ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING

(MECHANICAL DESIGN ENGINEERING STREAM)

FRACTURE BEHAVIOR OF BIDIRECTIONAL WOVEN GLASS FIBER REINFORCED EPOXY COMPOSITE MATERIAL WITH DIFFERENT FIBER ORIENTATION

A MASTERS THESIS SUBMITTED TO SCHOOL OF GRADUATE STUDIES OF ADDIS ABABA INSTITUTE OF TECHNOLOGY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR DEGREE OF MASTERS OF SCIENCE IN MECHANICAL DESIGN ENGINEERING STREAM

MAIN ADVISOR: DANIEL T.(Dr.)

CO ADVISOR: MULUGETA H. (PhD CANDIDATE)

DONE BY: ALEMSEGED MOREDA

July 2019

Addis Ababa, Ethiopia

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This is to certify that the thesis prepared by Alemseged Moreda, entitled: fracture behavior of woven glass fiber reinforced epoxy composite material with different fiber orientation and submitted in partial fulfillments of the requirements for the degree of Masters of Science (Mechanical and Industrial Engineering) complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the Examining committee:

Behailu (PhD candidate)	________________	________________
Internal Examiner	Signature	Date
Dr. Samuel (Dr.)	________________	________________
Internal Examiner	Signature	Date
DR Daniel T.	________________	________________
Advisor	Signature	Date
Mr. Mulugeta H. (PhD candidate)	________________	________________
Co - advisor	Signature	Date
Dr. Yilma	________________	________________
School Dean	signature	Date

Declaration

I, the under signed declare that this thesis work is my original work and has not been presented for a degree in any other university, and that all sources of material are duly acknowledged.

Alemseged Moreda	__________________	__________________
Student	Signature	Date

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

Dr. Daniel Tilahun (PhD)	__________________	__________________
Advisor	Signature	Date
Mr. Mulugeta H. (PhD candidate)	__________________	__________________
Co - advisor	Signature	Date

Acknowledgment

First, I would like to thank God for giving me endurance for the completion of this thesis. I would like to express my heartfelt appreciation and gratitude to my advisors Dr. Daniel T and Mr. Mulugeta H. for their encouragement and helpful guidance throughout the course of this thesis work. Without their guidance and support, this work would have been impossible. They inspired and encouraged me to work on this project. Their supervision, advice, guidance, and encouragement have helped me tremendously.

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Abstract

Glass fiber is by far the most predominant fiber used in the reinforced polymer industry and among the most versatile. E Glass fiber reinforced polymer matrix composites have been widely used as a substitute materials in automobile and aerospace applications, because of their lightweight characteristics and better mechanical properties. Although glass fibers used for different applications, they have the problem of crack formation_and propagation at a working load. Even if many studies have been made on woven (bidirectional) glass fiber reinforced epoxy composite materials, we cannot stop or minimize the crack propagation yet. Therefore, there is a need to conduct research in order to investigate the fracture behavior of this composite material.

Fracture behavior of woven glass fiber epoxy composite material, will be studied using the experimental method. The fracture toughness; associated with fiber tensile failure in a woven glass fiber reinforced epoxy composite material is measured using a compact tension test. Investigation deals with the characterization of tensile properties according to the ASTM standard D E399. Hand layup technique was employed to prepare the compact tensile specimen.

The values of the tensile fiber failure critical energy release rate were determined for all orientations (0^0, 30^0, 45^0, and 60^0). The energy release rates of all the samples are 198.66 kJm^{-2} for CTS 0, 229.22 kJm^{-2} for CTS 30, 268.64 KJm^{-2} for CTS 45 and 232.98 KJm^{-2} for CTS 60. The woven glass fiber reinforced epoxy composite material with 0^0 orientation has an overall improvement of 22.62% strain energy release rate over that of CTS 30, CTS 45 and CTS 60.

Keywords: fracture toughness, energy release rate, woven glass fiber, glass epoxy composite,

List of Abbreviations and Acronyms

Abbreviations/Acronyms	
BD	Bidirectional
FRP	Fiber reinforced plastics
MPa	Mega Pascal
KJ	Kilo joule
CTS	Compact tension specimen
ROM	Rule of Mixture
G_{IC}	Critical strain energy release rate
SBS	Short beam strength
DNS	Double-notched shear strength
CSERR	Critical strain energy release rate
σ	Stress
LEFM	Linear Elastic Fracture Mechanics
SIF	Stress intensity factor
W	Width
B	Thickness
ASTM	America Society for Testing and Material
E	Equivalent module
C	Compliance geometric correction function
GB	General purpose
V	Volume
mm	Millimeter

m	Meter
V_{cp}	Volume of composite material
V_{ep}	Volume of epoxy resin
V_{gf}	Volume of glass fiber
L	Length
M_{gf}	Mass of glass fiber
M_{ep}	Mass of epoxy resin
M_h	Mass of hardener
M_{mat}	Mass of matrix
CT0	Compact tension sample of 0 degree orientation
CT30	Compact tension sample of 30 degree orientation
CT45	Compact tension sample of 45 degree orientation
CT60	Compact tension sample of 60 degree orientation
ml	Milliliter
UTM	Universal Testing Machine
a	Crack length
Min	Minute
$\bar{x}$	Mean
δ^2	Variance
δ	Standard deviation
KN	kilo Newton
N	Newton

Chapter One

Introduction

1.1 Background of the Study

A composite material commonly defined as a combination of two or more distinct materials, each of which retains its own distinctive properties, to create a new material with properties that cannot achieved by any of the components acting alone. If the composite designed and fabricated correctly, it combines the strength of the reinforcement with the toughness of the matrix to achieve a combination of desirable properties not available in any single conventional material. Some composites also offer the advantage of being tailorable so that properties, such as strength and stiffness, can easily be changed by changing amount or orientation of the reinforcement materials. Using this definition, it can be determined that a wide range of engineering materials fall into this category [1].

