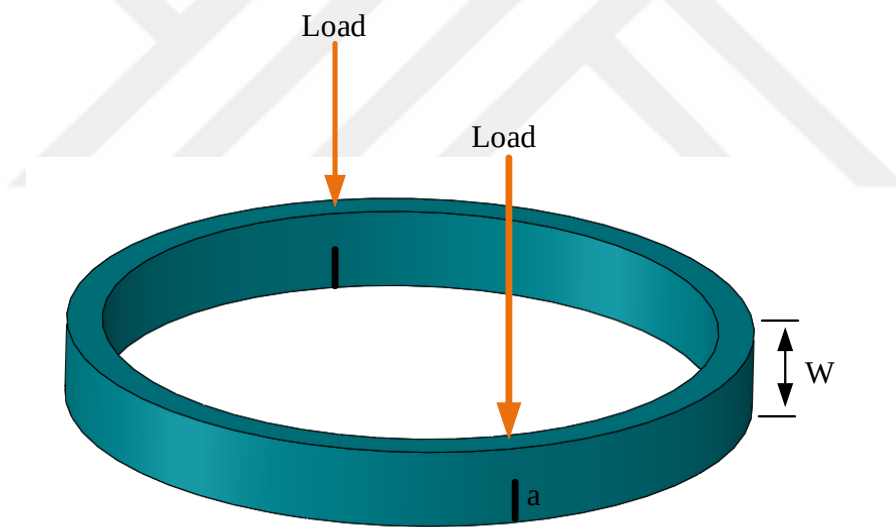


Figure 3.25. PRNB specimen 3D model



Figure 3.26. PRNB specimens

3.10 PRNB Fixture

PRNB fixture consists of a loading pin grip, a loading pin, a circular shape specimen and two support pins. As seen in Figure 3.27, the specimen is placed between a loading pin and two support pins. A load is applied to the crack point, the load enforces the specimen to create mode-I fracture behavior.

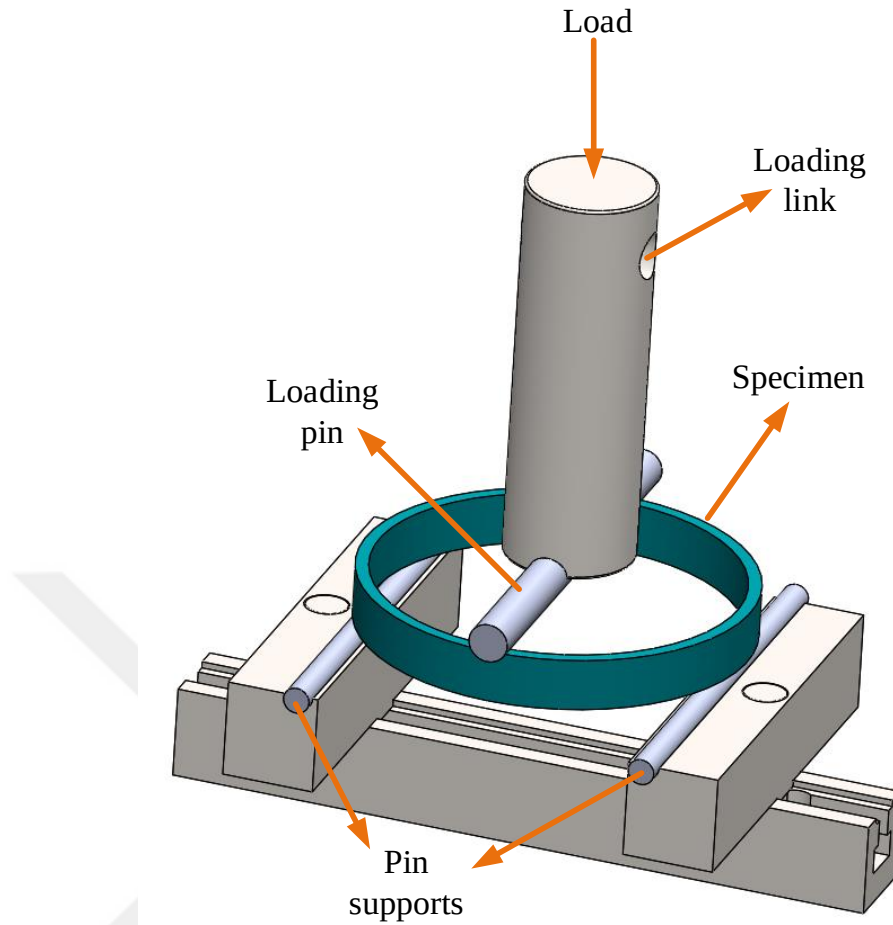


Figure 3.27. PRNB fixture with specimen

The experimental study outline is illustrated in Figure 3.28. It can be seen the used methods for circular shape materials. Hoop tensile stress values were determined using the SDT method. Additionally, the elastic modulus was obtained with the slope in the stress strain graph obtained from the SDT method. Then, fracture toughness values were determined using the CTS method, which is a common and mature method. The other fracture method, PRNB, was used by taking the fracture toughness value obtained with the CTS method as a reference. Thus, the PRNB correction factor was obtained. With the approach in this study, first the tensile stress of the material and then the fracture toughness were determined. When calculating of strain energy release rate, the elastic modulus of the material was used from the data in the hoop tensile test. In addition, it is shown how to obtain the fracture toughness value for PRNB, which is an alternative method that can be used to measure fracture toughness for curved-shaped materials.

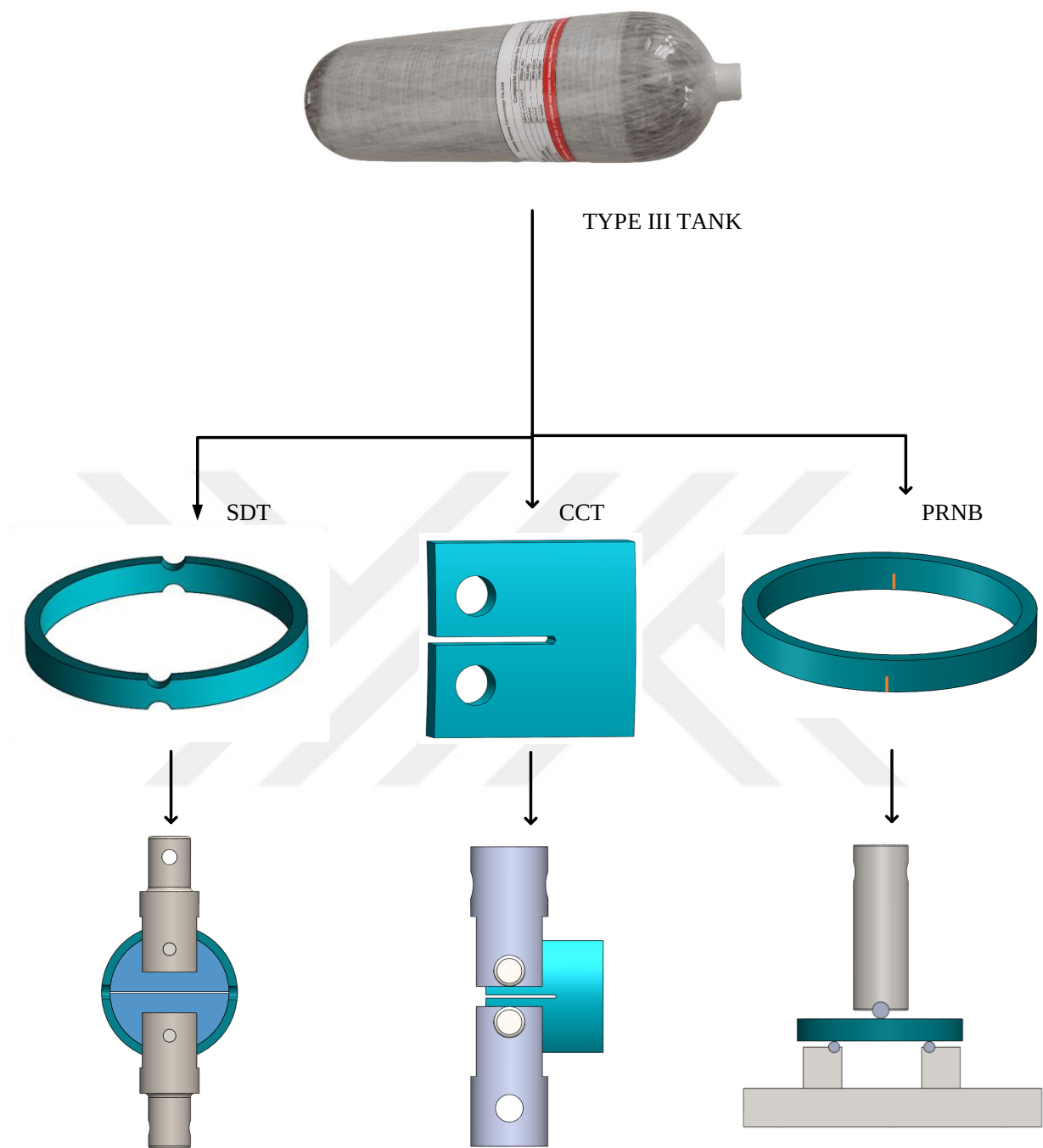


Figure 3.28. Outline of the experimental study

4. ANALYSIS AND DISCUSSION

4.1. Performing Tensile Tests With SDT Fixture

The split disk tensile test is a crucial experimental method used in materials science and engineering to determine the hoop tensile properties of tubular materials under tensile loading conditions. For determining hoop tensile property of type III composite tank, the tensile test of SDT specimens was carried out in the quality laboratory of ŞA-RA factory. The universal vertical tensile test machine has a 1000 kN load capacity. SDT specimens and fixtures were placed in a universal testing device. The SDT fixture transferred the load from the machine to the sample with both half disks to reach up to tensile load failure. As a result of the experiments, stress-strain graphs were obtained using the experimental data. The test setup of the related study is shown in Figure 4.1. The failed of the SDT specimen after the test is shown in Figure 4.2.



Figure 4.1. Universal tensile test machine and SDT test fixture



Figure 4.2. Failure of SDT specimen after tensile test

After the tensile test of the three SDT specimens, the first specimen reached to 157809 N, the second specimen reached to 140646 N and the third specimen reached 138533 N and then broke at the reduced section of the specimens. The graphs of the three specimens obtained after the test are given in Figures 4.3-4.5, respectively. In addition, the comparative results of the three specimens are shown in Figure 4.6.

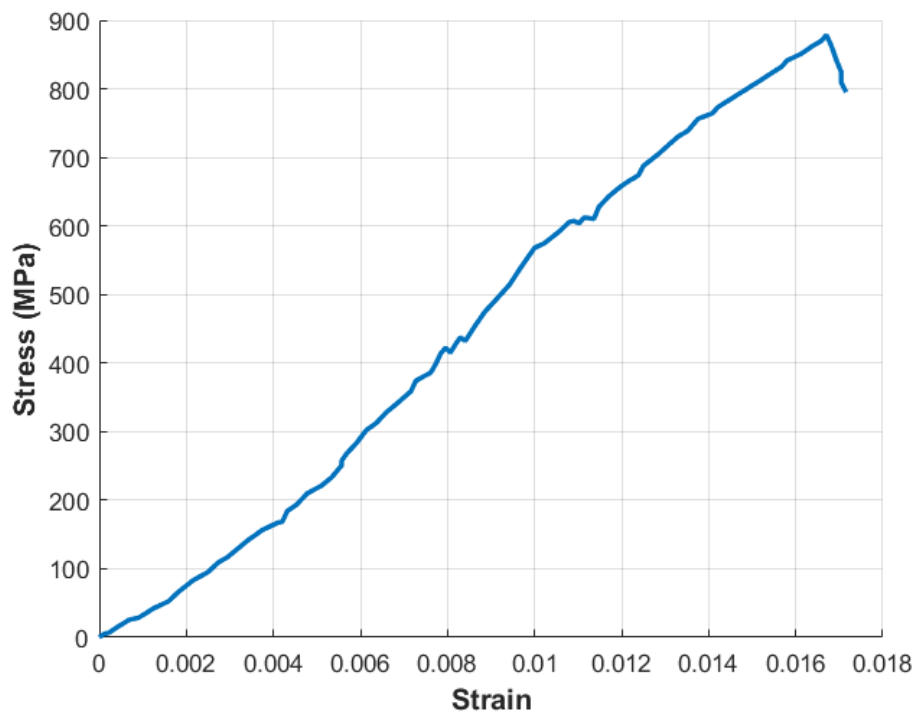


Figure 4.3. Stress-strain graph of first specimen

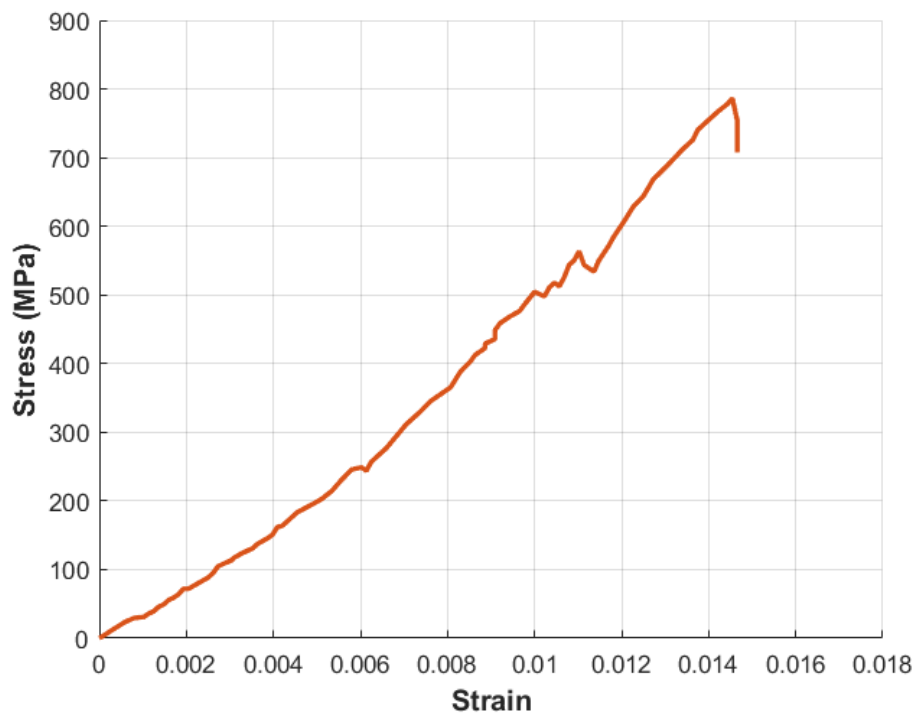


Figure 4.4. Stress-strain graph of second specimen

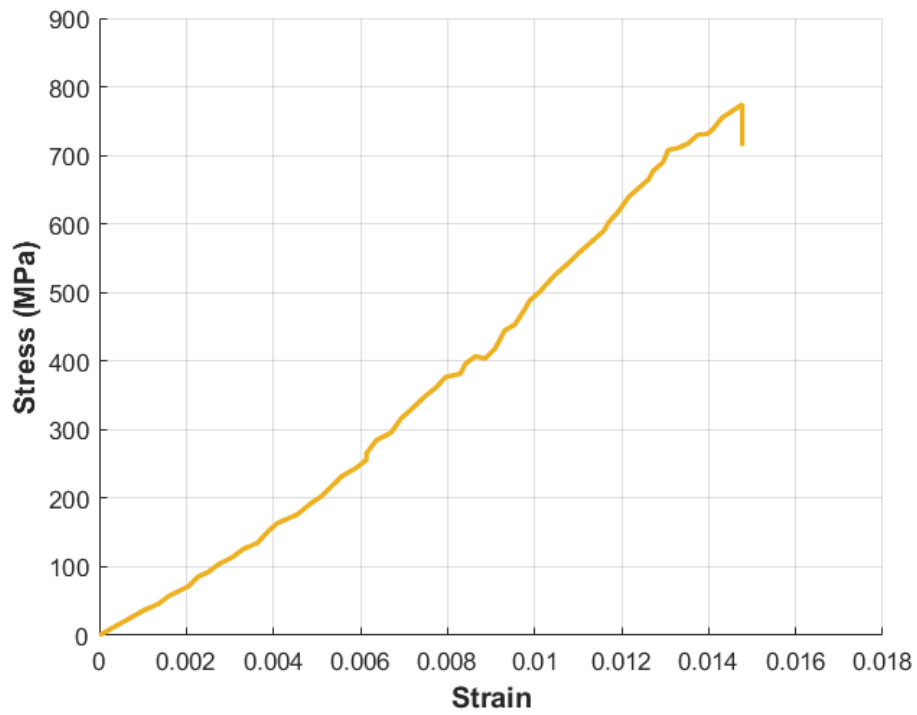


Figure 4.5. Stress-strain graph of third specimen

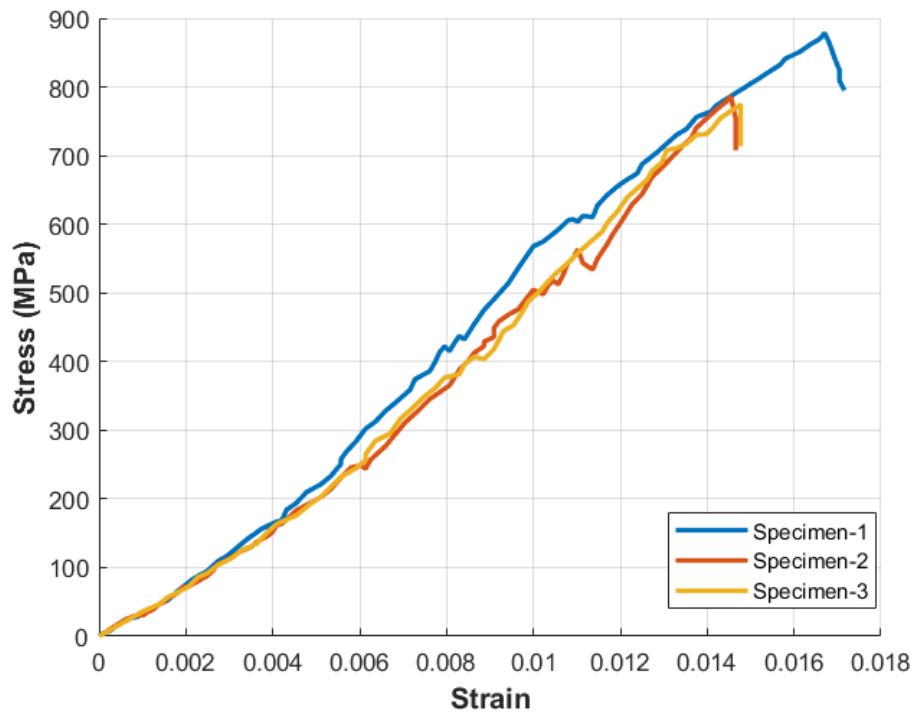


Figure 4.6. Stress-strain graph of the three specimens

The elastic modulus of the material was calculated by averaging the values obtained from the results of all three experiments. Using stress-strain relation, elastic modulus of specimen was determined as 53.116 GPa.

After tensile test the specimens, the failed specimens were showed in Figure 4.7, it can be seen that all specimens failed in the gage section because of high stress concentration. When stress was reached to its maximum strength, the specimen was started to break. The specimens consist of an aluminum liner, $[\pm 45]_{19}$ interlayers, and outer $[90]_4$ layers. The aluminum liner was ruptured due to exceeding ultimate tensile strength. The carbon fiber interlayers display fiber matrix debonding and delamination failures were observed. The outer glass fiber $[90]_4$ layers occurred fiber fracture. In addition, it can be seen that liner and interlayer carbon fiber layers broke at middle point of gage section, however the outer glass fiber layers failed at start point of gage section.

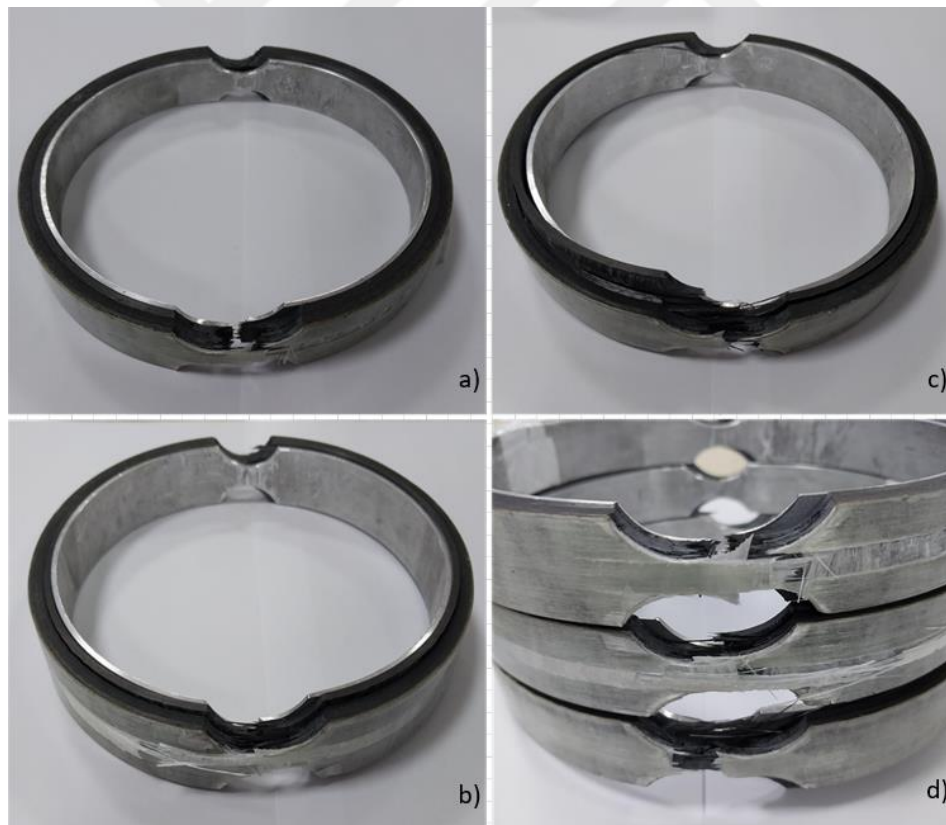


Figure 4.7. Failure of specimen after hoop tensile test: a) first specimen, b) second specimen, c) third specimen, d) hoop tensile specimen after the test

4.2. Performing Numerical Tensile Test With Dog Bone Specimen

Finite element analysis is an important tool in predicting and interpreting material behavior under different conditions, so this saves time and cost. Tensile Finite Element Analysis is a numerical simulation technique used to analyze the mechanical behavior of materials under tension. This technique involves dividing the material into small elements and solving the equations of motion for each element. The stress and strain distributions within the material can be obtained, as well as other mechanical properties such as load-deflection curves, fracture initiation, and failure modes. Tensile FEM analysis has been widely used to study the mechanical properties of various materials. The rapid development of computational techniques based on the finite element method has enabled the analysis of systems with complex geometry and design. This technique has been applied to analyze cyclically loaded gear vibrations, as well as to compute load-deflection curves and the interaction of arch structures with the filling. Additionally, miniature tensile testing techniques using FEM analysis have been implemented to predict the mechanical properties of materials and assess stress concentrations in various models. Furthermore, FEM has been gradually used for the analysis of textile flexible materials such as fiber, yarn, and fabric since the 1970s. Finite element modeling allows for accurate analysis of complex systems and structures' static and dynamic behavior, including the mechanical properties of materials under load application [168]. Dog bone tensile test model was created using Abaqus software. The numerical model was designed using D-638 ASTM standards. The numerical model geometry is given in Figure 4.8.