1.1.1 Classification of composite materials

There are two distinct levels by which composite materials are classified. The first approach based on nature of the matrix constituent. These include organic-matrix composites or polymer matrix composites, metal matrix composites, and ceramic matrix composites [1]. Composite materials said to have two constituents. The reinforcing constituent is the fiber that embedded in the matrix. Typically, reinforcing materials are strong with low densities while the matrix is usually a ductile material. The second approach to classification based on the reinforcement form. These include particulate composite, flake composite, fiber reinforced composite and laminated composite. Fiber reinforced composite material is shown in the Figure 1. 1 [1].

Also Composite materials can take many forms but they separated into three categories based on the strengthening mechanism. In fiber-reinforced composites, the fiber is the primary load-bearing component. Fiberglass composites are examples of fiber-reinforced composites [1].

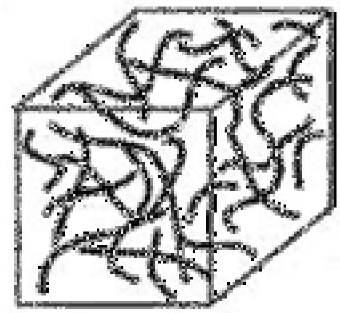


Figure1. 2: Fiber reinforced composite material [2]

1.1.2 Fiber reinforced composites

Structural composites typically use fiber as the reinforcement because many materials are stiffer and stronger in the fiber form than in the bulk form [2].

Fiber reinforced composites can be classifies into continuous fiber composite, woven fiber composite, chopped fiber composite and hybrid composite. In a woven glass fiber composite material, the fibers braided or knitted to create interlocking fibers that often have orientations orthogonal to the structural plane. They do not delaminate but have low strength and stiffness compared to the continuous fiber composite. They are used in structures where there is a need to have a structural, thermal or electrical property in the out of plane direction [2].

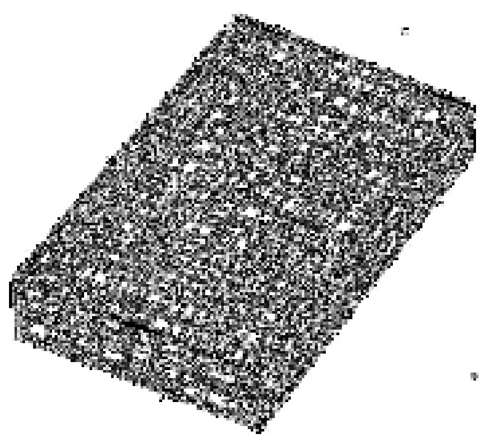


Figure1. 3: woven fiber composite [2]

1.1.3 Application of fiber reinforced composite materials in industries

Marine:

Nowadays, fiberglass becomes the common material for recreational boats and yachts for many years. These are not traditional laminated composites; rather the glass fibers are oriented randomly giving the structure more uniform material properties. Fairly being cheap, glass fiber used in large structures [3].

Sporting goods:

As carbon fiber provides lightweight and high stiffness, it used for golf clubs and tennis rackets.

Automotive:

Due to their higher costs, automotive industry has adopted composite materials slowly. Particulate reinforced plastics have been used for some time but fiber reinforced composites have only really been used in high end sports cars but are starting to make their way into traditional vehicles. Racecars have used carbon fiber materials for many years [3].

Aerospace:

Carbon fiber composites now quit common in commercial and military aviation. The Boing 787 and Airbus A350XWB have roughly 50% of their structure from composite materials. Carbon fiber materials are also common in helicopter systems, rocket motors, satellite systems, and turbine engines [3].

In this research, fracture behavior of bidirectional woven glass fiber reinforced epoxy composite materials with different fiber orientation, going to investigate.

1.2 Statement of the Problem

In today's world, there are many different materials used for different applications. These materials have their own material properties including; mechanical, chemical, thermal, and electrical properties. Fiber reinforced composite materials are among them. These materials are used in many sectors such as automotive, aircraft, and shipping industries. Bodies manufactured from fiber reinforced composite materials and other materials face catastrophic failure. Besides the failure due to the nature of material and/or overload, these failures occur due to improper selection of materials and manufacturing processes, improper fiber orientation and fiber epoxy proportion etc. The failure of these materials causes loses of many lives and assets. [27]

In today's science and /or a technologically driven world, glass fiber reinforced epoxy composite materials are the most important materials used in different industries.

Since glass fiber reinforced epoxy composite material is predominantly used, there is a need to conduct research in order to investigate the crack properties of the glass fiber reinforced composite material. In this thesis work, fracture behavior of woven glass fiber epoxy composite material will be investigated by using compact tension test specimen as per ASTM standard DE399.

1.3 Objective

1.3.1 General Objective:-

The general objective of this research is to study the fracture behavior (properties) of bidirectional woven glass fiber reinforced epoxy composite materials.

1.3.2 Specific Objective:-

- Experimental measurement of fracture toughness
- To investigate effect of fiber orientation

1.4 Scope and Limitation

Scope

In this research, fracture behavior of bidirectional woven glass fiber reinforced epoxy composite material investigated experimentally.

Limitation

➢ Numerical analysis will not be done

1.5 Methodology

Figure 1.3 represents the flow chart of methodology.

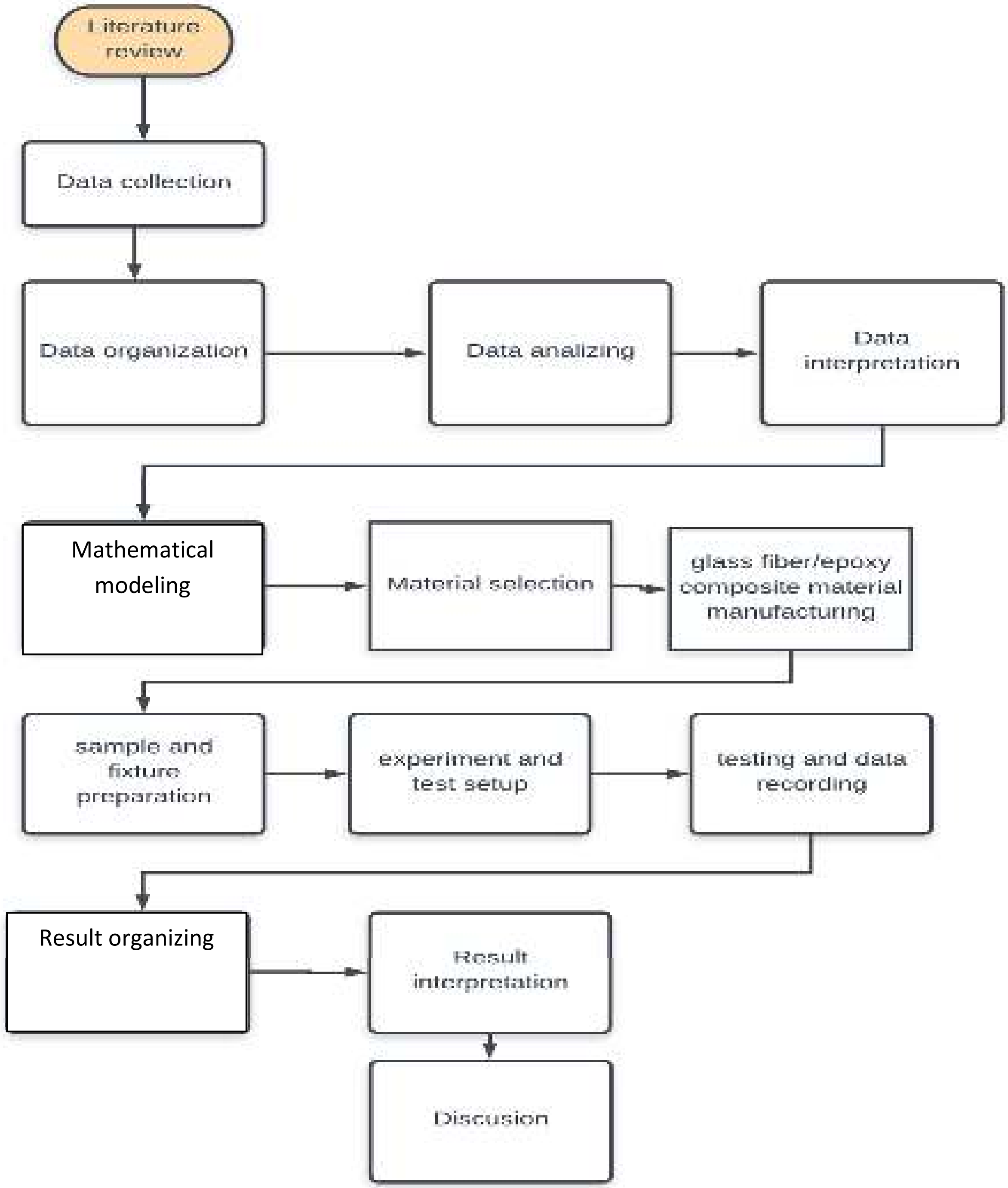


Figure1. 4: Methodology flow chart

1.6 Thesis Organization

This thesis work focuses on the fabrication and fracture toughness characterization of glass fiber reinforced epoxy composite material and in discussing the result. The manuscript comprises of six chapters.

Chapter 1: Introduces the background of glass fiber reinforced epoxy composite materials and objectives of the project, methodology, statement of the problem, and scope.

Chapter 2: Reviewed all relevant research papers regarding glass fiber reinforced epoxy composite materials, ranging from polymer types, fiber types, and composite's chemical, mechanical properties.

Chapter 3: This chapter states different theory's which used for the prediction of fracture mechanics parameters for experiment cases.

Chapter 4: This experiment deals with characterization of the fracture toughness Properties of glass fiber reinforced epoxy composite. In this chapter the methods and materials for the preparation of test specimen discussed and also the fracture toughness Properties investigation designs plan stress intensity factor and strain energy release rate of glass fiber epoxy, has been discussed.

Chapter 5: Here, the Characterization of composite material, which is the fracture toughness Properties, performed well and discussed in detail.

Chapter 6: This chapter dedicated to the conclusion and future work of this thesis.

Chapter two

2. Literature Review

2.1 Composite materials fabrication method

There are different methods to fabricate fiber reinforced composite materials. Many were developed to meet specific design or manufacturing challenges faced with fiber reinforced polymers. Selection of a method for a particular part, therefore, will depend on the materials, the part design and end-use or application.