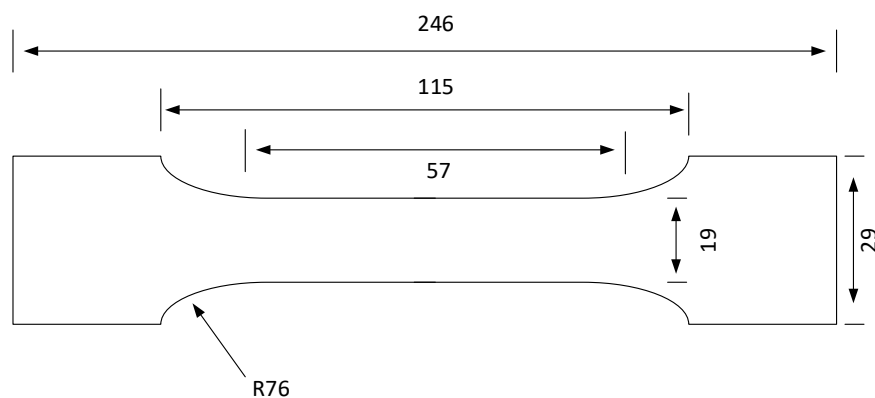


Figure 4.8. Dog-bone tensile test sample geometry

The finite element analysis was created with 2D shell modeling. Compared to 3D modeling, it can be created with simpler definitions and sections, which saves time. For this reason, it was designed with shell modeling and tensile test numerical studies were carried out for the material of type III composite pressure tank. The steps of design dog bone tensile model and material property definition are shared in Figures 4.9-4.12.

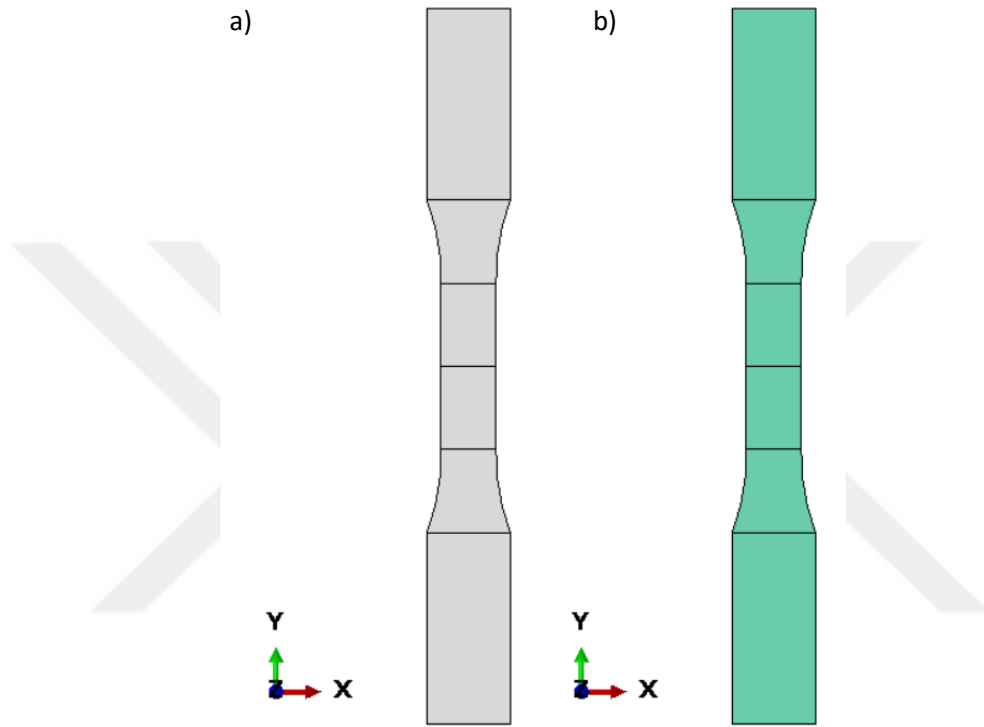


Figure 4.9. Tensile model: a) creation of dog-bone specimen, b) property definition

For composite tank modeling using Abaqus, the mechanical properties of carbon fiber, glass fiber, and aluminum 6061 materials were defined and the materials were made available in the model. As shown in Figures 4.10 and 4.11, the creation of the composite layer with the defined materials is shown. The composite tank structure consists of a total of 43 layers and the composite layers formed are illustrated in Figure 4.12.

Name: Carbonepoxy

Description:

Material Behaviors

Elastic

General Mechanical Thermal Electrical/Magnetic Other

Elastic

Type: Engineering Constants

☐ Use temperature-dependent data

Number of field variables: 0

Moduli time scale (for viscoelasticity): Long-term

☐ No compression

☐ No tension

Data

	E1	E2	E3	Nu12	Nu13	Nu23	G12	G13
1	141000	11400	11400	0.28	0.28	0.4	5000	5000

OK Cancel

Figure 4.10. Material definition for the model

Section integration: ☒ During analysis ☐ Before analysis

Thickness integration rule: ☒ Simpson ☐ Gauss

Plies Offset Shell Parameters Display

☐ Make calculated sections symmetric

	Ply Name	Region	Material	Thickness	CSYS	Rotation Angle	Integration Points
10	✓ Ply-10	(Picked)	Carbonepoxy	0.2	<Layup>	45	3
11	✓ Ply-11	(Picked)	Carbonepoxy	0.2	<Layup>	-45	3
12	✓ Ply-12	(Picked)	Carbonepoxy	0.2	<Layup>	45	3
13	✓ Ply-13	(Picked)	Carbonepoxy	0.2	<Layup>	-45	3
14	✓ Ply-14	(Picked)	Carbonepoxy	0.2	<Layup>	45	3
15	✓ Ply-15	(Picked)	Carbonepoxy	0.2	<Layup>	-45	3
16	✓ Ply-16	(Picked)	Carbonepoxy	0.2	<Layup>	45	3
17	✓ Ply-17	(Picked)	Carbonepoxy	0.2	<Layup>	-45	3
18	✓ Ply-18	(Picked)	Carbonepoxy	0.2	<Layup>	45	3
19	✓ Ply-19	(Picked)	Carbonepoxy	0.2	<Layup>	-45	3
20	✓ Ply-20	(Picked)	Carbonepoxy	0.2	<Layup>	45	3
21	✓ Ply-21	(Picked)	Carbonepoxy	0.2	<Layup>	-45	3
22	✓ Ply-22	(Picked)	Carbonepoxy	0.2	<Layup>	45	3
23	✓ Ply-23	(Picked)	Carbonepoxy	0.2	<Layup>	-45	3
24	✓ Ply-24	(Picked)	Carbonepoxy	0.2	<Layup>	45	3
25	✓ Ply-25	(Picked)	Carbonepoxy	0.2	<Layup>	-45	3
26	✓ Ply-26	(Picked)	Carbonepoxy	0.2	<Layup>	45	3
27	✓ Ply-27	(Picked)	Carbonepoxy	0.2	<Layup>	-45	3
28	✓ Ply-28	(Picked)	Carbonepoxy	0.2	<Layup>	45	3

Figure 4.11. Fiber layer orientation of the composite material

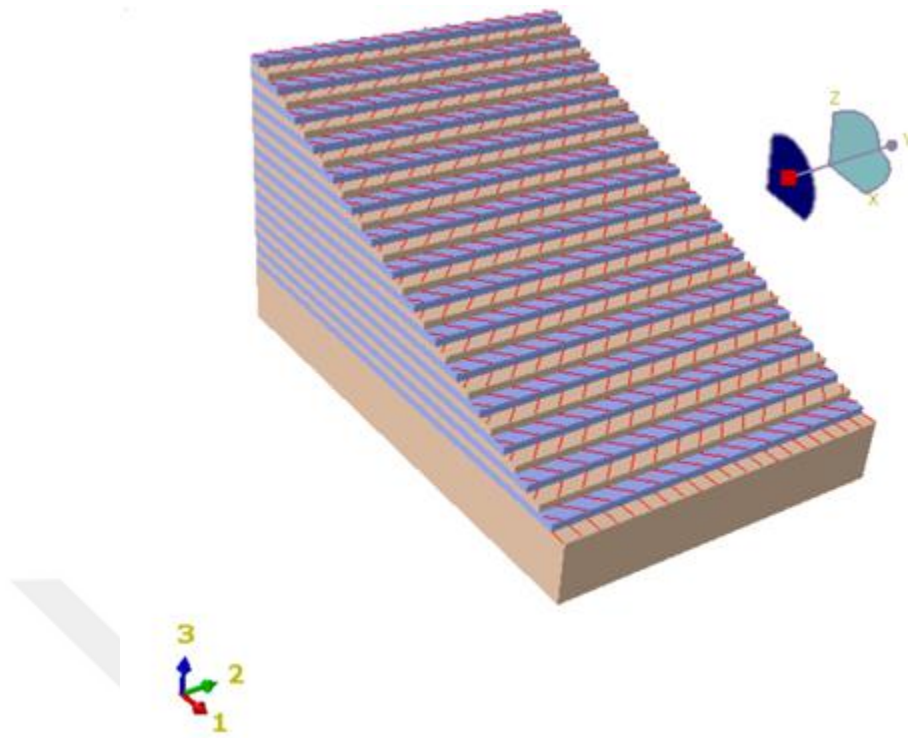


Figure 4.12. Displaying of fiber layer orientation

Boundary conditions were defined for tensile test conditions. One of the two reference points was used for load application and the other was used for fix point. Therefore, a 1000 N load was applied to the upper reference point and the other reference point was defined as encastre. In addition, since the upper point is only subjected to tensile force, it will move upwards. Therefore, the movement of this reference point is free in the upward direction, and other movements are restricted as displayed in Figure 4.13.a section. The model contains 1625 nodes, 1448 elements, and 1488 linear quadrilateral S4R elements. Mesh assignments of the model is shown in Figure 4.13.b section.

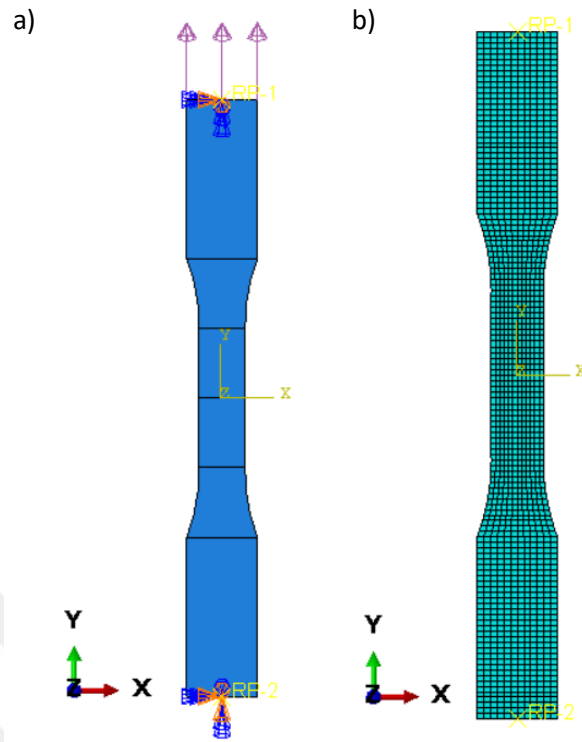


Figure 4.13. Boundary condition and mesh assignment of dog bone model

Finally, the model was run to obtain the elastic modulus of the composite pressure tank. 1000 N load value was defined to obtain the elastic modulus of the pressure tank material. As a result of the operations, the highest stress value was obtained at the gage section and the lowest values were obtained at the reference point of the model. The stress behavior of the model under a 1000 N load is shown in Figure 4.14. The numerical model was used to obtain elastic modulus of the material. Using ratio of stress and strain, elastic modulus was computed as 53.998 GPa. Experimental result was 53.116 GPa, it is seen that the deviation amount was around 1.66 % according to experimental and numerical results. The finite element model result is given in Figure 4.15.

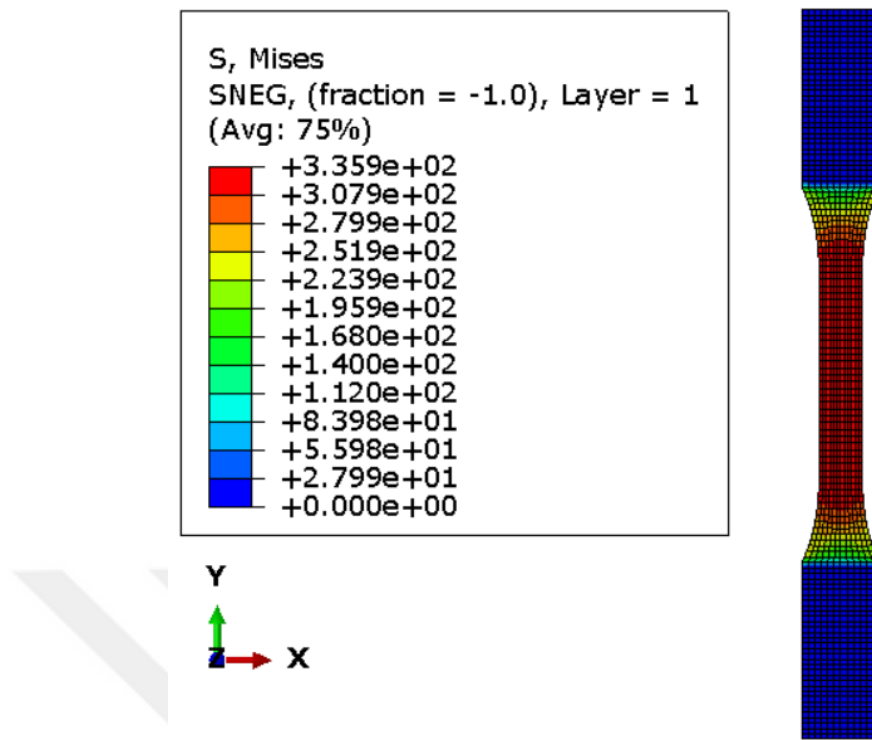


Figure 4.14. Dog-bone sample numerical tensile test

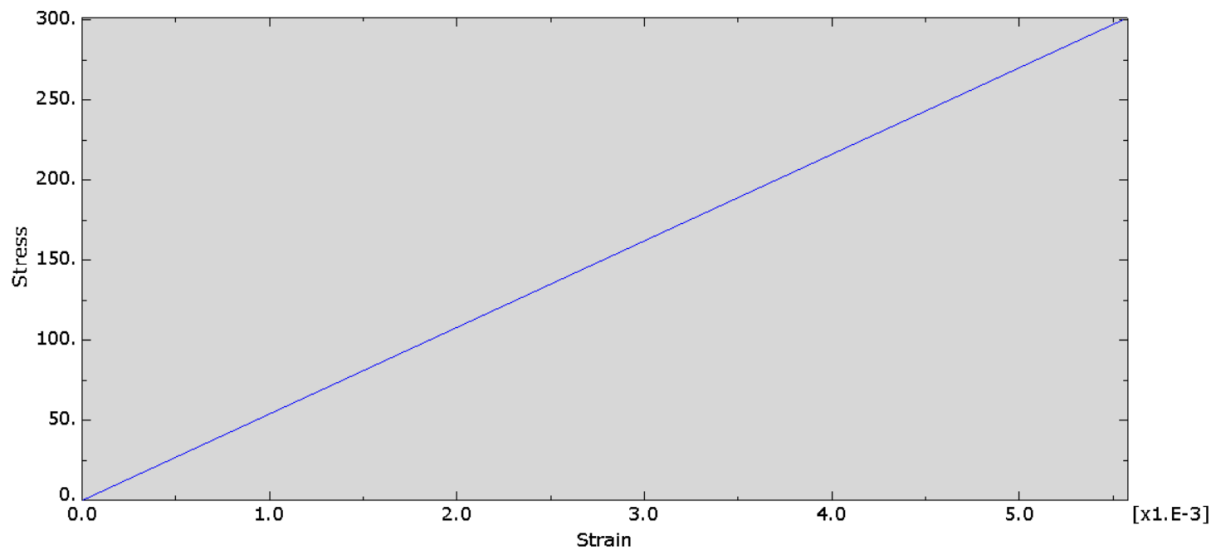


Figure 4.15. Stress-strain graph of the numerical model

In experimental specimens failed at reduced (gage) section due to high stress constitution. This causes different failures due to distinct material layers. In these layers split up was seen in metal liner, fiber rupture was observed in outer 90-degree fiber orientations, fiber-matrix debonding, delamination, and substituting rupture occurred at $[\mp 45]$ layers. Similarly,

Kaynak et al. [66] stated fiber matrix debonding failure appeared at $[\mp 45]$ degree layers after the split disk tensile test dominantly. The formation of shear stress between the layers resulted in fiber-matrix debonding and delamination. Except this condition, they reported the method can measure hoop tensile stress with low deviations. Gul et al. [169] investigated hoop tensile property of pressure tank body utilizing split disk tensile test to see effect curvature of gage section. They carried out numerical and experimental studies, they concluded curvature of the gage section of the split disk specimen affects the stress results. The curvature reduces measured a small deviation compared to a flat gage section. In another study, Yoon and Kim [161] suggest split disk tensile test for circular or tubular shape materials compared with tensile coupon test method. They proposed split disk tensile test for tubular or circular shape materials because it can measure close to real hoop tensile property. Jemii et al. [63] conducted experimental and numerical tests for split disk tensile method. They stated that quality modeling of the numerical model allows it to successfully predict experimental results. Also, the results confirm each other. In this study, a type III composite tank was investigated for hoop tensile stress determination. For this purpose, split disk tensile tests were implemented and compared to flat tensile test numerical model. It concluded that both split disk tensile test and flat tensile test results were in good agreement with each other.

4.3. Performing Fracture Tests With CTS Fixture

Curved compact tension specimens were prepared based on ASTM D5045 standards. The curve radius are at inner point 70 mm and outer surface radius 80 mm. Therefore the specimens have 10 mm composite layer with 6061 aluminum liner and fiber layers. The three specimens were shown in Figure 4.16. A curved compact tension (CCT) fixture was manufactured using 4140 steel to be designed by the tensile test required conditions for the experiment. The compact tensile fixture transfers the load applied from the universal tensile test machine to the specimen via pin connections. The resulting tensile force causes the specimen to break into mode I fracture mode, known as opening mode. The compact tensile test specimen and fixture were connected to the universal tensile test machine and the experimental setup is shown in Figure 4.17.

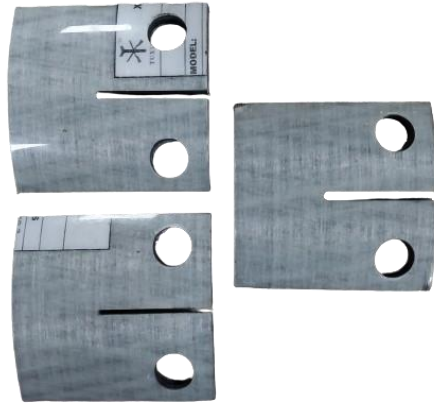


Figure 4.16. CCT specimens

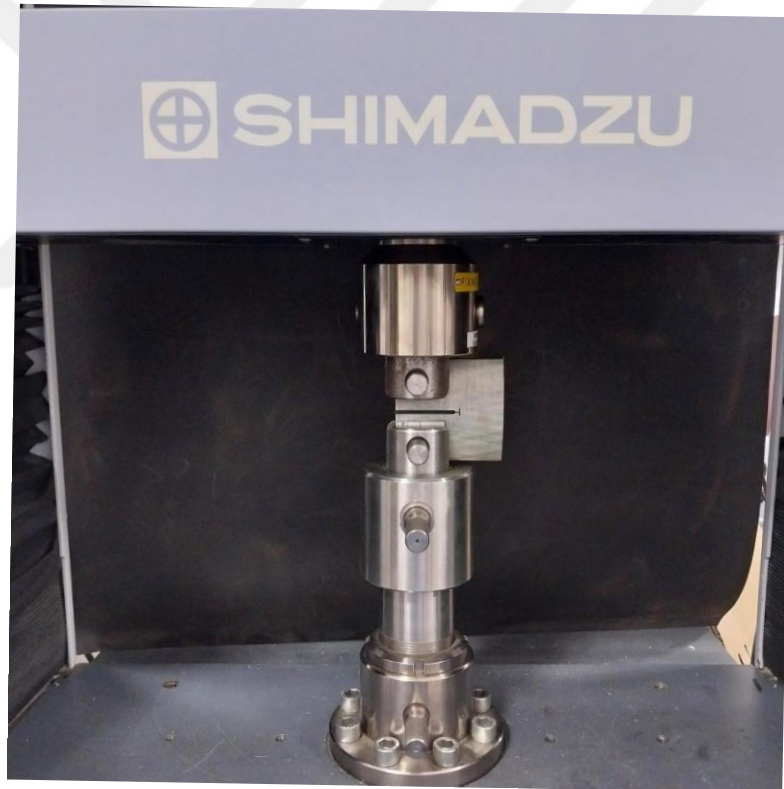


Figure 4.17. Experimental setup of curved compact tension

Three specimens were used for the experiments. Tensile force was applied to the specimens in order to perform opening behavior and the obtained graphs are shown in Figures 4.18-4.21 for each specimen separately and the force displacement graphs for all three together. With the application of the tensile force, the stress values at the crack tip increased proportionally to

the force. The specimen failed when the force reached the critical stress intensity factor, which is critical for the crack.

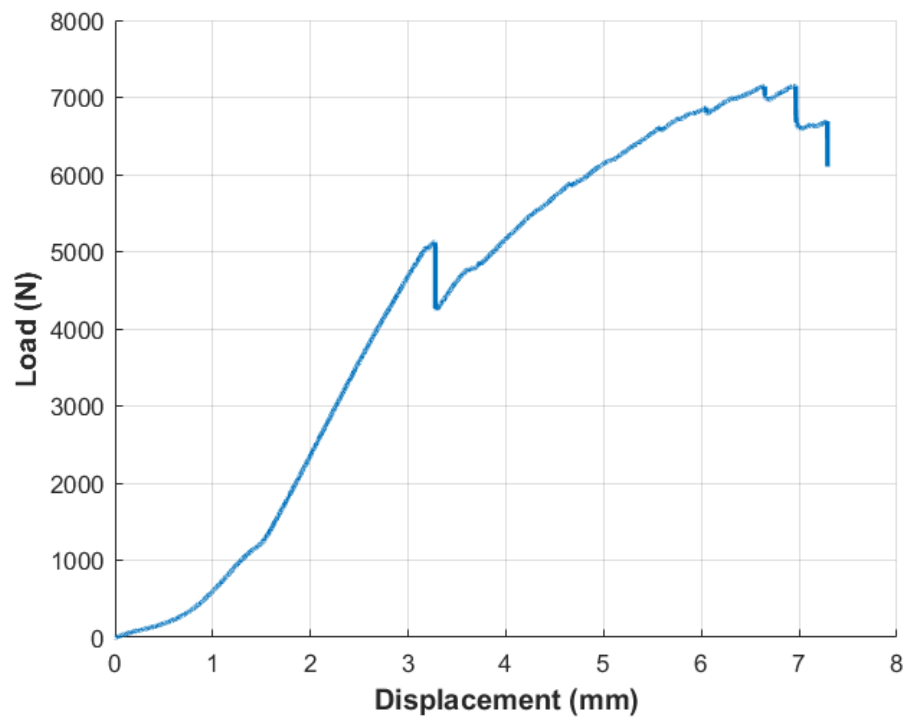


Figure 4.18. Load-displacement graph of first CCT specimen

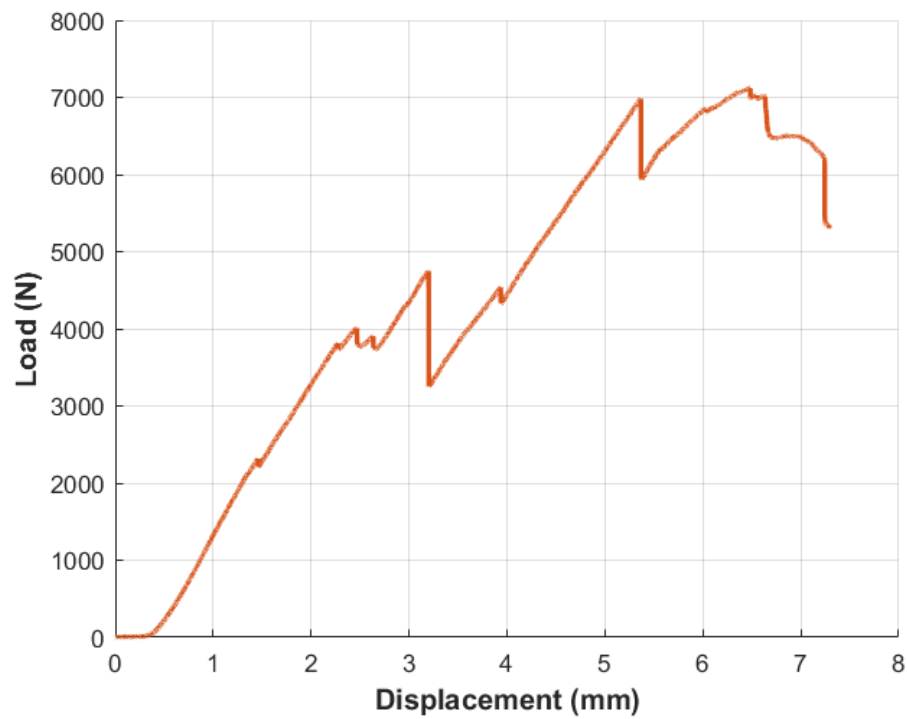


Figure 4.19. Load-displacement graph of second CCT specimen

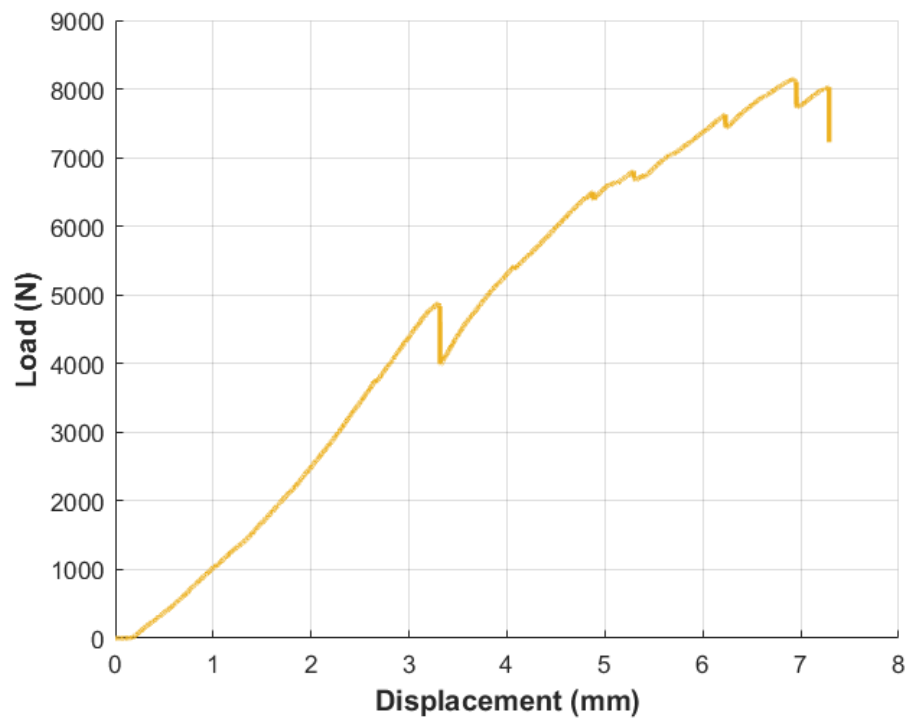


Figure 4.20. Load-displacement graph of third CCT specimen

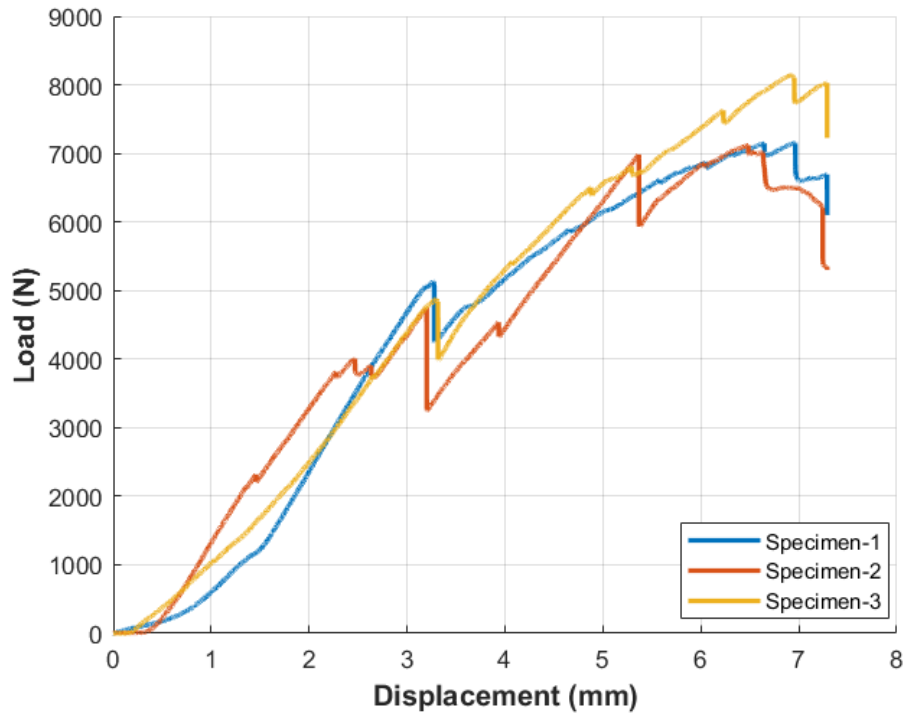


Figure 4.21. Load-displacement graph of CCT specimens

The critical load required to calculate the stress intensity factor was obtained from experimental studies. The results of three different specimens were analyzed for the repeatability of the experiments. The results of all three specimens are shown in Figure 4.21 as load-displacement graph. The specimens reached critical load values of 8127, 7149, and 7120 N respectively. Mean of these critical loads were determined as 7465 N. Critical stress intensity factor and strain energy release rate measured as $36.90 \text{ MPa}\sqrt{\text{m}}$, 25634.65 J/m^2 using the Equations 4.1 and 4.2, respectively. The crack width ratio (a/w) is 0.5, so the correction factor $f(a/w)$ is 9.66 for the compact tension specimens. The correction factor values that vary depending on the different crack-width ratios are listed in Table 4.1.

Table 4.1. Correction factor depending on crack width ratio [170]

a/w	$f(a/w)$	a/w	$f(a/w)$
0.450	8.34	0.500	9.66
0.455	8.46	0.505	9.81
0.460	8.58	0.510	9.96
0.465	8.70	0.515	10.12
0.470	8.83	0.520	10.29
0.475	8.96	0.525	10.45
0.480	9.09	0.530	10.63
0.485	9.23	0.535	10.80
0.490	9.37	0.540	10.98
0.495	9.51	0.545	11.17
-	-	0.550	11.36

$$K_I = \frac{P_c}{B\sqrt{w}} f_I(a/w) \quad (4.1)$$

$$G_I = \frac{K_I^2}{E_I} \quad (4.2)$$

Figure 4.22 shows a CCT specimen under load. When the figure is examined, it is seen that the composite layer produces resistance to fracture without significant damage on the front face of the specimens. However, when the shape of the inside of the specimen is examined, it is seen that the aluminum inner liner in the composite layer is separated from the carbon layer. It is also seen in Figure 4.23 that the 90-degree glass fiber layers were separated from the carbon layer.



Figure 4.22. CCT specimen under load application



Figure 4.23. View of the CCT specimen from different angles during load application

When the inside side of the specimen is examined, the aluminum liner layer can be seen on the inside of the specimen is shown in Figure 4.24. Due to the opening behavior caused by the force in the layer of all three specimens, the crack started from the crack tip and proceeded inwards at an uneven angle. In addition, the aluminum liner was separated from the carbon

layer after experimental studies. While the outer part of the composite layer was less damaged, the crack in the aluminum layer in the inner part of the composite tank progressed inwards with the applied load. This shows that the 90 layer orientation composite layers are more successful in load-carrying than the aluminum 6061. However, it is seen in Figure 4.23 that damages occurred in the inner part of the composite layer. This shows that the high winding angle increases the mode I fracture resistance. Also, it shows that as the winding angle decreases, the fracture resistance of the composite layer tends to decrease.

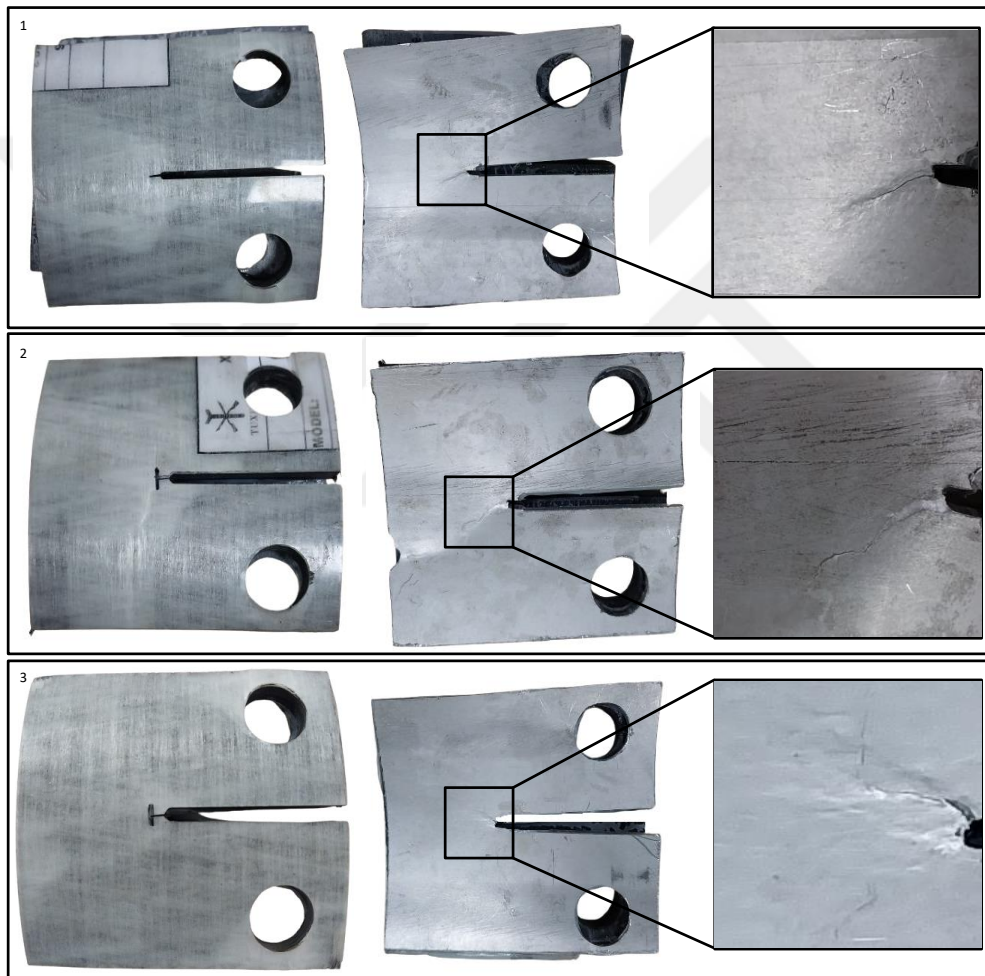


Figure 4.24. Front and back views of the CCT specimens

In Figure 4.25, the three CCT specimens were shown after experimental study. It can be seen in Figure 4.26 that the load-displacement graph gives details about composite failure types with the specimen background picture. The load was suddenly dropped due to delamination of aluminum liner and carbon fiber plies. After this condition, the load started to increase until the other layer (point 2) is separated. The second point occurs because of delamination between glass layers and carbon layers. At point 3, delamination, debonding, and fiber-resin brekage can be seen in the Figure. While tensile stress occurs at the point where the load is applied, compression stress occurs at the other part. The fault came about compression stress when the load was applied to the load holes.



Figure 4.25. Backside view of CCT specimens

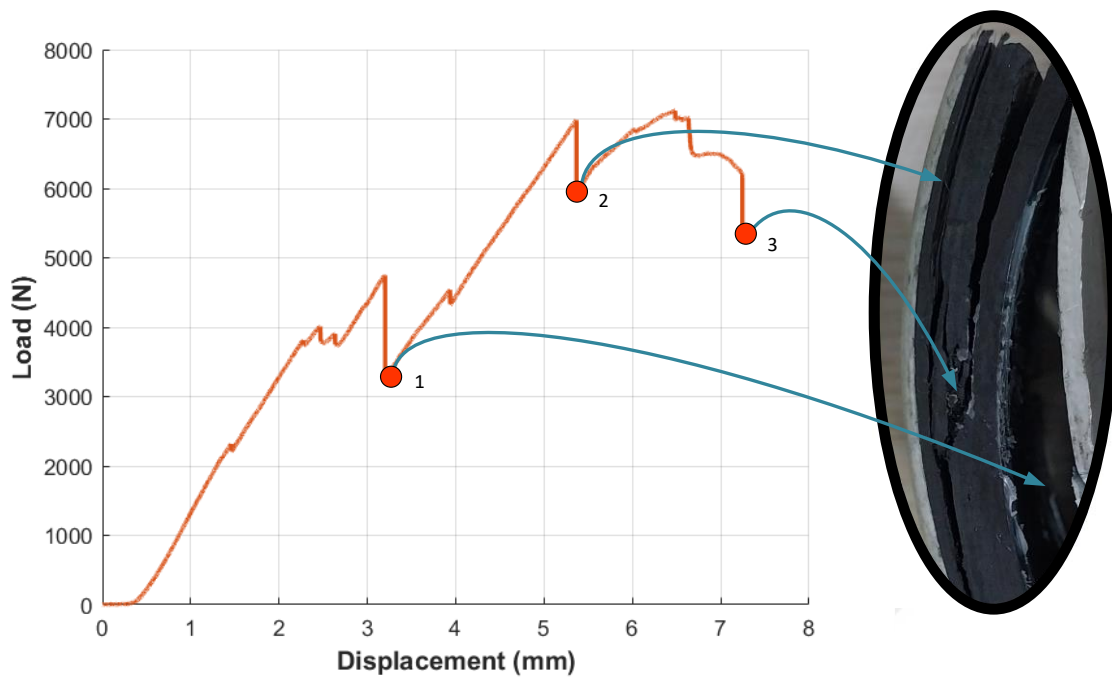


Figure 4.26. Composite layer faults of CCT specimen

4.4. Performing Numerical CTS Test

Finite Element Analysis is a powerful numerical method used in engineering and science to solve complex problems. This technique allows for a detailed understanding of the stress distribution, deformation, and failure mechanisms of the material, aiding in the design and optimization of structures to ensure its safety. Therefore, numerical method used to analyze and predict the behavior of structures and components under various loading conditions. Finite Element Analysis with Compact Tension is a numerical simulation technique used to analyze the mechanical behavior and structural response of materials subjected to tension, with the CTS specimen being specifically designed to assess fracture toughness [171]. This technique involves dividing the material or structure into small elements and then analyzing each element individually using mathematical equations to determine its behavior and response [172]. By utilizing FEA with CTS, fracture behavior of materials can accurately predicted under tension load, helping to ensure the safety and reliability of structures and components [173]. In this study, a compact tension model was prepared as regards ASTM D5045 standard is shown in Figure 4.27. A seen in the Figure, crack length is 30 mm, width length is 60 mm so crack width ratio (a/w) is 0.5 value. The numerical model was shown in Figure 4.28, it was created as flat plate 2D using shell and this facilitates computation

compared to 3D model due to more less element number. The model consists of 43 layers whose materials are aluminum 6061, carbon epoxy, and glass epoxy that is illustrated in Figure 4.29. The layer orientations were assigned as one layer for aluminum 6061, $[\pm 45]_{19}$, and $[90]_4$ fiber wrapping angle for carbon epoxy, and glass epoxy on aluminum 6061 liner, respectively.

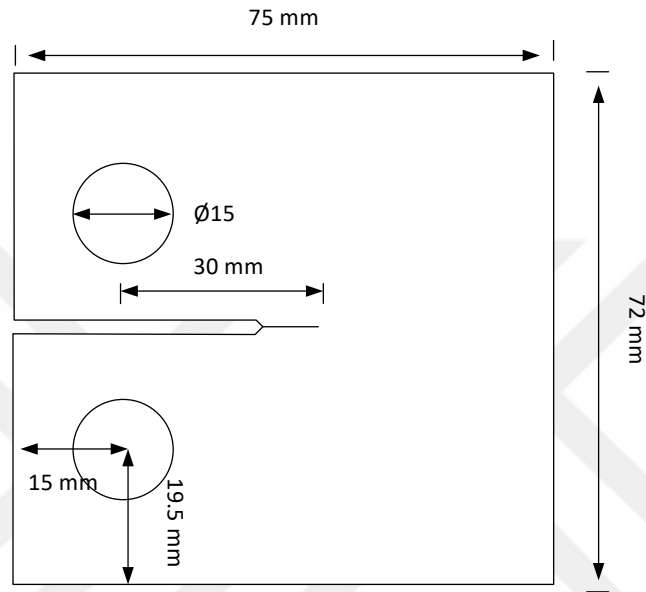


Figure 4.27. Dimension of CTS model

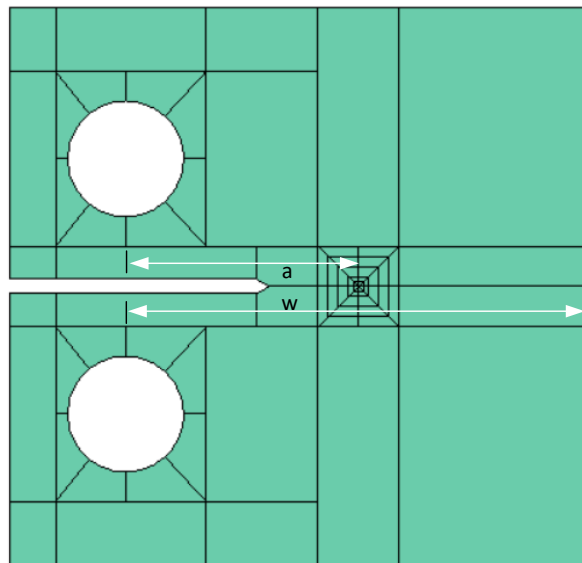


Figure 4.28. Numerical model of CTS

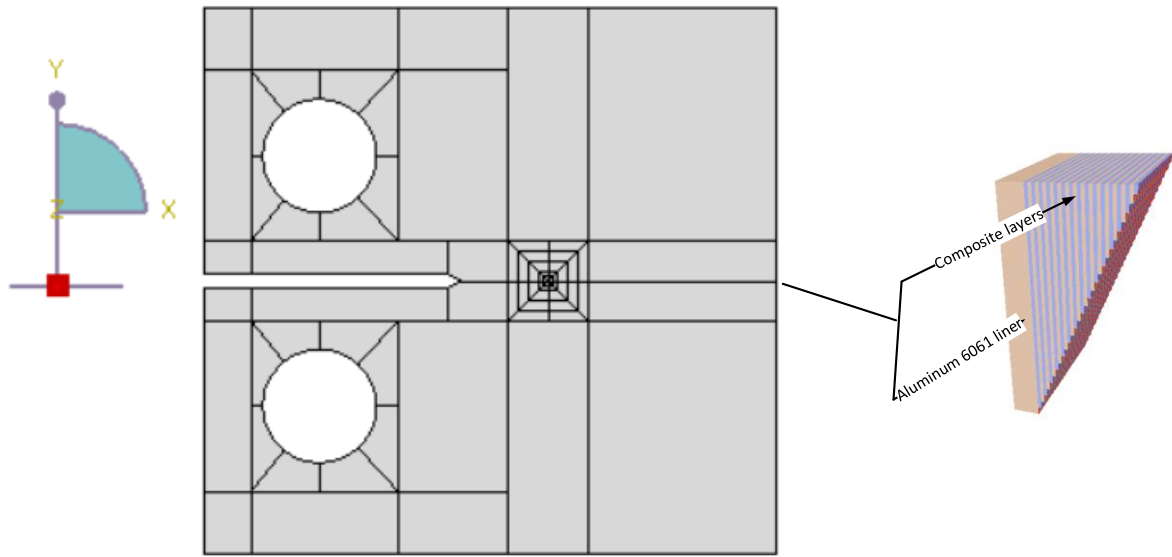


Figure 4.29. Composite layers of the numerical model of CTS

The boundary conditions used in the modeling of compact tensile specimens increase the success of prediction when the application points are defined correctly. There are two holes in this model. Two reference points were created for the center of the holes that is displayed in Figure 4.30. The holes were used to define a load and pin connection for mode I application to the model.

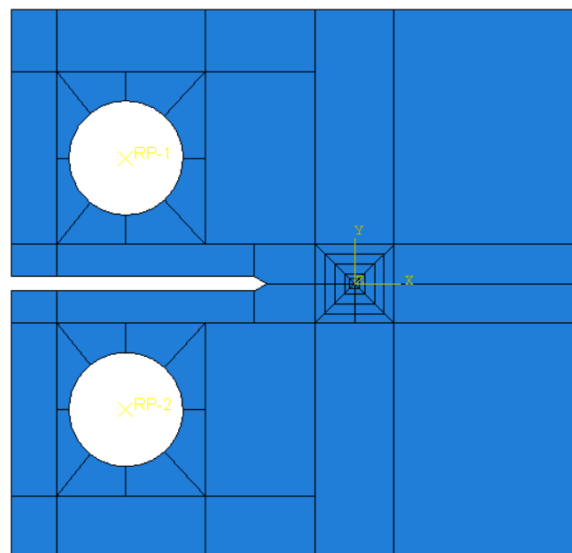


Figure 4.30. Adding reference point to CTS model

Boundary conditions were assigned to these reference points using coupling definition. Related representation is shown in Figures 4.31. The crack tip point and the direction of crack propagation is defined along the x-axis. The crack of the model is defined using a crack seam before the crack point. When the numerical analysis is performed with these definitions, the crack will show a progression behavior along the x-axis realistically starting from the midpoint. Definitions of how cracks behave are shown in Figure 4.32.