Hand lay-up: is a simple method for composite production. The process consists of building up

Or placing layers of composite fiber in a sequenced layup using a matrix of resin and hardener [4].

The surfaces will be thoroughly cleaned in order to ensure that they were free from oil, dirt etc., before bonding at room temperature and pressure. The laminate will allowed curing for about 24 hours and then it cut to obtain test specimens with different orientations of glass fiber [5].

Filament- winding process: is a relatively slowly with possibility to control the fiber direction and the diameter of parts can be varied along the part. During the process, roving or tape is drawn through a resin bath and wind in a rotational mandrel. When the mandrel is removed, a hollow shape is the result. With this process can be realized variety parts as pipe, tubing, pressure vessels, tanks, and items of similar shape.

Pultrusion process: Represents a continuous transportation of fiber bundles through a resin matrix bath, following by a dropping of them into a preheated die. With this process results parts with complex shapes, such as tubing, channels, I-beams, Z- sections and flat bars.

Resin transfer molding process: In this process, a set of mold halves are loaded with reinforcement material then clamped together. Resin is then pumped, or gravity fed into the mold infusing the reinforcement material. Once the mold is filled with resin, it is plugged and allowed to cure. After curing, the mold halves are separated and the part removed for final trimming and finishing [6].

2.1.1 Molding methods of composite materials

There are many processing methods of composite materials, and big differences in different types of molding processes of composite materials. The molding process about hand lay-up fiber reinforced plastics (FRP), as represented using figure 2.1, is a typical process of preparing thermo setting polymer matrix composites. We see that there are many manual labors in process. Compounding of fibers and resins and curing reaction process of resin system are the forming processes of composite materials and at the same time, the formation processes of composite material products. Preparation of materials and products completes in the same process, which is another character that the composite materials are different from metallic materials.

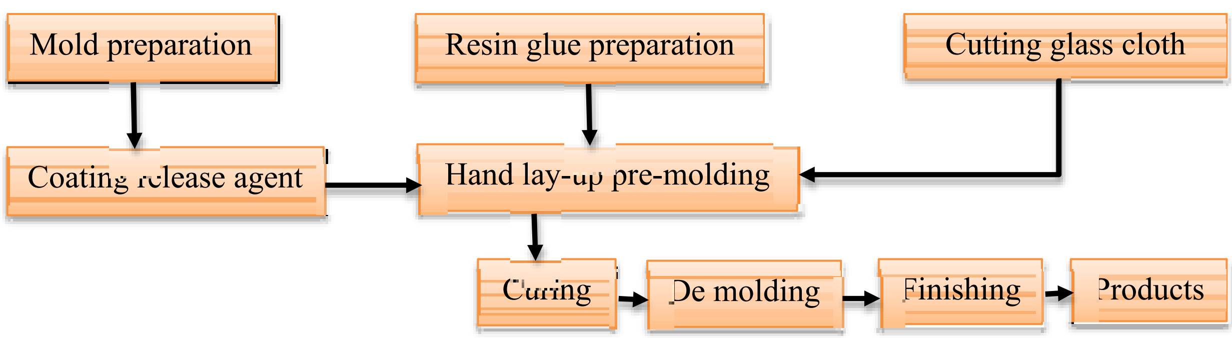


Figure2. 1: Technique flow-charts of FRP by hand lay-up [7].

2.1.2 Composite material and its applications

Different composite materials have many applications in engineering, biomechanics, and in many other applications.

Fiber reinforced composite materials are demanded by the industry because of their high specific strength, especially for applications where weight reduction is critical [5].

An advanced composite material is made of a fibrous material embedded in a resin matrix, generally laminated with fibers oriented in alternating directions to give the material strength and stiffness. Fibrous materials are not new; wood is the most common fibrous structural material known to man. [8].

Applications of composites on aircraft include:

- Fairings
- Flight control surfaces
- Landing gear doors
- Leading and trailing edge panels on the wing and stabilizer
- Interior components
- Floor beams and floor boards
- Vertical and horizontal stabilizer primary structure on large aircraft
- Primary wing and fuselage structure on new generation large aircraft
- Turbine engine fan blades
- Propellers

Graphite fibers: are used in place where required greater strength and higher thermal conductivity, have six times the tensile strength of carbon fibers.

Carbon fibers: are used in rocket nozzle thoughts and ablation characteristics and insulating capability.

Recent advance on the silica/polymer composite materials combining the unique properties of the inorganic fillers and the organic polymers have widely been achieved in academic and industrial fields and use for many applications such as uptakes for organic compounds and heavy metal ions, functional coatings, bio-applications [9].

Institutd'Electroniqueet de Télécommunications de Rennes, Université de Rennes developed an electromagnetic absorbing material to replace the polyurethane foam currently used in anechoic chambers. In order to solve issues related to the polyurethane foam (flexibleness, imprecise cut and inhomogeneous load dispersion), they propose the synthesis of new absorbent composites made of epoxy foam loaded with carbon particles [10].

Research on material science and engineering showed that the applications of Zinc ferrite material ($ZnFe_2O_4$) and its composites in the fields of sensors, photo-catalysis and lithium ion batteries, etc. [11].

Çukurova University, Chemistry Department studied that Novel shapeable phase change (PCM) composite materials are the energy storing materials in latent heat storage systems. Storage performance of a PCM plays a vital role in efficient latent heat storage applications. Many applications can benefit from storing latent heat [12].

Scientists' synthesized and characterized carbon/ceramic composite materials for environmental applications. Resulted carbon/ceramic composite materials demonstrated appropriate efficiency in adsorption of benzene used as a model toxic compound [13].