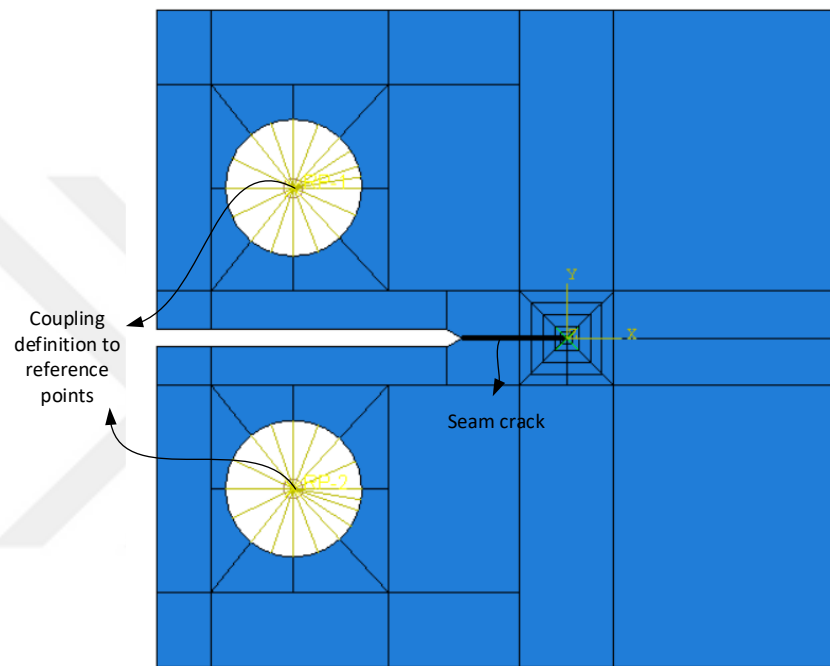


Figure 4.31. Coupling definition to reference points

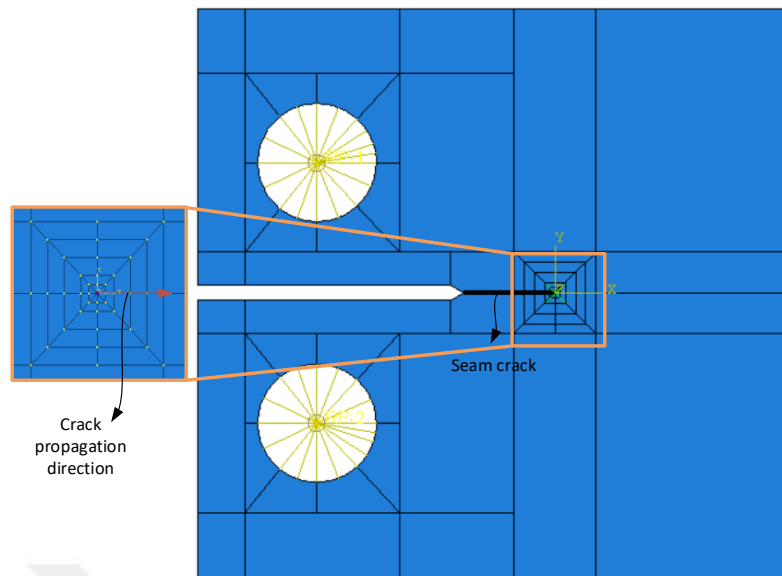


Figure 4.32. Crack definition to CTS model

After the crack was added to the model, it was defined to the step module to see the stress intensity factor as shown in Figure 4.33. The whole model was selected as default, but it was changed to crack by changing the options. It additionally defined 5 contour areas around the crack.

Name: H-Output-1
 Step: Step-1
 Procedure: Static, General

Domain: Crack : Crack

Frequency: Every n increments n: 1

Timing: Output at exact times

Number of contours: 5

☐ Step for residual stress initialization values:

Type: ☐ J-integral
☐ Ct-integral
☐ T-stress
☒ Stress intensity factors

Crack initiation criterion: ☒ Maximum tangential stress
☐ Maximum energy release rate
☐ $K_{II}=0$

Figure 4.33. Stress intensity factor definition to CTS model

Previously created coupling and reference points were used in the definition of boundary conditions and load. The bottom of these points was defined to allow the specimen to rotate on the axis which is displayed in Figure 4.34. At the upper reference point, the load that would cause the specimen to generate failure was applied as a force (N).

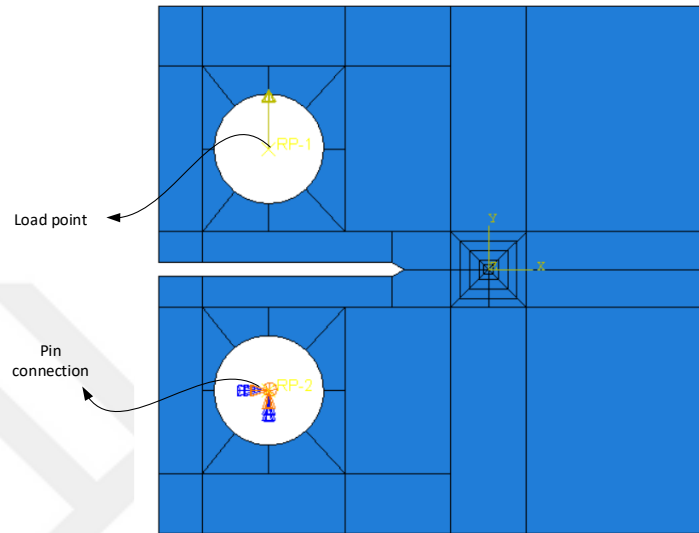


Figure 4.34. Boundary condition definitions

Mesh quality is very important for the CTS model to calculate the correct result. For this reason, partitioning zones were created on the model. These partition zones ensure that the elements are transferred to other elements in an orderly manner. The modeled compact tensile model is shown in Figure 4.35, and it was created with 4872 points and 4635 linear quadrilateral S4R types elements. Finally, the job tab was selected from the module. After a job was created for the model, it was run for fracture energy computation.

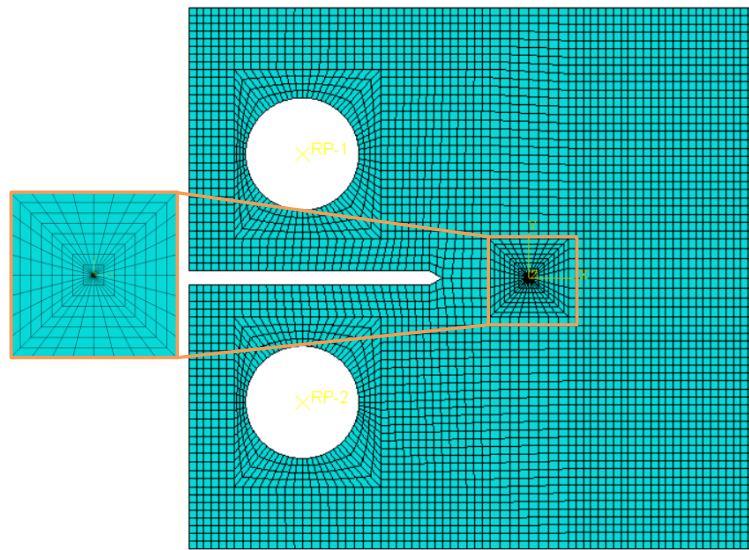


Figure 4.35. Mesh pattern of CTS specimen

Numerical studies complement the experimental studies, providing an understanding of the complex mechanics of cracks. To simulate a crack model under different loading conditions, finite element analysis is commonly used. Numerical models enable researchers to explore different material properties, crack geometry, and loading conditions and provide an in-depth understanding of the fracture behavior of material. The research explores relation of experimental and numerical fracture toughness of the composite tank. For this purpose, flat compact tension numerical model was developed to estimate fracture toughness of the tank. The stress distribution at the crack point caused by the critical load is shown in Figure 4.36. By employing experimental mean load to the numerical model, critical stress intensity factor and strain energy release rate were computed as $35.89 \text{ MPa}\sqrt{m}$, 23854.44 J/m^2 , respectively. The experimental and numerical results are close to each other with 2.7 percent deviation for critical stress intensity factors. The investigation of the fracture behavior of materials with pressure vessels or tubular-shaped materials is an important subject and is critical for safe operation under pressure. To measure fracture toughness of a material, CTS specimen is preferred due to well-known method. In addition, it is utilized for circular shape materials, and recognized as curved compact tension specimen. Similarly, Sung et al. [99] carried out a numerical study for effects of curvature on fracture toughness and they reported there was a small deviation is about 1.97 percent when compared with a flat CTS specimen. The results show that curved compact tension method is a appropriate for measuring fracture toughness of circular shape materials.

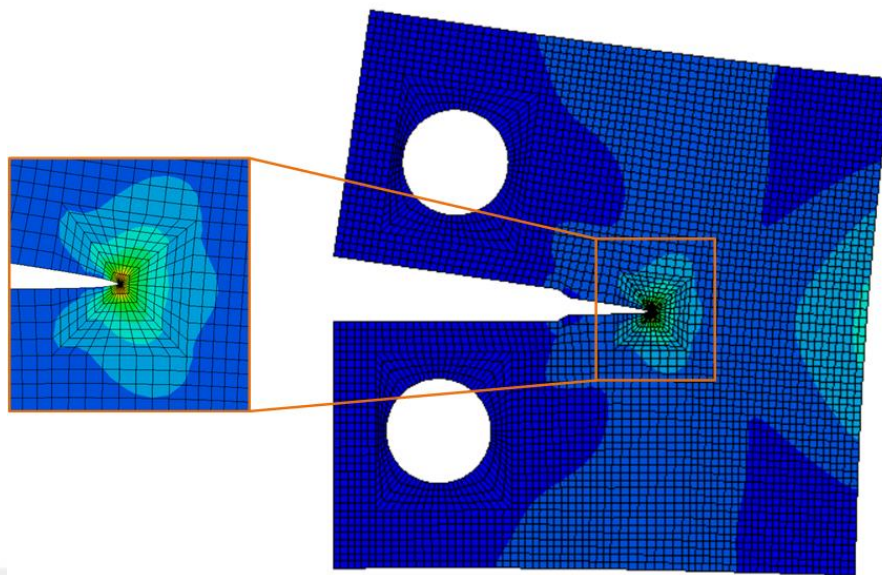


Figure 4.36. Results of numerical study

4.5. Performing Fracture Test With PRNB Method

The pipe ring bending fracture method is a practical testing technique to assess the mechanical properties and integrity of pipes or tubing. It involves subjecting the pipe to a specific bending deformation and observing any cracks or fractures that may occur. This method is particularly useful for detecting potential weak points or flaws in the pipe, which could lead to failure under normal operating conditions. By analyzing the cracks or fractures, it can be determined severity of any defects and make informed decisions regarding repair or designing of the pipe or circular shape tubes. Furthermore, the pipe ring notched bending fracture method involves creating intentional notches or grooves on the outer surface of the pipe before subjecting it to bending deformation. These notches serve as stress concentrators, allowing for more accurate assessment of the pipe's fracture resistance and failure behavior. This method is important for industries such as liquid or gas storage, transportation of oil and gas, aerospace, and construction, where the structural integrity of pipes is crucial for safety and operational efficiency [174]. In this study, PRNB specimens were prepared based on ASTM E-1820 standards. The specimens radius have 10 mm composite layer consisting of 6061 aluminum liner and fiber plies, and the specimens are shown in Figure 4.37. The specimen was prepared with notches are 10mm and width is 20 mm length to build up crack width (a/w) is 0.5 ratio.



Figure 4.37. PRNB specimens

The PRNB fixture was setup with SENB fixture by modifying to carry out fracture experiments. For this purpose, three 12 mm x 180 mm support pin were used. One of them was utilized to transfer load to the PRNB specimens. By applying load to the specimen, it was ensured to break from the notched part of the specimen. Thus, the load causes crack propagation at middle point. This results compression force actualized mode-I behavior. The experimental setup is shown in Figure 4.38.



Figure 4.38. PRNB experimental setup

PRNB specimens were one by one placed in a universal testing machine. A compression load was applied to generate the mode-I behavior of the PRNB specimen. At the end of the experimental studies, the force-displacement graphs of each specimen are presented in Figures 4.39-4.42 for a comparative view of the three specimens. The maximum loads applied until crack failure of the three specimens were 5300, 5554, and 5580 N. The average value of these loads was determined as 5478 N.

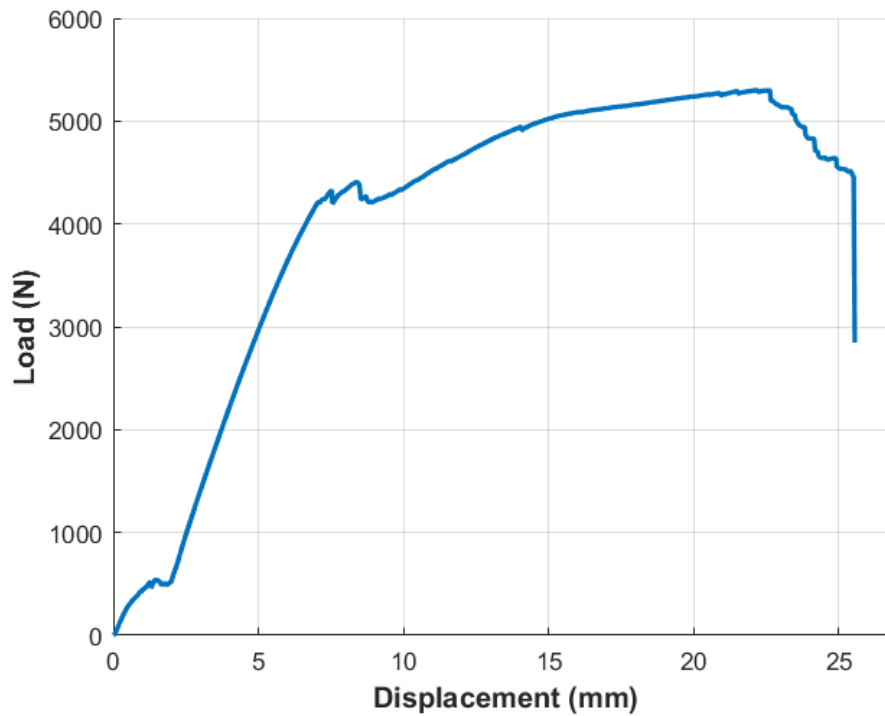


Figure 4.39. Load-displacement graph of first PRNB specimen

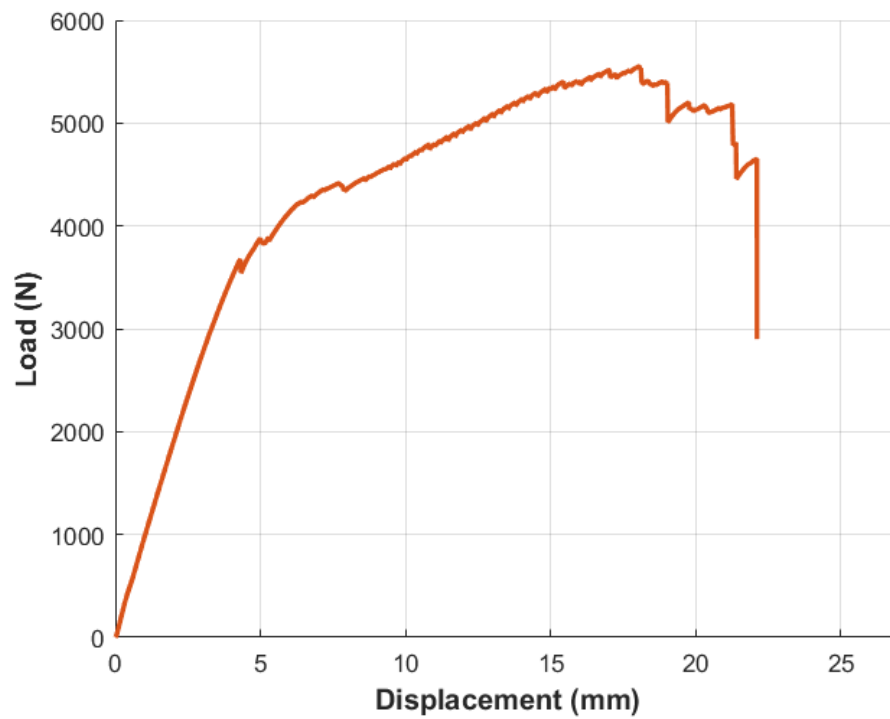


Figure 4.40. Load-displacement graph of second PRNB specimen

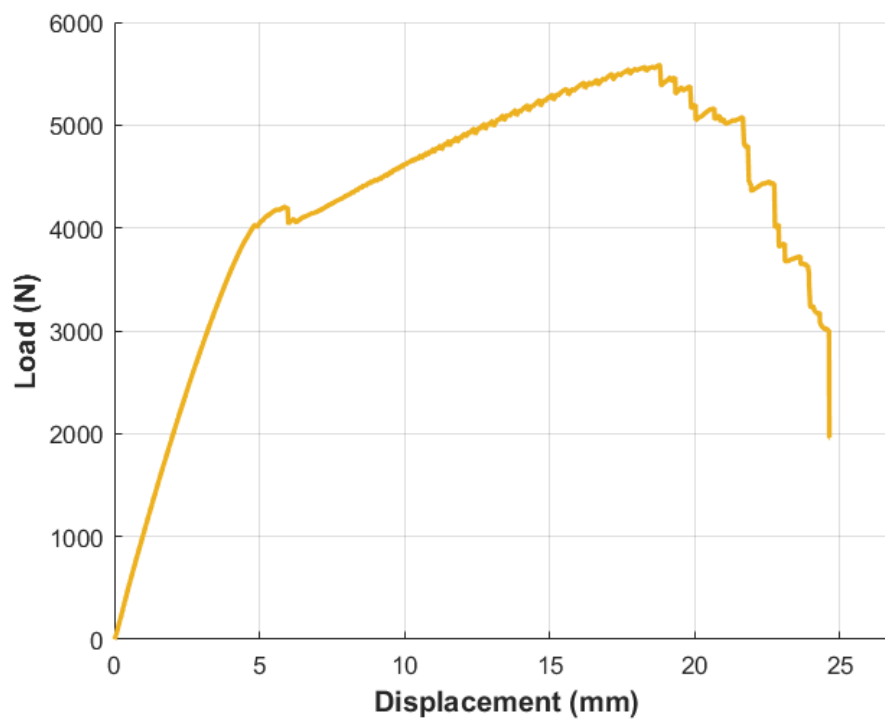


Figure 4.41. Load-displacement graph of third PRNB specimen

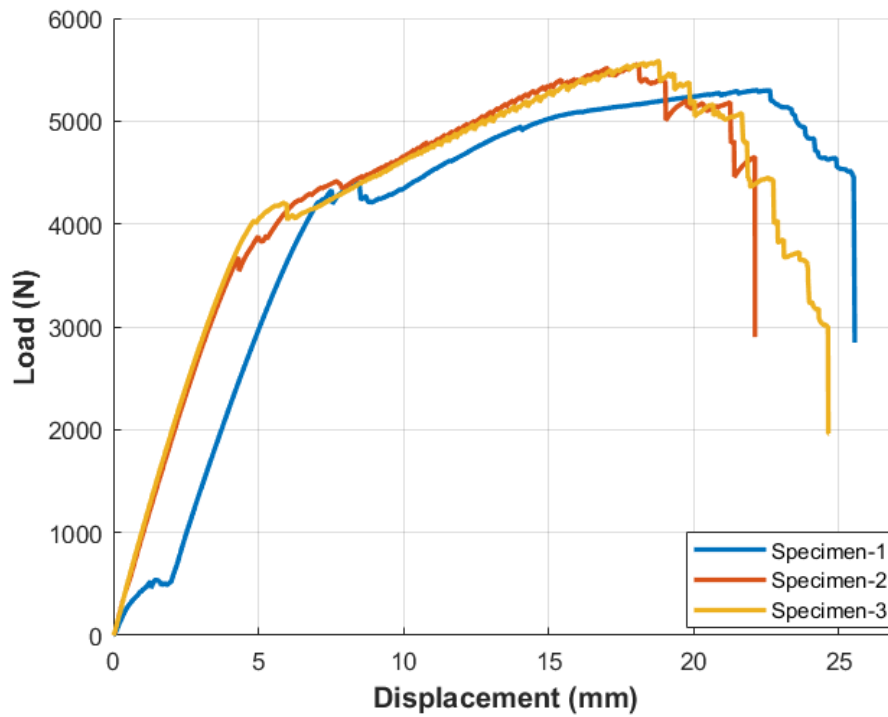


Figure 4.42. Load-displacement graph of all PRNB specimens

The specimens resulted in crack failure after the maximum critical load was applied. Figure 4.43 shows the condition of the specimen before and after critical load implementation. Applying load at the center of the specimen created shear stress and caused crack propagation. The crack starting points of the back side and front of the specimens after the experiments are shown in Figure 4.44.