Anew composite material obtained by green synthesis, through deposition of zinc oxide onto calcium carbonate precipitated in green seaweeds extract is used for therapeutic purposes. The therapeutic effect of prepared composite material; was assessed in vivo as a topical application for the burns treatment and compared with that of ZnO [14].

2.2 Glass fiber

A Glass fiber or Fiber glass can be defined as A material consisting of extremely fine filaments of glass that are combined in yarn and woven into fabrics, used in masses as a thermal and acoustical insulator, or embedded in various resins to make boat hulls, fishing rods, and the like.

Although melting glass and drawing into fibers is an ancient technique, long continuous fiber drawn from glass introduced in the 1930's by Owens Corning as glass wool and given the popular name fiberglass [15].

Fiberglass materials are popular for their attributes of high strength compared to relatively lightweight. Fiberglass really is made of glass, similar to windows or the drinking glasses. The glass heated until it is molten. Then it forced through superfine holes; creating glass filaments that are very thin. Therefore, thin they are, better measured in microns [16].

Fiber glass weighs more than carbon fiber, the second most common reinforcement, and is not as stiff, but it is more impact resistant and has a great elongation to break (that is, it elongates to a greater degree before it breaks). Depending upon the glass type, coating chemistry (sizing), filament type, and fiber form; a wide range of properties and performance levels can be achieved. Glass filaments supplied in bundles called strands. It is a collection of continuous glass filaments. Roving generally refers to a bundle of untwisted strands packed like thread, on a large spool. Single end roving consists of strands made up of continuous multiple glass filaments that run the length of the strand. Multiple-end roving contains lengthy but not entirely continuous strands, which added or dropped in a staggered arrangement during the spooling process. Yarn is a collection of strands that twisted together [17].

Fiberglass really is made of glass, similar to windows or the drinking glasses in the kitchen. The glass heated until it is molten, then it forced through superfine holes, creating glass filaments that very thin, so thin they better measured in microns. These threads can then be woven into larger swatches of material or left in the somewhat less structured although more familiar puffy substance used for insulation or soundproofing. This will depend on, whether the extruded strands made longer or shorter, and the quality of the fiberglass. For some applications, it is important for the glass fibers to have fewer impurities, which involves additional steps in the manufacturing process [18].

2.2.1 Types of glass fiber

There are different types of glass fibers. These are; A-glass: With regard to its composition, it is close to window glass. In the Federal Republic of Germany, it mainly used in the manufacture of process equipment. C-glass: This kind of glass shows better resistance to chemical impact.

E-glass: This kind of glass combines the characteristics of C-glass with very good insulation to electricity. AE-glasses are Alkali resistant glass. Generally, glass consists of quartz sand, soda, sodium sulfate, potash, feldspar, and a number of refining and drying additives. The characteristics, with them the classification of the glass fibers to be made, are defined by the combination of raw materials and their proportions. S-glass – High strength glass made with magnesium alumino silicates used where high strength, high stiffness, extreme temperature resistance, and corrosive resistance needed. S-2 glass is similar to, but with somewhat improved properties with, S-glass. S-2 is a brand name originally created by Owens-Corning but spun off in 1998 and is now a registered trademark of AGY Holdings Corp. Fibers used for structural reinforcement composites generally fall into the categories of E-glass, AE-glass, and S-glass. Of all the fibers available for structural strengthening and reinforcement, E-glass is by far the most used and is the least expensive [19].

2.2.2 Woven glass fiber

Researchers showed that the design and engineering of woven fabrics and their use as layering materials to form composite structures for ballistic personal protection [21].

2.2.1 Strength Characteristics

Structural properties, such as stiffness, dimensional stability, and strength of a composite laminate, depend on the stacking sequence of the plies. The stacking sequence describes the distribution of ply orientations through the laminate thickness. As the number of plies with chosen orientations increases, more stacking sequences are possible. For example, a symmetric eight-ply laminate with four different ply orientations has 24 different stacking sequences.

2.2.3 Fiber Orientation

The strength and stiffness of a composite buildup depends on the orientation sequence of the plies. The practical range of strength and stiffness of carbon fiber extends from values as low as those provided by fiberglass to as high as those provided by titanium. This range of values is determined by the orientation of the plies to the applied load. Proper selection of ply orientation in advanced composite materials is necessary to provide a structurally efficient design [8].

2.3 Matrix

Types of matrix

There are three main types of composite matrix materials:

Ceramic matrix: ceramic matrix composites are a subgroup of composite materials. They consist of ceramic fibers embedded in ceramics matrix, thus forming a ceramic fiber reinforced ceramic (CFRC) material. Ceramic matrix composites designed to overcome the major disadvantages such as low fracture toughness, brittleness, and limited thermal shock resistance, faced by the traditional technical ceramics.

Metal matrix: Metal matrix composites (MMCs) are composite materials that contain at least two constituent parts. These parts are a metal and another material or different metal. The metal matrix reinforced with the other material to improve strength and wear.

Polymer matrix: Polymer matrix composites (PMCs); are divided into three sub types, namely, thermoses, thermoplastic, and rubber. Polymer is a large molecule composed of repeating structural units connected by covalent chemical bonds. Polymer matrix composites are less dense than metals or ceramics, can resist atmospheric and other forms of corrosion and exhibit superior resistance to the conduction of electrical current [21].