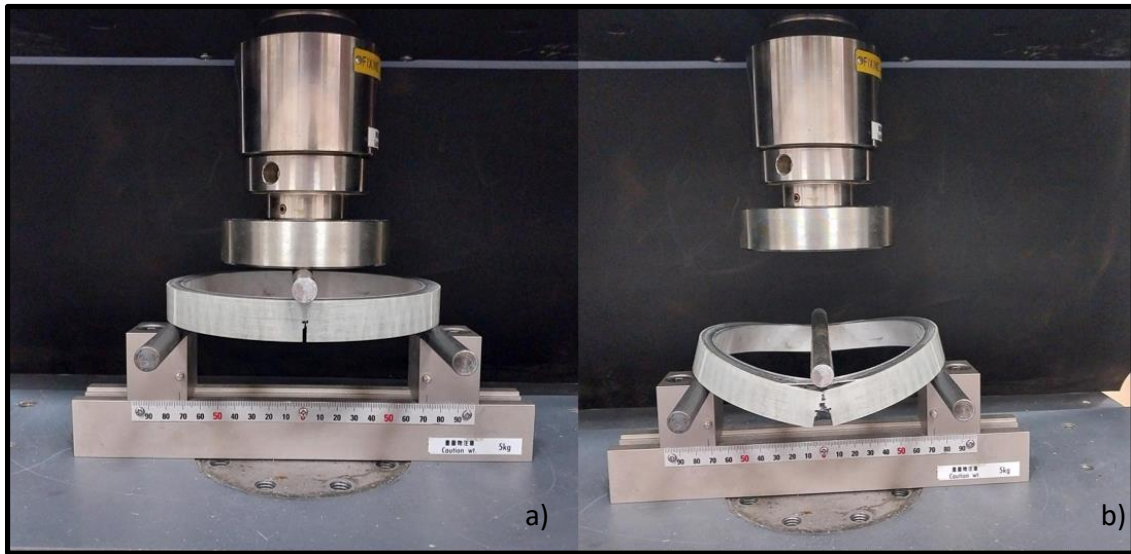


Figure 4.43. Mode I fracture experiments with PRNB specimen: a) experimental setup, b) failed PRNB specimen after the experiment

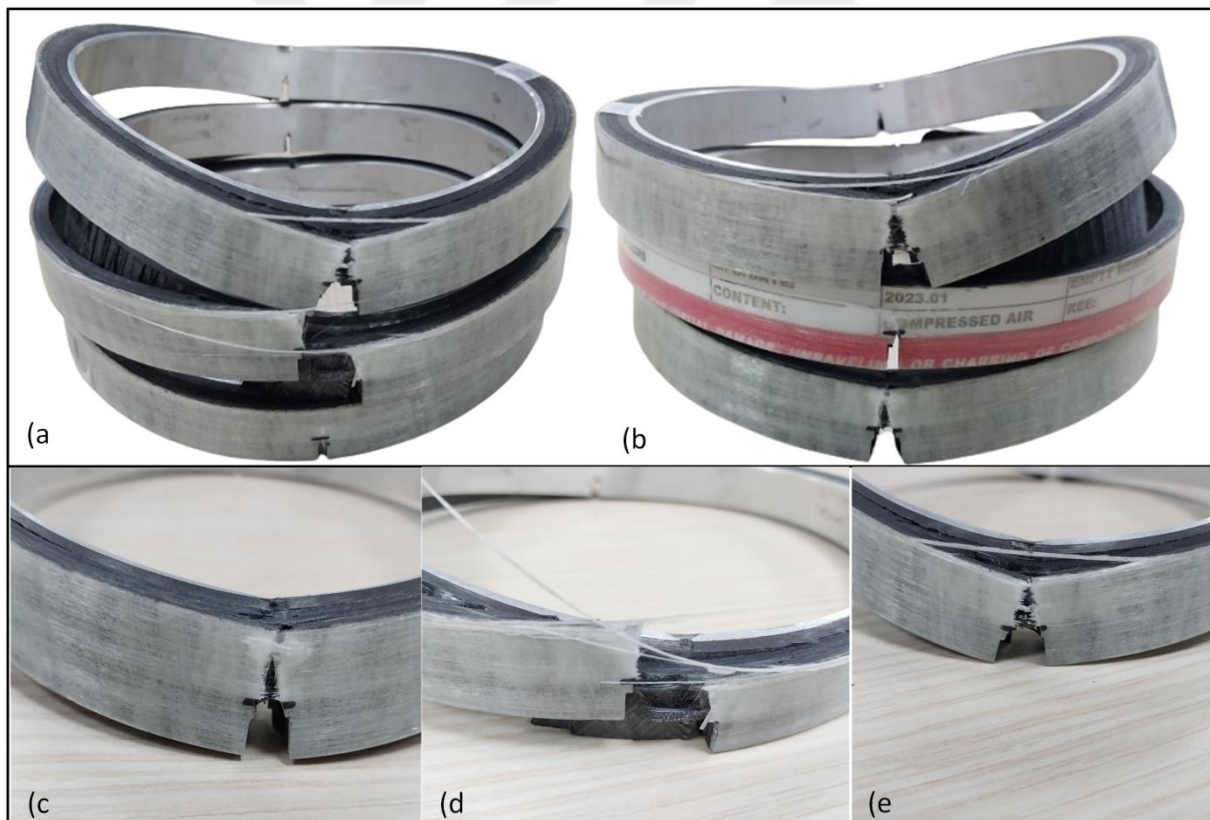


Figure 4.44. Final crack form of PRNB specimens after fracture tests: a) front view, b) backside view, c) first specimen, d) second specimen, e) third specimen

PRNB is an immature method in some aspects, especially for measuring fracture toughness of a material. This method is prepared according to ASTM E 1820 but the standard is not fully adequate for the PRNB method. Therefore, the PRNB stress equation was used to calculate the stress intensity factor. The stress (σ_A) is formed both shear and bending stress in section A. This condition is illustrated in Figure 4.45. The stresses in section A with un-notched are expressed in the following Equations [175]. Where c is perpendicular distance from centerline, a is crack length, w is width, F is force or load, σ_b is bending stress, τ is shear stress, σ_A is Von Mises stress at section A, R is radius of circle, B is thickness of material, $2T$ is distance between support pins.

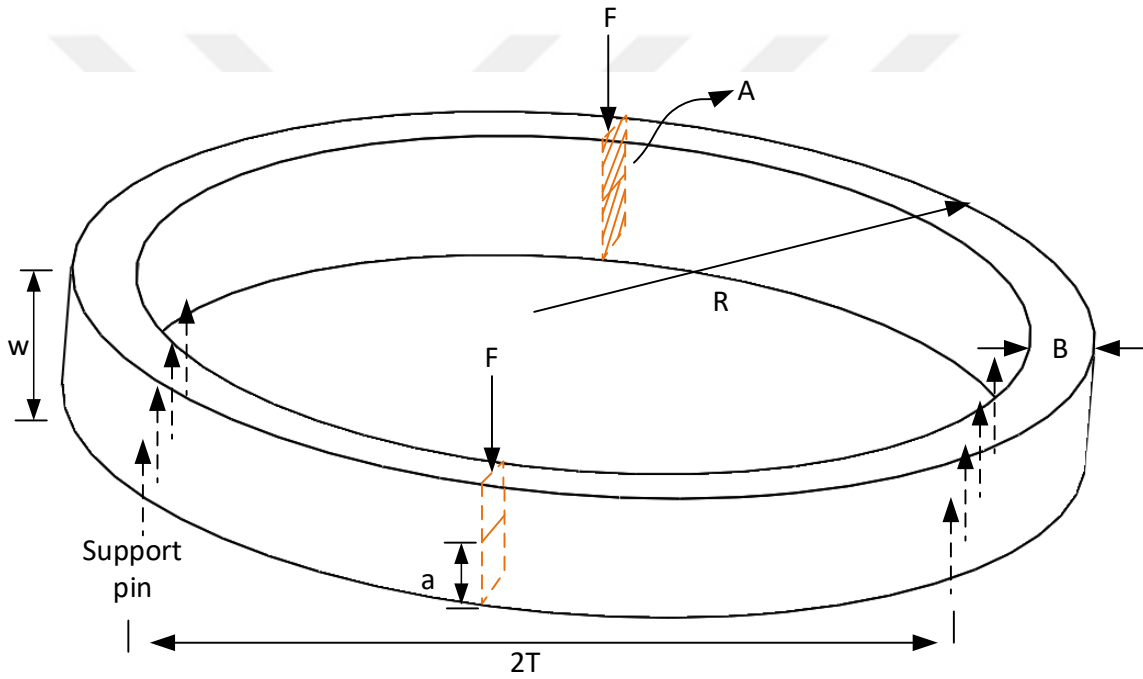


Figure 4.45. Cross-section of a PRNB specimen in the loading line plane

$$\sigma_A = \sqrt{3\tau + \sigma_b} \quad (4.3)$$

$$\sigma_b = \frac{3FT}{BW^2} \quad (4.4)$$

$$\tau = \frac{F}{2BW} \quad (4.5)$$

$$\sigma_A = \sqrt{\left(\frac{6FTc}{BW^3}\right)^2 + 3\left(\frac{F}{2BW}\right)^2} \quad (4.6)$$

$$T = 0.9R \quad (4.7)$$

When the PRNB specimen is subjected to bending, the bending stress in section A reaches its maximum at point 1, but no bending stress occurs in the center. This situation is shown in Figure 4.46. At the point where the force is applied, the stress is in the form of compression, while at the bottom of the specimen, it is in the form of tensile stress.

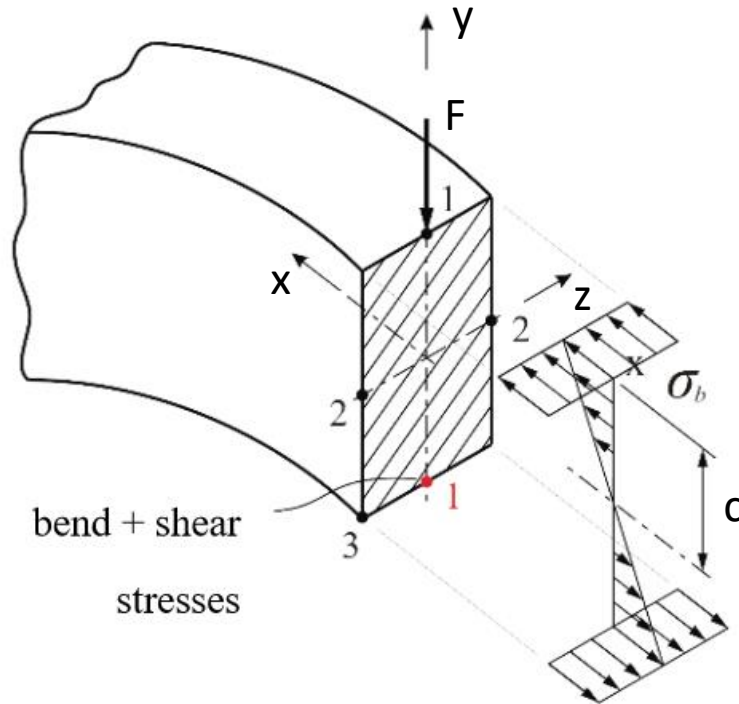


Figure 4.46. Stress buildup of a PRNB specimen (edited) [174]

The PRNB specimen has two cracks for determining the fracture toughness of a material. The stress differs from section A due to having a crack. Because the crack length is 10 mm and the specimen width is 20 mm, the fracture length corresponds to the midpoint. It can be seen in Figure 4.47, the stress consists only shear stress. In before section, mode-I stress intensity factor and mode-I strain energy release rate of the composite material was determined using

CTS method. By calculating stress at mid-point, correction factor ($f_I(a/w)$) was obtained. The relations between K_I and G_I were expressed in the following Equations.

General stress intensity factor is given as:

$$K_I = \sigma \sqrt{\pi a} f_I(a/w) \quad (4.8)$$

Relation of strain energy release rate and stress intensity factor is stated as:

$$G_I = \frac{K_I^2}{E_I} \quad (4.9)$$

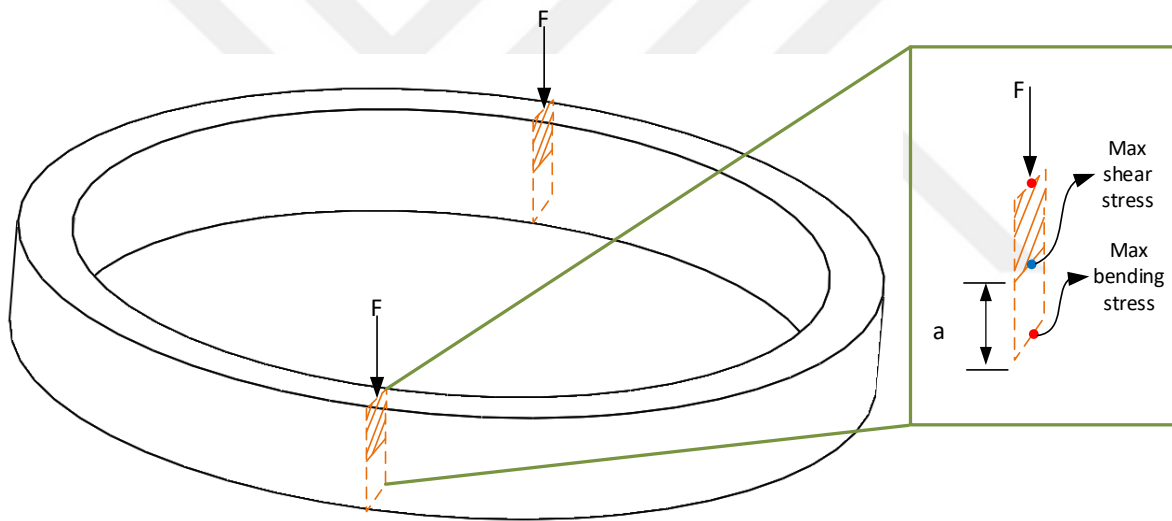


Figure 4.47. Stress creation at crack section of PRNB specimen

4.6. Performing Numerical PRNB Test

Finite element modelling is a useful tool for comparing experimental results with numerical results and evaluating the accuracy of the results. One of the important aspects of FEM is the creation of a finite element model, which involves decomposing the notched pipe into small elements to simulate its behaviour under various conditions. By performing experimental tests and comparing the FEM results with analytical solutions, the accuracy and reliability of the model can be verified. In addition, FEM can be applied in the design and optimization of pipe

or circular shape specimens to ensure their safety and reliability. For this purpose, the PRNB FEM model was created with Abaqus is displayed in Figure 4.48 for comparing the numerical model with the actual experimental results.

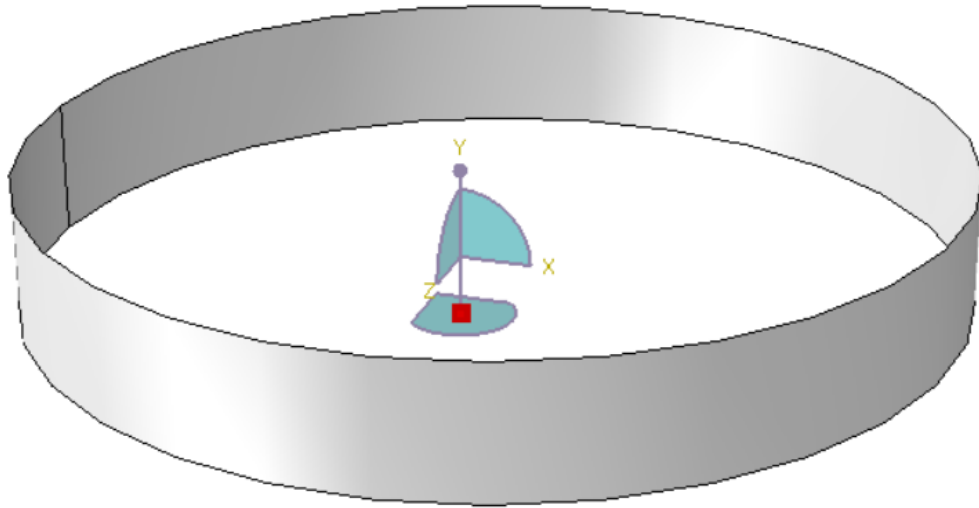


Figure 4.48. Numerical model of PRNB specimen

The numerical model was constituted as a composite form with 43 plies, it consists of aluminum 6061 liner and carbon and glass fibers to compose layers. The aluminum liner was covered with carbon fibers $[\pm 45]_{19}$ layer orientation then glass fibers were placed on carbon layers using 90 angle wrapping orientation. The model is illustrated in Figure 4.49.

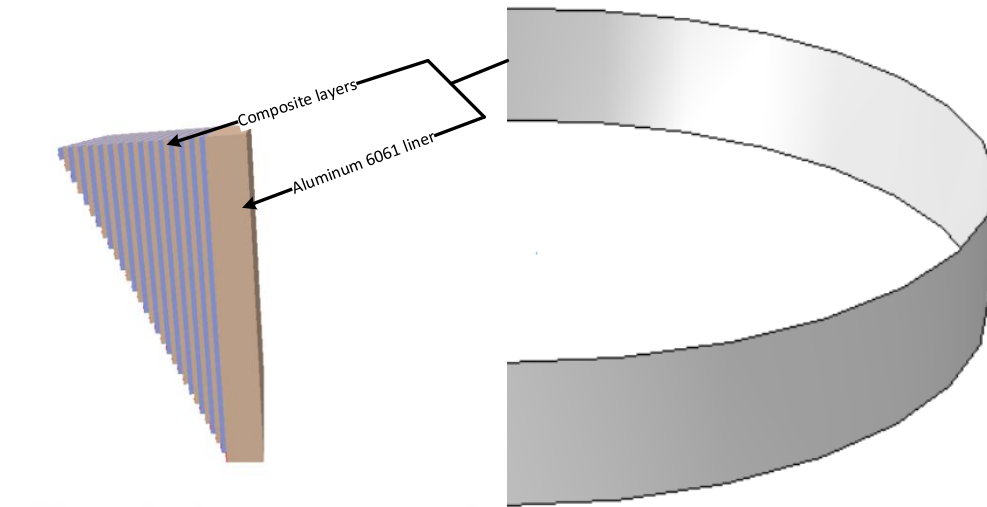


Figure 4.49. Structure of PRNB specimen

PRNB model was set based on ASTM E-1820 standards as shown in Figure 4.48. The specimen geometry has a radius at the inner point is 70 mm and the outer surface radius is 80 mm. So the specimens have a 10 mm composite layer with 6061 aluminum liner and fiber layers. Using the ASTM standards, the model dimensions are assigned as the crack length is 10 mm, the width is 20 mm and the crack width ratio (a/w) is 0.5 for the PRNB model. The crack was formed with crack seam at the midpoint of PRNB model. It can be seen in the Figure 4.50.

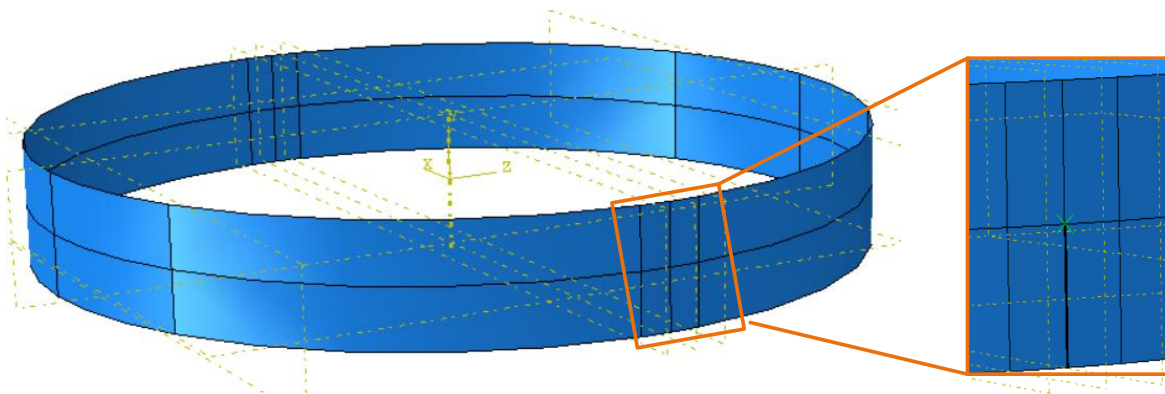


Figure 4.50. Crack assigning to PRNB model

When creating the boundary conditions of the PRNB model, modeling was done realistically. Load was applied to the model from the top point and supported by two pins from the bottom. In this case, the load was applied to the model from the top point on both sides from the point where the fracture was located. Pin connections are also defined at the bottom of the model. The boundary conditions of the model are shown in Figure 4.51.

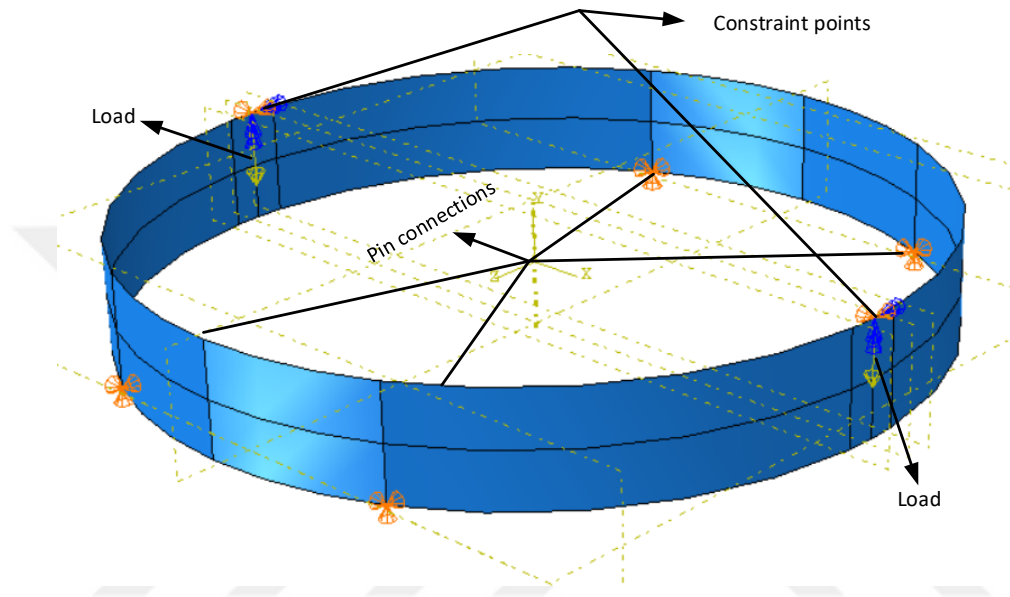


Figure 4.51. Boundary conditions of PRNB model

According to the information taken up from the model Abaqus, the model contains the total number of nodes 9260, 8800 S4R type linear quadrilateral elements. The model created according to the specified elements and points is shown in Figure 4.52.

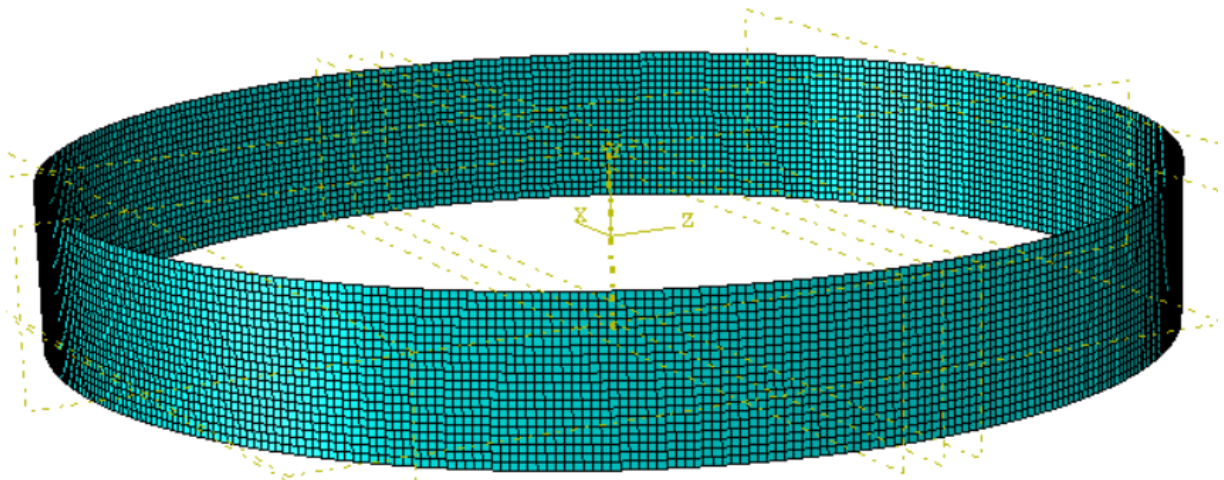


Figure 4.52. PRNB specimen mesh definitions

The study explores the various factors that can affect the fracture behavior of type III composite pressure tanks, such as material properties, geometric parameters, and loading conditions. In addition, it implemented the validation and verification of the finite element model through experimental testing and comparison. By running of the PRNB model, stress intensity factor was computed as $35.73 \text{ MPa}\sqrt{m}$, also the fracture toughness of the material was predicted successfully with accuracy 96.83 percent when it is compared to both compact tension numerical and experimental results. The model result is displayed in Figure 4.53. Correction factor of PRNB can be determined using a different fracture toughness measurement method or numerical model of PRNB for a certain PRNB specimen dimensions. Likeb and Gubeljak [174] studied PRNB and SENB methods for investigating fracture toughness measurement performance of PRNB method. They proposed the PRNB method that is convenient for tubular shape materials. Similarly in previous research paper, Likeb et al. [176] explored fracture toughness prediction using PRNB and SENB methods numerically. They found numerical SENB measurements were higher around 10-15 % compared to PRNB model results. Musrati et al. [177] carried out experimental and numerical studies using PRNB and a modified compact tension method for determining fracture toughness. They stated that the PRNB method is a useful method for pipes or similar shapes, and it can be used for measuring fracture behavior, successfully. Unlike these studies, both compact tension and PRNB numerical models were created for type III composite tank in this study, and the models accomplished fracture toughness value of the tank. When comparing experimental study results, it concluded that their results are in good agreement.