Epoxy Resin:

Low viscosity (500-800 centipoise 77°F) clear straw yellow modified epoxy resin. Modifications include additives to promote leveling, air detrainment in rolled coatings, resiliency, toughness, high impact resistance, and recoat ability, without removing amine blush or sanding between coats. Shelf life is unlimited in closed containers stored below 90°F. Haziness and crystallization will occur if stored at cold temperatures (below 50°F) for prolonged periods. Immersing the closed container in hot tap water and heating to 120°F or above will bring the resin back to a clear state. Neither crystallization nor heating will adversely affect the product. Crystallization will reoccur if the material not totally brought back to a clear bright state after heating. Simply warming cold material to room temperature will not melt the crystals. Heat must used [22].

Hardeners

All hardeners are mixtures of aliphatic polyamines, cycloaliphatic polyamines and/or amido amines. Other materials are included to promote extremely low moisture sensitivity during cure, and the ability to form clear, tough, non-milky films. There is no practical shelf life for hardeners stored in closed containers below 90°F. Ten year old material have been used with no discernible difference between it and fresh lots. Accelerators should not be used with these hardeners [22].

2.4 Previous research work on glass fiber/epoxy composite

2.4.1 Fracture analysis of composite materials

Influence of glass fiber percentage on mechanical properties

Wazery et al 2001[23] studied the influence of glass fiber percentage on the mechanical properties such as tensile strength, bending strength and impact strength. The sample was developed with varying fiber percentages (15%, 30%, 45%, and 60% by weight percentage) and hardness of composites was evaluated by using Brinell hardness tester. The results revealed that remarkable improvement in the mechanical properties of the fabricated composite with an increasing in glass fiber contents. The study showed that best mechanical properties obtained at 60 wt. % of glass fiber of fabricated composites.

Mohamed A Torabizadeh 2012 [24] studied on tensile, compressive and shear properties of bidirectional glass/epoxy composites subjected to mechanical loading and low temperature services. In order to fully characterize bidirectional composite, several experimental tests are performed using an environmental test chamber and a universal testing machine. Thermo-mechanics loads are applied to a glass/epoxy bidirectional composite at room temperature (20^0c), -20^0c, and -60^0c. The results indicate that low temperatures have a significant effect on composite failure mode. It is also found that the strength and modulus of bidirectional composites both increased with decreasing the temperature in all cases including tensile, compressive, and shear loads. On the other hand, the results show that strain to failure decreased by decreasing the temperature.

Through-thickness fracture behavior of bidirectional glass fibers/epoxy composites under various in-planes loading using the compact tension test was made. The pure mode I, pure mode II and mixed mode I/II fracture behavior of a Bidirectional (BD) glass fiber epoxy composite material was investigated. The through-thickness crack propagation of the composite was examined, and the energy absorbing processes associated with the through thickness fracture of Bidirectional (BD) glass fiber epoxy composite material was characterized using compact tension shear (CTS) specimen testing. Fracture parameters such as mode I and mode II components of fracture toughness, and mixed mode toughness were reported for unidirectional glass fiber epoxy as a function of loading angle. In all modes of loading, the crack started from the notch tip and followed the fiber direction. It observed that the value of toughness increased from 1.02 $MPm^{0.5}$ to 2.57 $MPm^{0.5}$ in the composite by changing the mode of loading from pure mode I to Pure mode II due to the change in the fracture mechanisms [25].

Fracture experiments were carried out on compact tension specimens of bidirectional and cross-ply S-glass/epoxy and graphite/epoxy. In bidirectional specimens, crack extension was always parallel to the fibers and was dependent on crack length. The study utilizes compact tension specimens to investigate fracture behavior in bidirectional and cross-ply composites. The main objectives are to identify the failure processes which occur in both types of laminates, determine the critical strain energy release rate, G_{IC}, and evaluate the suitability of a fracture mechanics approach to cross-ply composites.

Composition of matrix and fiber optimization

Sudipto Shekhor Mondol investigated material properties of woven glass fiber reinforced epoxy composite by varying fiber content and conducted tensile and impact tests. For tensile test, as fiber content increases the strength of the composite also increases, but at some point it will decline due to lack of bonding element. During impact test there is no major change in the impact strength for different fiber resin ratio [26].

Effects of Orientation

Gayatri Vineela et al [27] studied impact behavior of fiber reinforced composites with change in fiber orientation. In this research, three types (45/90, 0/90, and 30/60) of glass/epoxy composite plates were investigated analytically and experimentally, subjected to drop weight impact of 80 mm diameter mild steel sphere. From the results, it is concluded that 30/60 laminate has more damaged resistance than the other orientations.

ChavanV.B. et al 2017[28] studied on Development of Glass Fiber/Epoxy Composite Material and its Characterizations and performed hardness test, tensile test and impact test. The effects of stacking sequences with different weight ratios of fiber matrix of glass/epoxy laminated composite plates were investigated. The effects of the fiber orientation 0° / 30° / 60° / 90° with fiber matrix proportion 1 : 2 is effective which absorbs more impact energy when compared to other fiber orientations and other fiber matrix proportions. The effects of the fiber orientation 0°/ $90^0/0^0/90^0$ with fiber matrix proportion 1:1.75 which shows better tensile strength when compared Fiber orientations and other fiber matrix proportions. The effects of the fiber orientation 0°/ $90^0/0^0/90^0$ with fiber matrix proportion 1:2 which shows better flexural strength when compared to other fiber orientations and other fiber matrix proportions.

2.4.2 Summary

A composite material defined as a combination of two or more materials that results in better properties than those of the individual components used alone. A fiber has a length that is much greater than its diameter. The length-to-diameter (l/d) ratio known as the aspect ratio and can vary greatly. Continuous-fiber composites are often made into laminates by stacking single sheets of continuous fibers in different orientations to obtain the desired strength and stiffness properties with fiber volumes as high as 60 to 70 percent. There are different methods to fabricate fiber reinforced composite materials. Hand lay-up is a simple method for composite production. Different composite materials have many applications in engineering, biomechanics, and in many others.

Structural properties, such as stiffness, dimensional stability, and strength of a composite laminate, depend on the stacking sequence of the plies. The stacking sequence describes the distribution of ply orientations through the laminate thickness.

The strength and stiffness of a composite buildup depends on the orientation sequence of the plies.

Although many studies made on fracture behavior of composite (bidirectional glass/epoxy composite) materials, still there is a need to study the fracture behavior of woven glass fiber/epoxy composite material. Since bidirectional (BD) woven glass fiber epoxy composite material faces the problem of crack, fracture properties of BD woven glass fiber epoxy laminated composite materials have to be investigate. The compact tension test specimen is used to investigate the fracture properties of woven glass fiber epoxy composite materials.

Chapter Three

Mathematical models

3.1 Damage analysis using fracture mechanics approach

3.1.1 Stress distribution around a crack

Consider the cracked material specimen in Figure 3.2. In the immediately vicinity of the crack the material does not behave in a linear elastic fashion and thus the large stresses predicted by LEFM and the above equation are not realized. In a metal, plastic yielding occurs to relieve and redistribute the stress. In other materials, such as polymers or ceramics, different types of deformation, such as crazing or micro-cracking, may occur. For plastics, the material is usually so brittle that stress concentration within the specimen will result in rippling. The above equation is also unrealistic far from the crack where the shape of the specimen and the loading conditions determine the stress field. In between these regions, however, is a region where the crack dominates the stress field and the material deforms elastically. This is called the region of K dominance. Equation (3.1) is valid in this region.

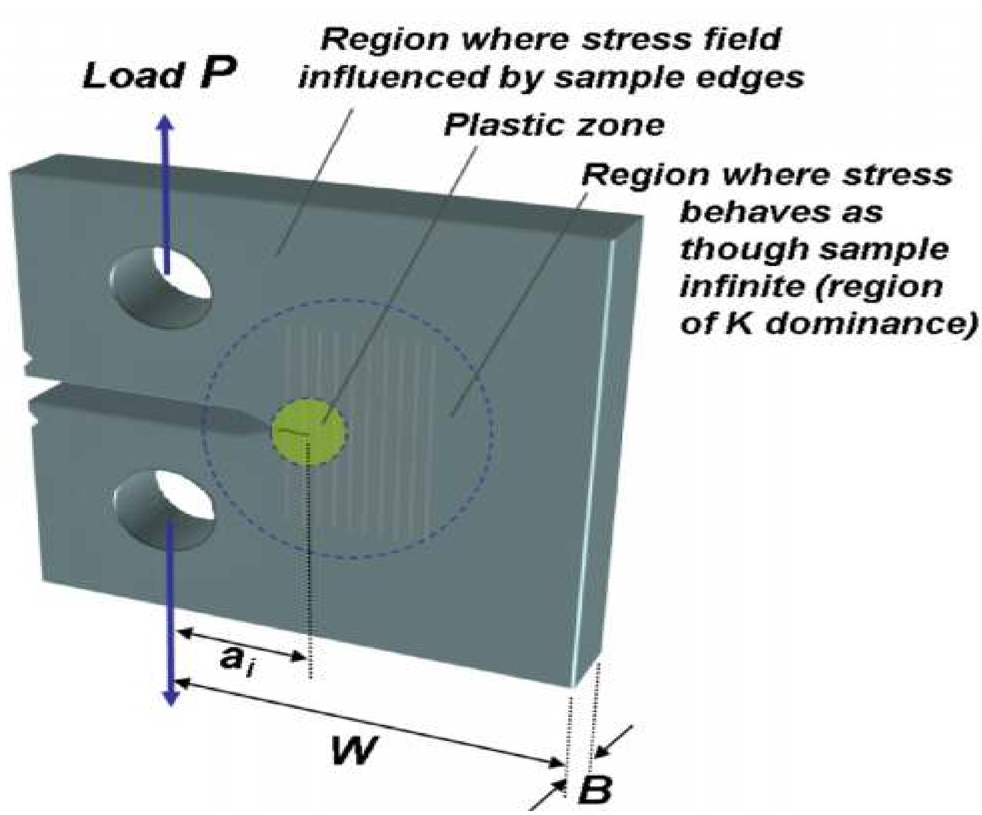


Figure3. 1: Finite cracked sample subjected to point load [30]

3.1.2 The Concept of Fracture mechanics and Fracture Toughness

Fracture toughness is the property, which is an indication of the amount of stress required to propagate a pre-existing flaw. It is a very important material property since the occurrence of flaws is not completely avoidable in the processing, fabrication, or service of a material/component. Flaws may appear as cracks, voids, metallurgical inclusions, weld defects, design discontinuities, or some combination thereof. Since engineers can never be totally sure that a material is flaw free, it is common practice to assume that a flaw of some chosen size will be present in some number of components and use the linear elastic fracture mechanics (LEFM) approach to design critical components. This approach uses the flaw size and features, component geometry, loading conditions and the material property called fracture toughness to evaluate the ability of a component containing a flaw to resist fracture [31].