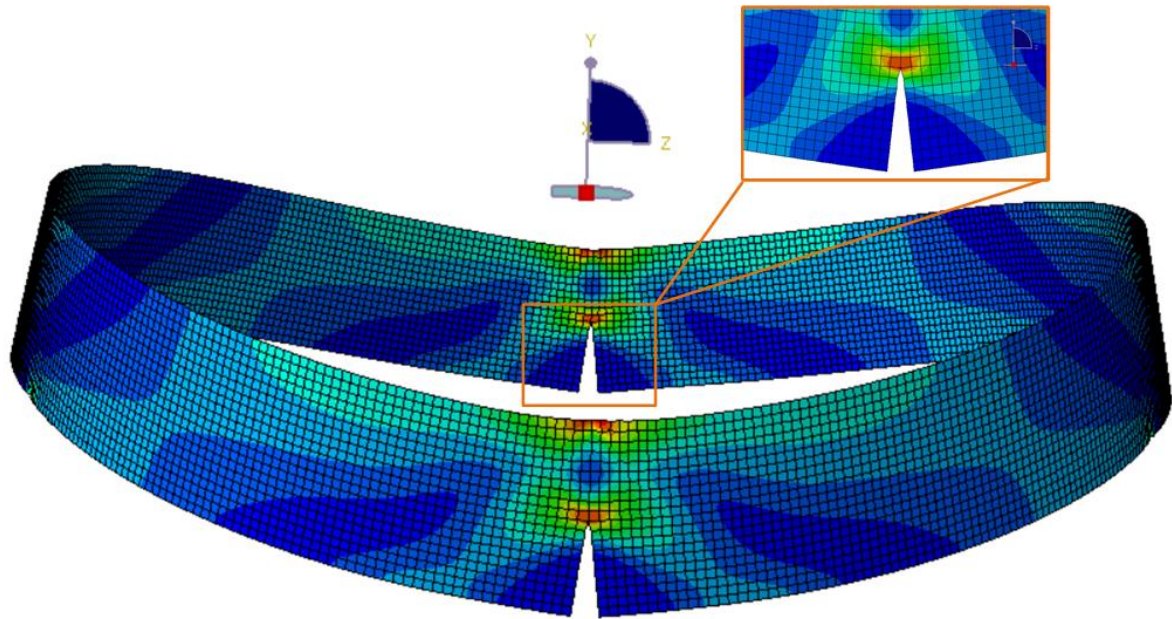


Figure 4.53. Crack region of the PRNB model

The data obtained as a result of both experimental and numerical studies are close to each other and also confirm each other. The fact that the finite element model predicts close to the experimental result shows that the model is successful. The numerical PRNB model allowed to evaluation of different situations such as different crack lengths and pressure applications. Therefore, the PRNB model provides an opportunity for fracture toughness to be computed as a function of pressure in the vessel by simulating different situations. Unlike the CTS model, pressure can be applied to this model. For real operating conditions, pressure was applied to the model and the crack length was varied to investigate how the crack length affects the operating pressures of the pressure vessel. To see the effect of fractures and pressures, the crack length and critical pressure value were tried to be determined using the PRNB model based on the critical fracture toughness value. The critical stress intensity factor determined is the mechanical property of the tank material. The applied inner pressure to the PRNB model, this pressure constitutes stress on the crack tip point. If this value reaches up to the critical stress intensity factor due to applied inner pressure, the inner pressure can be named critical inner pressure. It refers to the internal pressure that should not be exceeded for the fracture safety of the tank. In this study, a numerical study was conducted to examine how different crack lengths affect the critical inner pressure. For this purpose, 2, 4, 6, 8, and 10 cracks with mm dimensions were created in the PRNB model and the critical inner pressure value was

determined for the cracks. The crack region of the numerical studies is shown in Figure 4.56. The PRNB model displayed that the fracture size significantly affects the working pressure of the composite tank. If the crack was 10 mm, the critical pressure is 7 MPa, while the critical pressure is 38 MPa for a 2 mm fracture. The numerical results were summarized in Table 4.2 and shown in Figures 4.54 and 4.55.

Table 4.2. Critical internal pressure change depending on crack length

		Crack length (mm)				
		2	4	6	8	10
K_{IC} (36.90 MPa $\sqrt{m}$)	Critical inner pressure (MPa)	38.00	25.50	16.50	11.00	7.00
Constant inner pressure (7 MPa)	K_I (MPa $\sqrt{m}$)	5.53	8.23	12.71	19.59	36.90

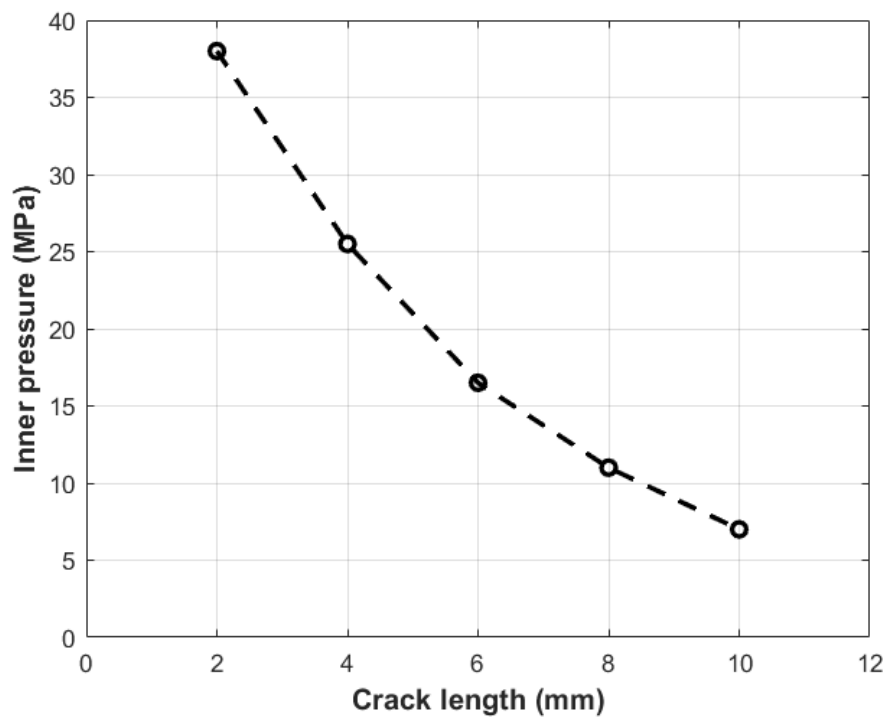


Figure 4.54. Critical inner pressure versus crack length

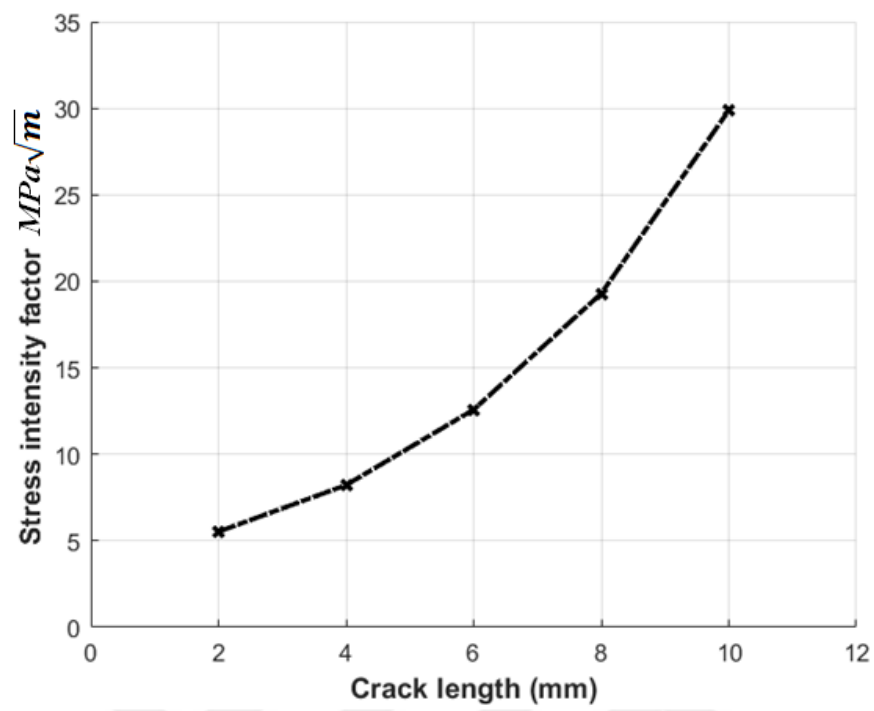


Figure 4.55. Stress intensity factor versus crack length

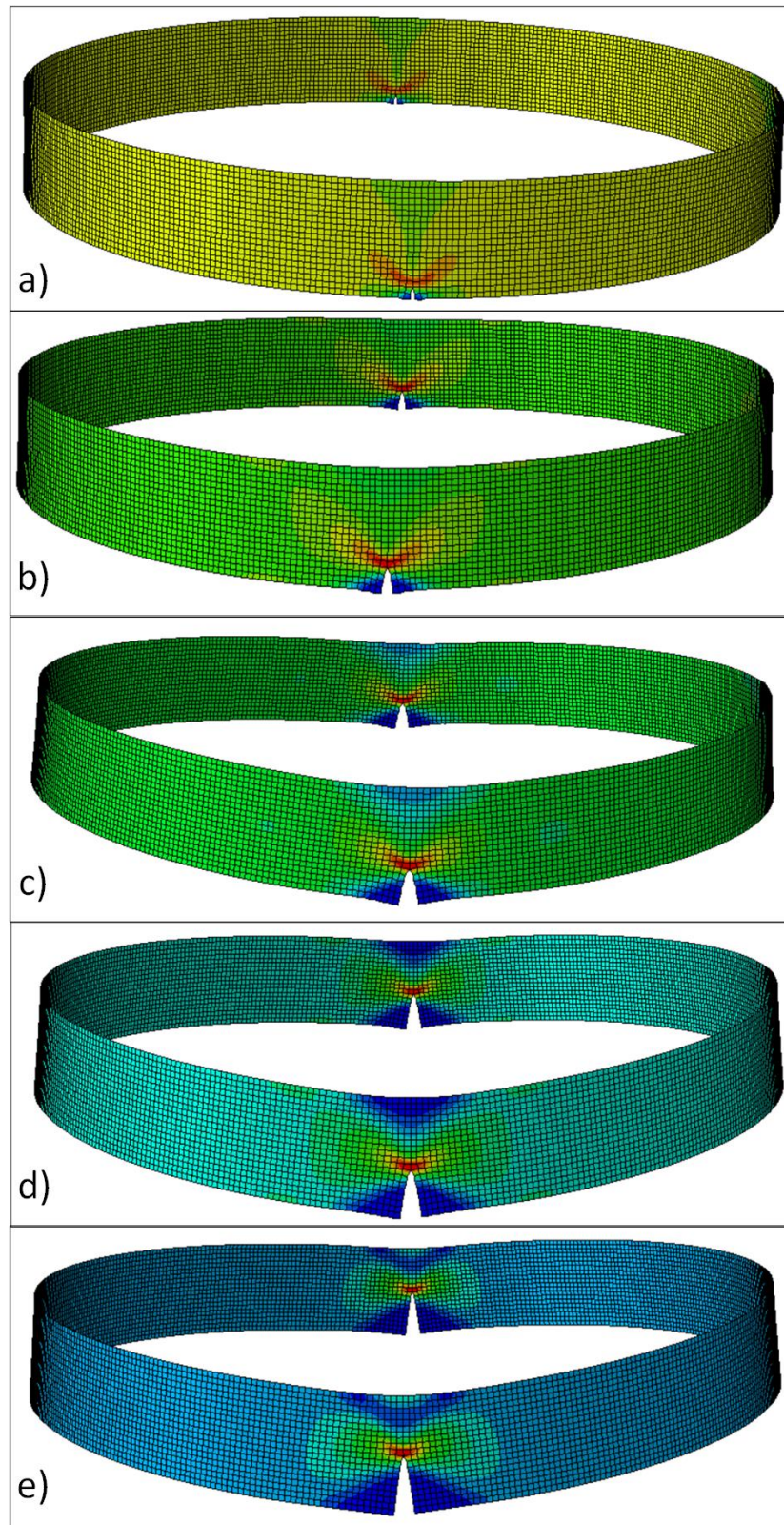


Figure 4.56. Crack regions of PRNB specimens (k constant) a) 2 mm crack length, b) 4 mm crack length, c) 6 mm crack length, d) 8 mm crack length, e) 10 mm crack length

5. CONCLUSION

Composite pressure tanks can successfully fulfill their duties in gas storage areas. Especially in fuel cell vehicles, composite pressure tanks that can withstand high pressure are preferred to increase the range. Gas storage at high pressures emerges as a critical situation in fuel cell vehicles. Therefore, it is necessary to examine and investigate the problems that may be encountered. Composite pressure tanks in fuel cell vehicles may be exposed to the environmental conditions to which the vehicle is exposed. In addition, the composite pressure tanks containing hydrogen must remain safe even in case these vehicles have an accident. Additionally, when filling and discharging of pressure tanks, the tank body may become fatigued due to pressure changes. The progression of micro-cracks in the body or due to operation endangers the safety of pressure tanks. Therefore, the safety of composite pressure tanks and determining safe operating pressure ranges are critical in hydrogen storage. In the classical approach, the strength of the material is determined in cases where there are no defects, voids, or micro cracks. This approach is based on the assumption that the material is perfect. However, depending on the operating or environmental conditions of composite pressure tanks, micro-cracks may occur and the crack size may increase. Whether fracture will occur under operating conditions or how critical the situation is can be determined by focusing on fracture toughness. Therefore, with the stress-oriented approach, fracture toughness should also be considered, and the working pressure ranges of composite pressure tanks that can operate safely under environmental conditions should be determined. For this purpose, it is aimed to be a guiding study in the development of high-tech composite pressure tanks in this field by performing a type III composite pressure tank stress-oriented, then fracture-oriented experimental and numerical studies.

Tensile test for flat plates is a method used to determine the tensile strength of the plate. When the curve-shaped material is flattened for measuring tensile stress, the material mechanical properties change. This process can change the mechanical properties of the material. This makes it difficult to obtain the actual strength values of the material. To measure the strength of curve materials, test samples should be taken close to the original shape of the material. Hoop tensile strength of the samples taken in the form of rings from composite pressure tanks or pipe materials can be determined by split disc tensile test. The SDT method transfers the load from the universal tensile test device to two separate discs and

creates stress in the gauge section of the samples by applying the tensile force. When this stress value reaches the ultimate stress value of the sample taken from the composite pressure tank, the sample breakage occurs. This value is determined as the hoop tensile stress value of the curve-shaped material. In addition, elastic modulus of the material was found from its slope by creating stress-strain graphs. With this method, the composite type III pressure tank material body can withstand was obtained with ultimate strength, stress-strain graph, and elastic modulus. In addition, tensile tests were carried out by numerical modeling of the composite pressure tank and compared with experimental results. According to the experimental and numerical results, the elastic modulus of the material was 53116 MPa and 53998 MPa respectively. The fact that the numerical model predicted the hoop tensile stress value of the material with a deviation of 1.66 percent showed that both the experimental and numerical models were successful.

There are many methods for measuring the fracture toughness of materials. Mode I, Mode II, Mode III, and a mixture of these three modes can be used to measure the desired fracture toughness values of materials. Stresses occur in the hoop and axial directions in the body of pressure tanks. The hoop stress is two times greater than the axial stress in Type I pressure tanks. In the case of type III containers, the stress in the hoop axis is again greater than the stress in the axis, although it varies according to the angle at which the fiber is wound. In this case, the critical mode for pressurized tanks is the mode I. For this reason, experimental and numerical studies have been conducted, focusing on the determination of Mode I fracture toughness of pressure tanks. Not all methods can be used to determine the Mode I fracture toughness of pressure vessels due to the curvature of the specimens taken from the vessel. This study was also concerned with this problem. Therefore, compact tensile specimen, one of the methods with known reliability, was used in the fracture toughness study. This method, known in the literature as the curved compact tensile method, can also be used to determine the fracture toughness of curved specimens. Besides this method, pipe ring notch bending was investigated experimentally and numerically. This method is more useful for determining the fracture toughness of curved specimens. It is particularly useful for circular specimens such as pipes or pressure vessels. It is difficult to take small-diameter specimens of curved materials and determine the fracture toughness due to the curvature of these materials. Furthermore, the numerical model of this procedure allows the determination of the critical internal pressure of

the pressure vessel as a function of the cracking width ratio. In this study, the fracture toughness of the tank was determined based on the CTS method, which is a widely accepted method. The fracture toughness of the tank was measured as $36.90 \text{ MPa}\sqrt{m}$ according to experimental studies with the CCT sample taken from the tank. In addition, the tank material was numerically modeled as CTS as a flat plate and predicted with 97.3% accuracy compared to the experimental results. To measure fracture toughness using the PRNB method, an analytical approach was suggested, and utilized for the PRNB method. In experimental studies, the fracture toughness of other PRNB samples taken from the tank was $36.90 \text{ MPa}\sqrt{m}$. It was estimated as $35.73 \text{ MPa}\sqrt{m}$ in the studies performed with the numerical model of this method. The results showed that the developed model estimated the fracture toughness of the tank with 96.83% accuracy. As a result of these studies, with the PRNB numerical model that we have developed, the pressure at which the fracture toughness is reached is determined and is referred to as the critical pressure value. In addition, the effect of the crack width ratio of the pressure vessel on the critical internal pressure values has been investigated. PRNB models with different fracture width ratios were developed. Using the numerical model, it was observed that the safe internal pressure was 38 MPa at a crack width ratio of 0.1, but decreased to 7 MPa at a crack width ratio of 0.5. These data show that the critical working pressure is seriously affected by the crack width ratio and that the safe working pressure of the pressure vessel is significantly reduced by the growth of the crack. Following the studies, the fracture toughness of the pressurized tank was compared with numerical models for both CTS and PRNB. In addition, this study presents, through both experimental and numerical studies, the methods that can be used to determine fracture toughness for pipes or pressure vessels. In addition, a different approach to the determination of fracture toughness has been developed as an alternative method that can be used to determine fracture toughness due to the inadequacy of the ASTM E 1850 standards for the PRNB method with the information available in the literature. The results of these studies will fill in the missing points in the ASTM standards for the determination of both the tensile strength and the fracture toughness of pipe or pressure vessel materials. Also, it will be a good reference way for future studies to be undertaken on this subject.

6. FUTURE STUDIES

In fuel cell vehicles, hydrogen is used as fuel, and storage in gaseous form is usually carried out in type III and type IV high-pressure composite tanks at pressure ranges of 35 - 70 MPa. The safety of the tank is one of the most important issues at these operating pressures. Since high storage pressures create high stresses in the body of the tank, the body's structure that can withstand the defined safety factor or higher pressures is the primary feature sought for these tanks. In fuel cell vehicles, higher storage pressure capacity will emerge as a need over time to increase the range of the fuel cell cars. Therefore, safety of the tanks will become a more important subject for augmenting gas storage capacity. Carrying out the studies listed below for safer tanks will be a guide in this field.

1. Since composite pressure vessels consist of a metal or polymer liner and a composite layer, delamination defects that may occur between liner and fiber wound layers can be investigated. In addition, fracture toughness between layers can be investigated by using different resins or adhesives.
2. To understand how winding angles of a composite layer, layer thickness and the use of different fiber materials change both the strength and fracture toughness of the tank, implementing different variations can be manufactured and tested with the fiber winding machine, and pioneering ideas for the production of safer tanks can be identified with this approach.
3. By creating numerical models, different liner materials can be used for tank, and the use of different materials, and the effect of material thickness can be investigated. In addition, optimization studies can be carried out to increase the storage performance of pressure tanks without inner liners. In light of these studies, weight reduction studies can be carried out by using less fiber winding.
4. As the cost of fibres used in composite pressure vessels is high, alternative natural fibres can be used or developed to reduce the cost of a tank. The strength and fracture toughness performances of these fibre materials at different winding angles and different layer thicknesses can be questioned.

5. Achieving higher gas storage capacity of composite pressure tanks can enable fuel cell vehicles to travel longer distances with increased hydrogen capacity. For this purpose, composite pressure tanks can be developed to provide higher storage capacity with increasing composite layers and different fiber winding orientations.

6. The curvature of body for composite pressure tanks or pipes, and the effects of curvature on the tensile strength and fracture toughness of materials can be investigated. For this aim, the tensile strength and fracture toughness behavior changes of the composite layer can be investigated by first manufacturing the composite layer in the form of a flat plate and then producing by increasing the curvature form.



REFERENCES

- [1] F. Dawood, M. Anda, and G. M. Shafiullah, "Hydrogen production for energy: An overview," *International Journal of Hydrogen Energy*, vol. 45, no. 7, pp. 3847–3869, Feb. 2020, doi: 10.1016/j.ijhydene.2019.12.059.
- [2] H. Ishaq, I. Dincer, and C. Crawford, "A review on hydrogen production and utilization: Challenges and opportunities," *International Journal of Hydrogen Energy*, vol. 47, no. 62, pp. 26238–26264, Jul. 2022, doi: 10.1016/j.ijhydene.2021.11.149.
- [3] N. Sazali, "Emerging technologies by hydrogen: A review," *International Journal of Hydrogen Energy*, vol. 45, no. 38, pp. 18753–18771, Jul. 2020, doi: 10.1016/j.ijhydene.2020.05.021.
- [4] X. Xu, Q. Zhou, and D. Yu, "The future of hydrogen energy: Bio-hydrogen production technology," *International Journal of Hydrogen Energy*, vol. 47, no. 79, pp. 33677–33698, Sep. 2022, doi: 10.1016/j.ijhydene.2022.07.261.
- [5] W. Zhang, A. Maleki, and M. Alhuyi Nazari, "Optimal operation of a hydrogen station using multi-source renewable energy (solar/wind) by a new approach," *Journal of Energy Storage*, vol. 53, p. 104983, Sep. 2022, doi: 10.1016/j.est.2022.104983.
- [6] X. Guo and M. Sepanta, "Evaluation of a new combined energy system performance to produce electricity and hydrogen with energy storage option," *Energy Reports*, vol. 7, pp. 1697–1711, Nov. 2021, doi: 10.1016/j.egy.2021.03.026.
- [7] J. Ren, N. M. Musyoka, H. W. Langmi, M. Mathe, and S. Liao, "Current research trends and perspectives on materials-based hydrogen storage solutions: A critical review," *International Journal of Hydrogen Energy*, vol. 42, no. 1, pp. 289–311, Jan. 2017, doi: 10.1016/j.ijhydene.2016.11.195.
- [8] M. Yue, H. Lambert, E. Pahon, R. Roche, S. Jemei, and D. Hissel, "Hydrogen energy systems: A critical review of technologies, applications, trends and challenges," *Renewable and Sustainable Energy Reviews*, vol. 146, p. 111180, Aug. 2021, doi: 10.1016/j.rser.2021.111180.
- [9] M. Ramadan, "A review on coupling Green sources to Green storage (G2G): Case study on solar-hydrogen coupling," *International Journal of Hydrogen Energy*, vol. 46, no. 59, pp. 30547–30558, Aug. 2021, doi: 10.1016/j.ijhydene.2020.12.165.
- [10] A. M. Abdalla, S. Hossain, O. B. Nisfindy, A. T. Azad, M. Dawood, and A. K. Azad, "Hydrogen production, storage, transportation and key challenges with applications: A review," *Energy Conversion and Management*, vol. 165, pp. 602–627, Jun. 2018, doi: 10.1016/j.enconman.2018.03.088.
- [11] S. Niaz, T. Manzoor, and A. H. Pandith, "Hydrogen storage: Materials, methods and perspectives," *Renewable and Sustainable Energy Reviews*, vol. 50, pp. 457–469, Oct. 2015, doi: 10.1016/j.rser.2015.05.011.
- [12] Y. Wang, B. Seo, B. Wang, N. Zamel, K. Jiao, and X. C. Adroher, "Fundamentals, materials, and machine learning of polymer electrolyte membrane fuel cell technology," *Energy and AI*, vol. 1, p. 100014, Aug. 2020, doi: 10.1016/j.egyai.2020.100014.
- [13] O. Z. Sharaf and M. F. Orhan, "An overview of fuel cell technology: Fundamentals and applications," *Renewable and Sustainable Energy Reviews*, vol. 32, pp. 810–853, Apr. 2014, doi: 10.1016/j.rser.2014.01.012.
- [14] A. Avcu, N. Choupani, and G. Tüccar, "A Numerical Investigation of The Fracture Energy of Materials for Fuel Cell End Plates," *European Mechanical Science*, vol. 5, no. 2, pp. 56–63, Jun. 2020, doi: 10.26701/ems.792302.

- [15] L. Giorgi, "Fuel Cells: Technologies and Applications," *TOFCJ*, vol. 6, no. 1, pp. 0–0, Jul. 2013, doi: 10.2174/1875932720130719001.
- [16] U. Lucia, "Overview on fuel cells," *Renewable and Sustainable Energy Reviews*, vol. 30, pp. 164–169, Feb. 2014, doi: 10.1016/j.rser.2013.09.025.
- [17] T. Wilberforce, A. Alaswad, A. Palumbo, M. Dassisti, and A. G. Olabi, "Advances in stationary and portable fuel cell applications," *International Journal of Hydrogen Energy*, vol. 41, no. 37, pp. 16509–16522, Oct. 2016, doi: 10.1016/j.ijhydene.2016.02.057.
- [18] Y. Luo, "Development and application of fuel cells in the automobile industry," *Journal of Energy Storage*, p. 19, 2021.
- [19] T. Sutharssan, D. Montalvao, Y. K. Chen, W.-C. Wang, C. Pisac, and H. Elemara, "A review on prognostics and health monitoring of proton exchange membrane fuel cell," *Renewable and Sustainable Energy Reviews*, vol. 75, pp. 440–450, Aug. 2017, doi: 10.1016/j.rser.2016.11.009.
- [20] Y. Wang, K. S. Chen, J. Mishler, S. C. Cho, and X. C. Adroher, "A review of polymer electrolyte membrane fuel cells: Technology, applications, and needs on fundamental research," *Applied Energy*, vol. 88, no. 4, pp. 981–1007, Apr. 2011, doi: 10.1016/j.apenergy.2010.09.030.
- [21] T. Yoshida and K. Kojima, "Toyota MIRAI Fuel Cell Vehicle and Progress Toward a Future Hydrogen Society," *Interface magazine*, vol. 24, no. 2, pp. 45–49, Jan. 2015, doi: 10.1149/2.F03152if.
- [22] M. A. J. Cropper, S. Geiger, and D. M. Jollie, "Fuel cells: a survey of current developments," *Journal of Power Sources*, vol. 131, no. 1–2, pp. 57–61, May 2004, doi: 10.1016/j.jpowsour.2003.11.080.
- [23] H. Pourrahmani *et al.*, "A Review on the Long-Term Performance of Proton Exchange Membrane Fuel Cells: From Degradation Modeling to the Effects of Bipolar Plates, Sealings, and Contaminants," *Energies*, vol. 15, no. 14, p. 5081, Jul. 2022, doi: 10.3390/en15145081.
- [24] A. G. Olabi, T. Wilberforce, and M. A. Abdelkareem, "Fuel cell application in the automotive industry and future perspective," *Energy*, vol. 214, p. 118955, Jan. 2021, doi: 10.1016/j.energy.2020.118955.
- [25] K. Xiong, W. Wu, S. Wang, and L. Zhang, "Modeling, design, materials and fabrication of bipolar plates for proton exchange membrane fuel cell: A review," *Applied Energy*, vol. 301, p. 117443, Nov. 2021, doi: 10.1016/j.apenergy.2021.117443.
- [26] A. K. Kaw, *Mechanics of composite materials*, 2nd ed. in Mechanical engineering, no. v. 29. Boca Raton, FL: Taylor & Francis, 2006.
- [27] E. J. Barbero, *Introduction to composite materials design*, Third edition. in Composite materials : analysis and design. Boca Raton: CRC Press, Taylor & Francis Group, CRC Press is an imprint of the Taylor & Francis Group, an informa business, 2018.
- [28] D. K. Rajak, D. D. Pagar, R. Kumar, and C. I. Pruncu, "Recent progress of reinforcement materials: a comprehensive overview of composite materials," *Journal of Materials Research and Technology*, vol. 8, no. 6, pp. 6354–6374, Nov. 2019, doi: 10.1016/j.jmrt.2019.09.068.
- [29] L. M. Manocha, "High performance carbon-carbon composites," *Sadhana*, vol. 28, no. 1–2, pp. 349–358, Feb. 2003, doi: 10.1007/BF02717143.
- [30] O. Kartav, "DOCTOR OF PHILOSOPHY," p. 138.

- [31] D. Rajak, D. Pagar, P. Menezes, and E. Linul, "Fiber-Reinforced Polymer Composites: Manufacturing, Properties, and Applications," *Polymers*, vol. 11, no. 10, p. 1667, Oct. 2019, doi: 10.3390/polym11101667.
- [32] K. K. Alaneme, E. A. Okotete, A. V. Fajemisin, and M. O. Bodunrin, "Applicability of metallic reinforcements for mechanical performance enhancement in metal matrix composites: a review," *Arab Journal of Basic and Applied Sciences*, vol. 26, no. 1, pp. 311–330, Jan. 2019, doi: 10.1080/25765299.2019.1628689.
- [33] J. Sun *et al.*, "A review on additive manufacturing of ceramic matrix composites," *Journal of Materials Science & Technology*, vol. 138, pp. 1–16, Mar. 2023, doi: 10.1016/j.jmst.2022.06.039.
- [34] Y. Song *et al.*, "CAE method for compression molding of carbon fiber-reinforced thermoplastic composite using bulk materials," *Composites Part A: Applied Science and Manufacturing*, vol. 114, pp. 388–397, Nov. 2018, doi: 10.1016/j.compositesa.2018.09.002.
- [35] A. B. M. Supian, S. M. Sapuan, M. Y. M. Zuhri, E. S. Zainudin, and H. H. Ya, "Hybrid reinforced thermoset polymer composite in energy absorption tube application: A review," *Defence Technology*, vol. 14, no. 4, pp. 291–305, Aug. 2018, doi: 10.1016/j.dt.2018.04.004.
- [36] M. Azeem *et al.*, "Application of Filament Winding Technology in Composite Pressure Vessels and Challenges: A Review," *Journal of Energy Storage*, vol. 49, no. August 2021, 2022, doi: 10.1016/j.est.2021.103468.
- [37] M. G. Sürer and H. T. Arat, "Advancements and current technologies on hydrogen fuel cell applications for marine vehicles," *International Journal of Hydrogen Energy*, vol. 47, no. 45, pp. 19865–19875, May 2022, doi: 10.1016/j.ijhydene.2021.12.251.
- [38] R. Moradi and K. M. Groth, "Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis," *International Journal of Hydrogen Energy*, vol. 44, no. 23, pp. 12254–12269, May 2019, doi: 10.1016/j.ijhydene.2019.03.041.
- [39] A. A. Alabbadi, O. A. Obaid, and A. A. AlZahrani, "A comparative economic study of nuclear hydrogen production, storage, and transportation," *International Journal of Hydrogen Energy*, vol. 54, pp. 849–863, Feb. 2024, doi: 10.1016/j.ijhydene.2023.08.225.
- [40] A. Air, M. Shamsuddoha, and B. Gangadhara Prusty, "A review of Type V composite pressure vessels and automated fibre placement based manufacturing," *Composites Part B: Engineering*, vol. 253, p. 110573, Mar. 2023, doi: 10.1016/j.compositesb.2023.110573.
- [41] H. Barthélémy, "Hydrogen storage – Industrial perspectives," *International Journal of Hydrogen Energy*, vol. 37, no. 22, pp. 17364–17372, Nov. 2012, doi: 10.1016/j.ijhydene.2012.04.121.
- [42] Y. Wang, J. Gong, and W. Jiang, "A quantitative description on fracture toughness of steels in hydrogen gas," *International Journal of Hydrogen Energy*, vol. 38, no. 28, pp. 12503–12508, Sep. 2013, doi: 10.1016/j.ijhydene.2013.07.033.
- [43] C. P. Fowler, A. C. Orifici, and C. H. Wang, "A review of toroidal composite pressure vessel optimisation and damage tolerant design for high pressure gaseous fuel storage," *International Journal of Hydrogen Energy*, vol. 41, no. 47, pp. 22067–22089, Dec. 2016, doi: 10.1016/j.ijhydene.2016.10.039.

- [44] H. Barthelemy, M. Weber, and F. Barbier, "Hydrogen storage: Recent improvements and industrial perspectives," *International Journal of Hydrogen Energy*, vol. 42, no. 11, pp. 7254–7262, Mar. 2017, doi: 10.1016/j.ijhydene.2016.03.178.
- [45] J. Li *et al.*, "Small-Scale High-Pressure Hydrogen Storage Vessels: A Review," *Materials*, vol. 17, no. 3, p. 721, Feb. 2024, doi: 10.3390/ma17030721.
- [46] C. Shen *et al.*, "Consequence assessment of high-pressure hydrogen storage tank rupture during fire test," *Journal of Loss Prevention in the Process Industries*, vol. 55, pp. 223–231, Sep. 2018, doi: 10.1016/j.jlp.2018.06.016.
- [47] R. Zalosh and N. Weyandt, "Hydrogen Fuel Tank Fire Exposure Burst Test," presented at the SAE 2005 World Congress & Exhibition, Apr. 2005, pp. 2005-01–1886. doi: 10.4271/2005-01-1886.
- [48] J. O. Abe, A. P. I. Popoola, E. Ajenifuja, and O. M. Popoola, "Hydrogen energy, economy and storage: Review and recommendation," *International Journal of Hydrogen Energy*, vol. 44, no. 29, pp. 15072–15086, Jun. 2019, doi: 10.1016/j.ijhydene.2019.04.068.
- [49] S. Kangal, O. Kartav, M. Tanoğlu, E. Aktaş, and H. S. Artem, "Investigation of interlayer hybridization effect on burst pressure performance of composite overwrapped pressure vessels with load-sharing metallic liner," *Journal of Composite Materials*, vol. 54, no. 7, pp. 961–980, Mar. 2020, doi: 10.1177/0021998319870588.
- [50] J. P. Berro Ramirez, D. Halm, J.-C. Grandidier, S. Villalonga, and F. Nony, "700 bar type IV high pressure hydrogen storage vessel burst – Simulation and experimental validation," *International Journal of Hydrogen Energy*, vol. 40, no. 38, pp. 13183–13192, Oct. 2015, doi: 10.1016/j.ijhydene.2015.05.126.
- [51] J. P. Berro Ramirez, D. Halm, J. C. Grandidier, S. Villalonga, and F. Nony, "700 bar type IV high pressure hydrogen storage vessel burst - Simulation and experimental validation," *International Journal of Hydrogen Energy*, vol. 40, no. 38, pp. 13183–13192, 2015, doi: 10.1016/j.ijhydene.2015.05.126.
- [52] D. S. Son and S. H. Chang, "Evaluation of modeling techniques for a type III hydrogen pressure vessel (70 MPa) made of an aluminum liner and a thick carbon/epoxy composite for fuel cell vehicles," *International Journal of Hydrogen Energy*, vol. 37, no. 3, pp. 2353–2369, 2012, doi: 10.1016/j.ijhydene.2011.11.001.
- [53] J. Marzbanrad, A. Paykani, A. Afkar, and M. Ghajar, "Finite element analysis of composite high-pressure hydrogen storage vessels," *Journal of Materials and Environmental Science*, vol. 4, no. 1, pp. 63–74, 2013.
- [54] L. Wang, C. Zheng, H. Luo, S. Wei, and Z. Wei, "Continuum damage modeling and progressive failure analysis of carbon fiber/epoxy composite pressure vessel," *Composite Structures*, vol. 134, pp. 475–482, 2015, doi: 10.1016/j.compstruct.2015.08.107.
- [55] X. Wang *et al.*, "ScienceDirect Advances on materials design and manufacture technology of plastic liner of type IV hydrogen storage vessel," *International Journal of Hydrogen Energy*, vol. 47, no. 13, pp. 8382–8408, 2022, doi: 10.1016/j.ijhydene.2021.12.198.
- [56] E. S. Barboza Neto, M. Chludzinski, P. B. Roese, J. S. O. Fonseca, S. C. Amico, and C. A. Ferreira, "Experimental and numerical analysis of a LLDPE/HDPE liner for a composite pressure vessel," *Polymer Testing*, vol. 30, no. 6, pp. 693–700, Sep. 2011, doi: 10.1016/j.polymertesting.2011.04.016.

- [57] B. Liao, D. Wang, L. Jia, J. Zheng, and C. Gu, "Continuum damage modeling and progressive failure analysis of a Type III composite vessel by considering the effect of autofrettage *," vol. 20, no. 1, pp. 36–49, 2019.
- [58] A. Błachut *et al.*, "Influence of fiber tension during filament winding on the mechanical properties of composite pressure vessels," *Composite Structures*, vol. 304, p. 116337, Jan. 2023, doi: 10.1016/j.compstruct.2022.116337.
- [59] A. W. Abdel-Ghany, I. Taha, and S. J. Ebeid, "Failure Prediction of Fiber Reinforced Polymer Pipes using FEA," vol. 4, no. 2, p. 7, 2016.
- [60] A. Onder, O. Sayman, T. Dogan, and N. Tarakcioglu, "Burst failure load of composite pressure vessels," *Composite Structures*, vol. 89, no. 1, pp. 159–166, 2009, doi: 10.1016/j.compstruct.2008.06.021.
- [61] S. Kangal, O. Kartav, M. Tanoğlu, E. Aktaş, and H. S. Artem, "Investigation of interlayer hybridization effect on burst pressure performance of composite overwrapped pressure vessels with load-sharing metallic liner," *Journal of Composite Materials*, vol. 54, no. 7, pp. 961–980, 2020, doi: 10.1177/0021998319870588.
- [62] O. Kartav, S. Kangal, K. Yüçetürk, M. Tanoğlu, E. Aktaş, and H. S. Artem, "Development and analysis of composite overwrapped pressure vessels for hydrogen storage," *Journal of Composite Materials*, vol. 55, no. 28, pp. 4141–4155, 2021, doi: 10.1177/00219983211033568.
- [63] H. Jemii, A. Bahri, A. Boubakri, D. Hammiche, K. Elleuch, and N. Guermazi, "On the mechanical behaviour of industrial PVC pipes under pressure loading: experimental and numerical studies," *J Polym Res*, vol. 27, no. 8, p. 240, Aug. 2020, doi: 10.1007/s10965-020-02222-1.
- [64] S. Bobba, Z. Leman, E. S. Zainudin, S. M. Sapuan, 1 Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Malaysia, and 2 Advanced Engineering Materials and Composites Research Centre, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Malaysia, "Hoop tensile strength behaviour between different thicknesses E-glass and S-glass FRP rings," *AIMS Materials Science*, vol. 6, no. 3, pp. 315–327, 2019, doi: 10.3934/matricsci.2019.3.315.
- [65] I. Barsoum and K. F. Al Ali, "A procedure to determine the tangential true stress-strain behavior of pipes," *International Journal of Pressure Vessels and Piping*, vol. 128, pp. 59–68, Apr. 2015, doi: 10.1016/j.ijpvp.2014.11.002.
- [66] C. Kaynak, E. Salim Erdiller, L. Parnas, and F. Senel, "Use of split-disk tests for the process parameters of filament wound epoxy composite tubes," *Polymer Testing*, vol. 24, no. 5, pp. 648–655, Aug. 2005, doi: 10.1016/j.polymertesting.2005.03.012.
- [67] T.-K. Hwang, J.-B. Park, and H.-G. Kim, "Evaluation of fiber material properties in filament-wound composite pressure vessels," *Composites Part A: Applied Science and Manufacturing*, vol. 43, no. 9, pp. 1467–1475, Sep. 2012, doi: 10.1016/j.compositesa.2012.04.005.
- [68] E. J. Walsh and D. O. Adams, "Development and Evaluation of the Quadrant Ring Test Method," *Exp Mech*, vol. 48, no. 3, pp. 319–326, Jun. 2008, doi: 10.1007/s11340-007-9089-x.
- [69] F. Saghir *et al.*, "Mechanical characterization of particulated FRP composite pipes: A comprehensive experimental study," *Polymer Testing*, vol. 93, p. 107001, Jan. 2021, doi: 10.1016/j.polymertesting.2020.107001.
- [70] M.-G. Kim, S.-G. Kang, C.-G. Kim, and C.-W. Kong, "Thermally induced stress analysis of composite/aluminum ring specimens at cryogenic temperature," *Composites*

- Science and Technology*, vol. 68, no. 3–4, pp. 1080–1087, Mar. 2008, doi: 10.1016/j.compscitech.2007.03.015.
- [71] J.-W. Kim *et al.*, “Assessment of carbon nanotube yarns as reinforcement for composite overwrapped pressure vessels,” *Composites Part A: Applied Science and Manufacturing*, vol. 84, pp. 256–265, May 2016, doi: 10.1016/j.compositesa.2016.02.003.
 - [72] M. Azeem, “Influence of winding angles on hoop stress in composite pressure vessels: Finite element analysis,” 2024.
 - [73] D. V. Srividya, S. Khadar Vali, B. Hadya, and S. Irfan Sadaq, “Failure analysis of composite pressure vessel by means of natural and synthetic fibers,” *Materials Today: Proceedings*, p. S2214785323041573, Aug. 2023, doi: 10.1016/j.matpr.2023.07.287.
 - [74] S. Doddamani, J. O. Kiran, M. Kaleemulla, and B. Bakkappa, “Fracture Toughness Testing of 6061Al–Graphite Composites Using SENB Specimens,” *J. Inst. Eng. India Ser. D*, vol. 100, no. 2, pp. 195–201, Oct. 2019, doi: 10.1007/s40033-019-00188-z.
 - [75] M. Abu-Okail, M. Nafea, M. A. Ghanem, M. N. El-Sheikh, A. E. El-Nikhaily, and A. Abu-Oqail, “Damage Mechanism Evaluation of Polymer Matrix Composite Reinforced with Glass Fiber via Modified Arcan Test Specimens,” *J Fail. Anal. and Preven.*, vol. 21, no. 2, pp. 451–461, Apr. 2021, doi: 10.1007/s11668-020-01078-3.
 - [76] A. Desai, C. M. Sharanaprabhu, and S. K. Kudari, “Study on translaminar fracture toughness under mixed mode I/II load for $(0/45)^\circ$ orientation unidirectional glass/epoxy composite,” *Materials Today: Proceedings*, vol. 38, pp. 2629–2632, 2021, doi: 10.1016/j.matpr.2020.08.206.
 - [77] N. Choupani, “Mixed-mode I/II Interlaminar Fracture of CF/PEI Composite Material,” p. 9.
 - [78] M. R. Molteno and T. H. Becker, “Mode I-III Decomposition of the J -integral from DIC Displacement Data: Mode I-III J -integral Decomposition from DIC Data,” *Strain*, vol. 51, no. 6, pp. 492–503, Dec. 2015, doi: 10.1111/str.12166.
 - [79] A. O. Ayhan and O. Demir, “A novel test system for mixed mode-I/II/III fracture tests – Part 1: Modeling and numerical analyses,” *Engineering Fracture Mechanics*, vol. 218, p. 106597, Sep. 2019, doi: 10.1016/j.engfracmech.2019.106597.
 - [80] M. H. Heydari, N. Choupani, and M. Shameli, “Experimental and Numerical Investigation of Mixed-Mode Interlaminar Fracture of Carbon-Polyester Laminated Woven Composite by Using Arcan Set-up,” *Appl Compos Mater*, vol. 18, no. 6, pp. 499–511, Dec. 2011, doi: 10.1007/s10443-011-9223-x.
 - [81] A. Szekrenyes, “OVERVIEW ON THE EXPERIMENTAL INVESTIGATIONS OF THE FRACTURE TOUGHNESS IN COMPOSITE MATERIALS,” p. 19.
 - [82] “Pipe Composite Fracture toughness_ Experimental and numerical analysis of mode-I interlaminar fracture.pdf.”
 - [83] S. Baali, “EXPERIMENTAL INVESTIGATION OF THE DELAMINATION BEHAVIOR OF GLASS-FIBRE REINFORCED COMPOSITE PIPES”.
 - [84] “Sako vd. - 2022 - Experiments on the mode II fracture toughness in E.pdf.”
 - [85] “Effect of a new specimen size on fatigue crack growth behavior in.pdf.”
 - [86] V. Asghari, N. Choupani, and M. Hanifi, “CVN–KJC correlation model for API X65 gas pipeline,” *Engineering Failure Analysis*, vol. 79, pp. 51–63, Sep. 2017, doi: 10.1016/j.engfailanal.2017.04.007.
 - [87] E. Alizadeh and M. Dehestani, “Analytical and numerical fracture analysis of pressure vessel containing wall crack and reinforcement with CFRP laminates,” *Thin-Walled Structures*, vol. 127, pp. 210–220, Jun. 2018, doi: 10.1016/j.tws.2018.02.009.

- [88] H. Jemii, A. Bahri, R. Taktak, N. Guermazi, and F. Lebon, "Mechanical behavior and fracture characteristics of polymeric pipes under curved three point bending tests: Experimental and numerical approaches," *Engineering Failure Analysis*, vol. 138, p. 106352, Aug. 2022, doi: 10.1016/j.engfailanal.2022.106352.
- [89] J. Chen and H. Pan, "Stress intensity factor of semi-elliptical surface crack in a cylinder with hoop wrapped composite layer," *International Journal of Pressure Vessels and Piping*, vol. 110, pp. 77–81, Oct. 2013, doi: 10.1016/j.ijpvp.2013.04.026.
- [90] D. Damjanović, D. Kozak, Y. Matvienko, and N. Gubeljak, "Correlation of Pipe Ring Notched Bend (PRNB) specimen and Single Edge Notch Bend (SENB) specimen in determination of fracture toughness of pipe material: Pipe Notched Bend Specimens Cut Out From Pipe for Fracture Toughness Testing," *Fatigue Fract Engng Mater Struct*, vol. 40, no. 8, pp. 1251–1259, Aug. 2017, doi: 10.1111/ffe.12581.
- [91] W. Musrati *et al.*, "Fracture analysis of axially flawed ring-shaped bending specimen," *Procedia Structural Integrity*, vol. 13, pp. 1828–1833, 2018, doi: 10.1016/j.prostr.2018.12.333.
- [92] H.-H. Hsu, "An evaluation of hydrided Zircaloy-4 cladding fracture behavior by X-specimen test," *Journal of Alloys and Compounds*, vol. 426, no. 1–2, pp. 256–262, Dec. 2006, doi: 10.1016/j.jallcom.2005.12.113.
- [93] D. Cartié, P. Davies, M. Peleau, and I. K. Partridge, "The influence of hydrostatic pressure on the interlaminar fracture toughness of carbon/epoxy composites," *Composites Part B: Engineering*, vol. 37, no. 4–5, pp. 292–300, Jun. 2006, doi: 10.1016/j.compositesb.2005.12.002.
- [94] G. Quino, J. El Yagoubi, and G. Lubineau, "Characterizing the toughness of an epoxy resin after wet aging using compact tension specimens with non-uniform moisture content," *Polymer Degradation and Stability*, vol. 109, pp. 319–326, Nov. 2014, doi: 10.1016/j.polymdegradstab.2014.08.005.
- [95] S. Sajith, K. S. R. K. Murthy, and P. S. Robi, "Experimental and numerical investigation of mixed mode fatigue crack growth models in aluminum 6061-T6," *International Journal of Fatigue*, vol. 130, p. 105285, Jan. 2020, doi: 10.1016/j.ijfatigue.2019.105285.
- [96] L. Jemblie, H. Bjaaland, B. Nyhus, V. Olden, and O. M. Akselsen, "Fracture toughness and hydrogen embrittlement susceptibility on the interface of clad steel pipes with and without a Ni-interlayer," *Materials Science and Engineering: A*, vol. 685, pp. 87–94, Feb. 2017, doi: 10.1016/j.msea.2016.12.116.
- [97] H. Liu, B. G. Falzon, G. Catalanotti, and W. Tan, "An experimental method to determine the intralaminar fracture toughness of high-strength carbon-fibre reinforced composite aerostructures," *Aeronaut. j.*, vol. 122, no. 1255, pp. 1352–1370, Sep. 2018, doi: 10.1017/aer.2018.78.
- [98] Y. Zheng, G. Z. Wang, S. T. Tu, and F. Z. Xuan, "Constraint characterization and fracture initiation analysis for semi-elliptical surface cracks in reactor pressure vessel," *International Journal of Pressure Vessels and Piping*, vol. 202, p. 104910, Apr. 2023, doi: 10.1016/j.ijpvp.2023.104910.
- [99] S.-J. Sung, J. Pan, S. St Lawrence, and D. A. Scarth, "Effects of curvature on ductile fracture initiation in curved compact tension specimens of hydrided irradiated Zr-2.5Nb materials with split circumferential hydrides," *Engineering Fracture Mechanics*, vol. 211, pp. 180–197, Apr. 2019, doi: 10.1016/j.engfracmech.2019.02.019.
- [100] S. Wu, J. Pan, and D. A. Scarth, "Finite element analyses of crack extensions in curved compact tension specimens of irradiated Zr-2.5Nb pressure tube materials by nodal

- release method and cohesive zone modeling approach,” *Engineering Fracture Mechanics*, vol. 271, p. 108676, Aug. 2022, doi: 10.1016/j.engfracmech.2022.108676.
- [101] W. Zhang, “Technical Problem Identification for the Failures of the Liberty Ships,” *Challenges*, vol. 7, no. 2, p. 20, 2016, doi: 10.3390/challe7020020.
- [102] B. Djordjevic, A. Sedmak, B. Petrovski, and A. Dimic, “Probability distribution on cleavage fracture in function of J for reactor ferritic steel in transition temperature region,” *Engineering Failure Analysis*, vol. 125, p. 105392, Jul. 2021, doi: 10.1016/j.engfailanal.2021.105392.
- [103] E. Şar, “A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES OF MIDDLE EAST TECHNICAL UNIVERSITY”.
- [104] A. M. Cassa, J. E. van Zyl, and R. F. Laubscher, “A numerical investigation into the effect of pressure on holes and cracks in water supply pipes,” *Urban Water Journal*, vol. 7, no. 2, pp. 109–120, 2010, doi: 10.1080/15730620903447613.
- [105] “Fracture Mechanics.pdf.”
- [106] C. T. Sun and Z.-H. Jin, *Fracture mechanics*. Waltham, MA: Academic Press, 2012.
- [107] C. H. Wang, “Introduction to Fracture Mechanics,” 1996, doi: 10.13140/RG.2.1.1444.2408.
- [108] P. Sharma, H. S. Mali, and A. Dixit, “Mechanical behavior and fracture toughness characterization of high strength fiber reinforced polymer textile composites,” *Iran Polym J*, vol. 30, no. 2, pp. 193–233, Feb. 2021, doi: 10.1007/s13726-020-00884-8.
- [109] N. Choupani, “Characterization of fracture in adhesively bonded double-lap joints,” *International Journal of Adhesion and Adhesives*, vol. 29, no. 8, pp. 761–773, 2009, doi: 10.1016/j.ijadhadh.2009.05.002.
- [110] D. Roucou, J. Diani, M. Brieu, and A. Mbiakop-Ngassa, “Critical strain energy release rate for rubbers: single edge notch tension versus pure shear tests,” *International Journal of Fracture*, vol. 216, no. 1, pp. 31–39, 2019, doi: 10.1007/s10704-018-00336-8.
- [111] L. P. Pook, “Crack paths and the linear elastic analysis of cracked bodies,” *Frattura ed Integrità Strutturale*, vol. 9, no. 34, p. 16, Sep. 2015, doi: 10.3221/IGF-ESIS.34.16.
- [112] S. Yoneyama, S. Arikawa, S. Kusayanagi, and K. Hazumi, “Evaluating J-integral from displacement fields measured by digital image correlation,” *Strain*, vol. 50, no. 2, pp. 147–160, 2014, doi: 10.1111/str.12074.
- [113] M. Borges, M. Caldas, F. Antunes, R. Branco, and P. Prates, “Fatigue crack growth from notches: A numerical analysis,” *Applied Sciences (Switzerland)*, vol. 10, no. 12, 2020, doi: 10.3390/APP10124174.
- [114] G. C. Tsai and J. W. Chen, “Effect of stitching on Mode I strain energy release rate,” *Composite Structures*, vol. 69, no. 1, pp. 1–9, 2005, doi: 10.1016/j.compstruct.2004.02.009.
- [115] “Elements of fracture.pdf.”
- [116] Y. Ju *et al.*, “Visualization method for stress-field evolution during rapid crack propagation using 3D printing and photoelastic testing techniques,” *Scientific Reports*, vol. 8, no. 1, pp. 1–10, 2018, doi: 10.1038/s41598-018-22773-0.
- [117] H. Moustabchir, J. Arbaoui, A. Zitouni, S. Hariri, and I. Dmytrakh, “Numerical analysis of stress intensity factor and T-stress in pipeline of steel P264GH submitted to loading conditions,” *Journal of Theoretical and Applied Mechanics (Poland)*, vol. 53, no. 3, pp. 665–672, 2015, doi: 10.15632/jtam-pl.53.3.665.

- [118] W. Hua *et al.*, “A review of mixed mode I-II fracture criteria and their applications in brittle or quasi-brittle fracture analysis,” *Theoretical and Applied Fracture Mechanics*, vol. 124, p. 103741, Apr. 2023, doi: 10.1016/j.tafmec.2022.103741.
- [119] E. Preiß, *Fracture toughness of freestanding metallic thin films studied by bulge testing*. 2018.
- [120] Š. Hajdu, “The investigation of the stress state near the crack tip of central cracks through numerical analysis,” *Procedia Engineering*, vol. 69, pp. 477–485, 2014, doi: 10.1016/j.proeng.2014.03.015.
- [121] A. F. Bower, *Applied mechanics of solids*. Boca Raton: CRC Press, 2010.
- [122] Š. Hajdu, “The Investigation of the Stress State near the Crack Tip of Central Cracks through Numerical Analysis,” *Procedia Engineering*, vol. 69, pp. 477–485, 2014, doi: 10.1016/j.proeng.2014.03.015.
- [123] N. Choupani, “Experimental and numerical investigation of the mixed-mode delamination in Arcan laminated specimens,” *Materials Science and Engineering A*, vol. 478, no. 1–2, pp. 229–242, 2008, doi: 10.1016/j.msea.2007.05.103.
- [124] C. Boğa, “Investigation of mechanical and fracture behavior of pure and carbon fiber reinforced ABS samples processed by fused filament fabrication process,” *RPJ*, vol. 27, no. 6, pp. 1220–1229, Jul. 2021, doi: 10.1108/RPJ-11-2020-0296.
- [125] R. Unnþórsson, M. T. Jonsson, and T. P. Runarsson, “NDT METHODS FOR EVALUATING CARBON FIBER COMPOSITES”.
- [126] H. Yavuz and D. H. Utku, “Parametric and non-parametric tests for the evaluation of interlaminar fracture toughness of polymer composites,” *Journal of Reinforced Plastics and Composites*, vol. 40, no. 11–12, pp. 450–462, Jun. 2021, doi: 10.1177/0731684420973078.
- [127] N. Chandarana, D. Sanchez, C. Soutis, and M. Gresil, “Early Damage Detection in Composites during Fabrication and Mechanical Testing,” *Materials*, vol. 10, no. 7, p. 685, Jun. 2017, doi: 10.3390/ma10070685.
- [128] M. Bowkett and K. Thanapalan, “Comparative analysis of failure detection methods of composites materials’ systems,” *Systems Science & Control Engineering*, vol. 5, no. 1, pp. 168–177, Jan. 2017, doi: 10.1080/21642583.2017.1311240.
- [129] E. S. Greenhalgh and M. J. Hiley, “FRACTOGRAPHY OF POLYMER COMPOSITES: CURRENT STATUS AND FUTURE ISSUES”.
- [130] D. M. Montenegro *et al.*, “Mode I transverse intralaminar fracture in glass fiber-reinforced polymers with ductile matrices,” *Composite Structures*, vol. 165, pp. 65–73, Apr. 2017, doi: 10.1016/j.compstruct.2016.12.008.
- [131] M. Nikbakht and N. Choupani, “Fracture Toughness Characterization of Carbon-Epoxy Composite using Arcan Specimen,” *International Journal of Mechanical and Mechatronics Engineering*, vol. 2, no. 5, pp. 690–696, 2008, doi: 10.5281/zenodo.1059685.
- [132] A. AVCU, “Fracture energy comparison of aluminum and boron composites for fuel cell end plates,” *International Journal of Energy Applications and Technologies*, vol. 7, no. 4, pp. 149–153, 2020, doi: 10.31593/ijeat.795403.
- [133] M. J. Laffan, S. T. Pinho, P. Robinson, and A. J. McMillan, “Translaminar fracture toughness testing of composites: A review,” *Polymer Testing*, vol. 31, no. 3, pp. 481–489, 2012, doi: 10.1016/j.polymertesting.2012.01.002.
- [134] X. K. Zhu and J. A. Joyce, “Review of fracture toughness (G, K, J, CTOD, CTOA) testing and standardization,” *Engineering Fracture Mechanics*, vol. 85, pp. 1–46, 2012, doi: 10.1016/j.engfracmech.2012.02.001.

- [135] B. R. Murray *et al.*, “Crack tip monitoring of mode I and mode II delamination in CF/Epoxy under static and dynamic loading conditions using digital image correlation & dagger;,” p. 5225, 2018, doi: 10.3390/icem18-05225.
- [136] H. Miyagawa, C. Sato, and K. Ikegami, “Interlaminar fracture toughness of CFRP in Mode I and Mode II determined by Raman spectroscopy,” *Composites Part A: Applied Science and Manufacturing*, vol. 32, no. 3–4, pp. 477–486, 2001, doi: 10.1016/S1359-835X(00)00104-4.
- [137] M. Srinivasan and S. Seetharamu, “Fracture Toughness of Metal Castings,” in *Science and Technology of Casting Processes*, M. Srinivasan, Ed., InTech, 2012. doi: 10.5772/50297.
- [138] P. C. Gope, V. K. Singh, and D. K. Rao, “Mode I fracture toughness of bio-fiber and bio-shell particle reinforced epoxy bio-composites,” *Journal of Reinforced Plastics and Composites*, vol. 34, no. 13, pp. 1075–1089, Jul. 2015, doi: 10.1177/0731684415586277.
- [139] A. Siddique *et al.*, “Mode I fracture toughness of fiber-reinforced polymer composites: A review,” *Journal of Industrial Textiles*, vol. 50, no. 8, pp. 1165–1192, Mar. 2021, doi: 10.1177/1528083719858767.
- [140] W. Musraty *et al.*, “Ductile fracture of pipe-ring notched bend specimens – Micromechanical analysis,” *Engineering Fracture Mechanics*, vol. 175, pp. 247–261, Apr. 2017, doi: 10.1016/j.engfracmech.2017.01.022.
- [141] Z. Yian, S. L. Keey, and C. G. Boay, “Effects of seawater exposure on mode II fatigue delamination growth of a woven E-glass/bismaleimide composite,” *Journal of Reinforced Plastics and Composites*, vol. 35, no. 2, pp. 138–150, 2016, doi: 10.1177/0731684415609139.
- [142] M. R. Ayatollahi and M. R. M. Aliha, “On determination of mode II fracture toughness using semi-circular bend specimen,” *International Journal of Solids and Structures*, vol. 43, no. 17, pp. 5217–5227, 2006, doi: 10.1016/j.ijsolstr.2005.07.049.
- [143] T. Tamilselvan, K. W. Lo, Y. B. Gong, and M. O. Lai, “a Study of Mode Ii Fracture Toughness Test Standardisation of Metals,” *ICF10, Honolulu, Hawaii - 2001*, 2001.
- [144] B. R. K. Blackman, A. J. Brunner, and J. G. Williams, “Mode II fracture testing of composites: a new look at an old problem,” *Engineering Fracture Mechanics*, vol. 73, no. 16, pp. 2443–2455, Nov. 2006, doi: 10.1016/j.engfracmech.2006.05.022.
- [145] A. M. Alshoaibi, “Computational Simulation of 3D Fatigue Crack Growth under Mixed-Mode Loading,” *Applied Sciences*, vol. 11, no. 13, p. 5953, Jun. 2021, doi: 10.3390/app11135953.
- [146] M. R. M. Aliha, A. Bahmani, and S. Akhondi, “Determination of mode III fracture toughness for different materials using a new designed test configuration,” *Materials and Design*, vol. 86, pp. 863–871, 2015, doi: 10.1016/j.matdes.2015.08.033.
- [147] A. E. Oskui, N. Choupani, and M. Shameli, “3D characterization of mixed-mode fracture toughness of materials using a new loading device,” *Latin American Journal of Solids and Structures*, vol. 13, no. 8, pp. 1464–1482, 2016, doi: 10.1590/1679-78252779.
- [148] D. Zhao and Y. Wang, “Mode III fracture behavior of laminated composite with edge crack in torsion,” *Theoretical and Applied Fracture Mechanics*, vol. 29, no. 2, pp. 109–123, Jun. 1998, doi: 10.1016/S0167-8442(98)00023-8.
- [149] M. R. M. Aliha and A. Bahmani, “Rock Fracture Toughness Study Under Mixed Mode I/III Loading,” *Rock Mech Rock Eng*, vol. 50, no. 7, pp. 1739–1751, Jul. 2017, doi: 10.1007/s00603-017-1201-7.

- [150] Y. Ge, X. Gong, A. Hurez, and E. De Luycker, "Test methods for measuring pure mode III delamination toughness of composite," *Polymer Testing*, vol. 55, pp. 261–268, Oct. 2016, doi: 10.1016/j.polymertesting.2016.08.025.
- [151] Bertorello, Argüelles, Mollón, Bonhomme, Viña, and Viña, "Use of a LHFB Device for Testing Mode III in a Composite Laminate," *Polymers*, vol. 11, no. 8, p. 1243, Jul. 2019, doi: 10.3390/polym11081243.
- [152] G. J. Becht and J. W. Gillespie, "Numerical and experimental evaluation of the Mode III interlaminar fracture toughness of composite materials," *Polymer Composites*, vol. 10, no. 5, pp. 293–304, Oct. 1989, doi: 10.1002/pc.750100505.
- [153] H. A. Richard, B. Schramm, and N. H. Schirmeisen, "Cracks on Mixed Mode loading - Theories, experiments, simulations," *International Journal of Fatigue*, vol. 62, pp. 93–103, 2014, doi: 10.1016/j.ijfatigue.2013.06.019.
- [154] G. M. Pearce, C. Tao, Y. H. E. Quek, and N. T. Chowdhury, "A modified Arcan test for mixed-mode loading of bolted joints in composite structures," *Composite Structures*, vol. 187, no. September 2017, pp. 203–211, 2018, doi: 10.1016/j.compstruct.2017.12.062.
- [155] O. Demir, S. İriç, A. O. Ayhan, and H. Lekesiz, "Investigation of mixed mode - I/II fracture problems - part 1: Computational and experimental analyses," *Frattura ed Integrità Strutturale*, vol. 10, no. 35, pp. 330–339, 2016, doi: 10.3221/IGF-ESIS.35.38.
- [156] M. Bozkurt, A. O. Ayhan, M. F. Yaren, and S. İriç, "Finite element modeling and experimental studies on mixed mode-I/III fracture specimens," *Frattura ed Integrità Strutturale*, vol. 10, no. 35, pp. 350–359, 2016, doi: 10.3221/IGF-ESIS.35.40.
- [157] G. M. Pearce, C. Tao, Y. H. E. Quek, and N. T. Chowdhury, "A modified Arcan test for mixed-mode loading of bolted joints in composite structures," *Composite Structures*, vol. 187, pp. 203–211, Mar. 2018, doi: 10.1016/j.compstruct.2017.12.062.
- [158] H. A. Richard, B. Schramm, and N.-H. Schirmeisen, "Cracks on Mixed Mode loading – Theories, experiments, simulations," *International Journal of Fatigue*, vol. 62, pp. 93–103, May 2014, doi: 10.1016/j.ijfatigue.2013.06.019.
- [159] E. S. Barboza Neto, M. Chludzinski, P. B. Roese, J. S. O. Fonseca, S. C. Amico, and C. A. Ferreira, "Experimental and numerical analysis of a LLDPE/HDPE liner for a composite pressure vessel," *Polymer Testing*, vol. 30, no. 6, pp. 693–700, 2011, doi: 10.1016/j.polymertesting.2011.04.016.
- [160] M. Azeem *et al.*, "Application of Filament Winding Technology in Composite Pressure Vessels and Challenges: A Review," *Journal of Energy Storage*, vol. 49, no. February, 2022, doi: 10.1016/j.est.2021.103468.
- [161] S.-H. Yoon and C.-G. Kim, "Comparison of Tensile Properties Between Split Disk Test and Tensile Coupon Test," 1997.
- [162] "Standard Test Method for Hoop tensile strength ASTM2290 standarts.pdf."
- [163] M. Sayuti, A. A. D. Sarhan, and F. Salem, "Novel uses of SiO₂ nano-lubrication system in hard turning process of hardened steel AISI4140 for less tool wear, surface roughness and oil consumption," *Journal of Cleaner Production*, vol. 67, pp. 265–276, Mar. 2014, doi: 10.1016/j.jclepro.2013.12.052.
- [164] M. Paessler, A. Miaris, R. Schledjewski, and P. Mitschang, "Ring Winding Technology: Increased Process Efficiency and Effects on the Mechanical Properties of Ring Specimens," in *Volume 6: Materials and Fabrication, Parts A and B*, Baltimore, Maryland, USA: ASME/EDC, Jan. 2011, pp. 69–77. doi: 10.1115/PVP2011-57540.

- [165] A. Zeinedini, "A novel fixture for mixed mode I/II/III fracture testing of brittle materials," *Fatigue Fract Eng Mater Struct*, vol. 42, no. 4, pp. 838–853, Apr. 2019, doi: 10.1111/ffe.12955.
- [166] J. Kazakeviciute, J. P. Rouse, D. Focatiis, and C. Hyde, "Small specimen techniques for estimation of tensile, fatigue, fracture and crack propagation material model parameters," *The Journal of Strain Analysis for Engineering Design*, vol. 57, no. 4, pp. 227–254, May 2022, doi: 10.1177/03093247211025208.
- [167] D. Damjanović, D. Kozak, and N. Gubeljak, "The influence of residual stresses on fracture behavior of Pipe Ring Notched Bend specimen (PRNB)," *Engineering Fracture Mechanics*, vol. 205, pp. 347–358, Jan. 2019, doi: 10.1016/j.engfracmech.2018.10.016.
- [168] X. Su and X. Liu, "Dynamic tensile process of blended fabric using finite element method," *IJCST*, vol. 32, no. 5, pp. 707–724, Apr. 2020, doi: 10.1108/IJCST-09-2019-0133.
- [169] W. Gul, Y. E. Xia, P. Gérard, and S. K. Ha, "Characterization of Polymeric Composites for Hydrogen Tank," *Polymers*, vol. 15, no. 18, p. 3716, Sep. 2023, doi: 10.3390/polym15183716.
- [170] E. E. Gdoutos, *Fracture mechanics: an introduction*, 2nd ed. in Solid mechanics and its applications, no. v. 123. Dordrecht, the Netherlands : Norwell, MA: Springer ; Sold and distributed in North, Central and South America by Springer, 2005.
- [171] Z. Q. Jiang *et al.*, "Establishment of a 3D FE model for the bending of a titanium alloy tube," *International Journal of Mechanical Sciences*, vol. 52, no. 9, pp. 1115–1124, Sep. 2010, doi: 10.1016/j.ijmecsci.2009.09.029.
- [172] A. Leonardi, F. Furguele, R. J. K. Wood, and S. Syngellakis, "Numerical analysis of brittle materials fractured by sharp indenters," *Engineering Fracture Mechanics*, vol. 77, no. 2, pp. 264–276, Jan. 2010, doi: 10.1016/j.engfracmech.2009.08.003.
- [173] S. Saxena, N. Ramakrishnan, and J. S. Chouhan, "Establishing methodology to predict fracture behaviour of piping components by numerically predicting specimen fracture data using tensile specimen test," *Engineering Fracture Mechanics*, vol. 77, no. 7, pp. 1058–1072, May 2010, doi: 10.1016/j.engfracmech.2010.01.006.
- [174] A. Likeb and N. Gubeljak, "The Determination of the Limit Load Solutions for the New Pipe-Ring Specimen Using Finite Element Modeling," *Metals*, vol. 10, no. 6, p. 749, Jun. 2020, doi: 10.3390/met10060749.
- [175] A. Likeb, N. Gubeljak, and Y. Matvienko, "Stress Intensity Factor and Limit Load Solutions for New Pipe-ring Specimen with Axial Cracks," *Procedia Materials Science*, vol. 3, pp. 1941–1946, 2014, doi: 10.1016/j.mspro.2014.06.313.
- [176] A. Likeb, N. Gubeljak, and Y. Matvienko, "The determination of the stress intensity factor solutions for the new pipe-ring specimen using FEA," *Arch Appl Mech*, vol. 89, no. 5, pp. 897–909, May 2019, doi: 10.1007/s00419-018-1481-8.
- [177] W. Musrati *et al.*, "Fracture assessment of seam and seamless steel pipes by application of the ring-shaped bending specimens," *Theoretical and Applied Fracture Mechanics*, vol. 103, p. 102302, Oct. 2019, doi: 10.1016/j.tafmec.2019.102302.