Suppose the load on the specimen is increased until it breaks, i.e. fracture as shown in the figure 3.2. The resistance to this fracture may be characterized by the stress intensity at fracture, K, called the fracture toughness. A stress intensity, K value represents a lower limiting value of the material's fracture toughness. This value is used to estimate the relation between failure stress and defect size for a material in service where conditions of high tensile loading would be expected [32].

Fracture Modes:

Figure 3.3 defines the three modes of loading: Mode I (opening or tensile mode), Mode II (sliding or shear mode), and Mode III (tearing mode). Fracture mechanics concepts are essentially the same for each mode. However the great majority of all actual cracking and fractures cases in metals are mode I problems. A crack in the very early stage of development will turn into a direction in which it experiences only Mode I loading, unless it is prevented from doing so by geometrical confinement. For this reason fracture mechanics of metal is generally confined to Mode I.

A Roman numeral subscript indicates the mode of fracture and the three modes of fracture are illustrated using figure 3.3.

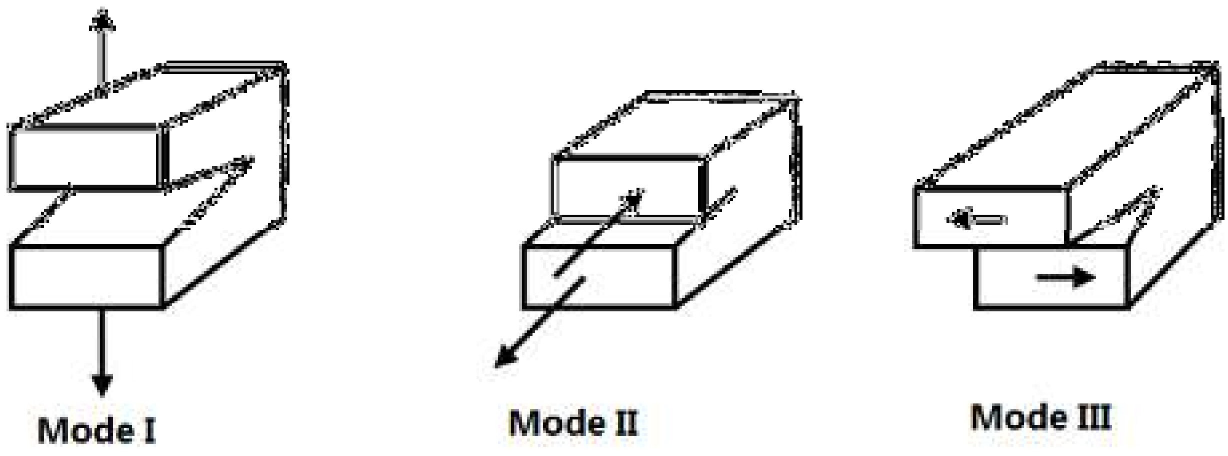


Figure3. 2: Loading Modes [32]

Mode I fracture is the condition in which the crack plane is normal to the direction of tensile loading. This is the most commonly encountered mode.

3.1.3 Stress intensity factor

A parameter called stress-intensity factor, K is used to determine the fracture toughness of most materials.

For compact tension specimen:

The fracture loads **P**, obtained from the tests are used to determine SIF values ($MPa.m^{\frac{1}{2}}$) as a measure of fracture toughness by using the following data reduction scheme.

$$\text{SIF} = \left(\frac{P}{BW^{1/2}}\right)f(x) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3.4)$$

Where: B = specimen thickness, cm, W = specimen width, cm, a = crack length, cm and

Where: $f(x) = \frac{(2+x)(0.866 + 4.64x - 13.32x^2 + 14.72x^3 - 5.64x^4)}{(1-x)^{3/2}}$ [2]

Where: $x = \frac{a}{w}$

$$0.45 < \frac{a}{w} < 0.55$$

The crack length, a, should be selected such that

3.1.4 Data reduction

Currently, no data reduction scheme for mode I intra-laminar fracture toughness characterization of laminated composite is available. Some researchers have used test standards from ASTM D E399 of the isotropic materials to calculate stress intensity factor to characterize the toughness of laminated composite materials using CT specimen. Usually the fracture behavior of materials expressed in terms of critical strain energy release rate which represents the energy required for crack growth [3]

The G_I of orthotropic laminated plate with the pre-crack under mode I loading can then be calculated from K_{IC} according to Paris et al [3].

$$G_{IC} = \frac{K^2{}_{IC}}{E^*} \quad \text{..........} \quad (3.5)$$

Where E is the equivalent module of composite given by [3]:

$$E^* = \frac{\sqrt{2E_1E_2}}{\sqrt{\sqrt{\frac{E_1}{E_2}} - v_{12} + \frac{E_1}{2G_{12}}}} \quad \text{..........} (3.6)$$

There are four data reduction schemes.

Area method

For the energy area method, the change of strain energy in the material can be calculated using the area under the load vs load line displacement curve from the loading point 1 to 2 as shown in Fig 3.4 The crack length that changes by a value Δa represents the dissipated energy during the crack propagation and is indicated by shaded region.

This method is among the simplest method of data reduction. The critical strain energy released can be calculated by [3]:

$$G_{IC} = \frac{1}{2 * t * \Delta a}(p_1d_2 - p_2d_1) \quad \text{..........} \quad (3.7)$$

Where: P1, P2 are loads and d1, d2are displacements at the points 1 and 2, respectively.

Compliance calibration method

A number of means are available by which the material property G_{IC} can be measured. One of these is known as compliance calibration method, which employs the concept of compliance as

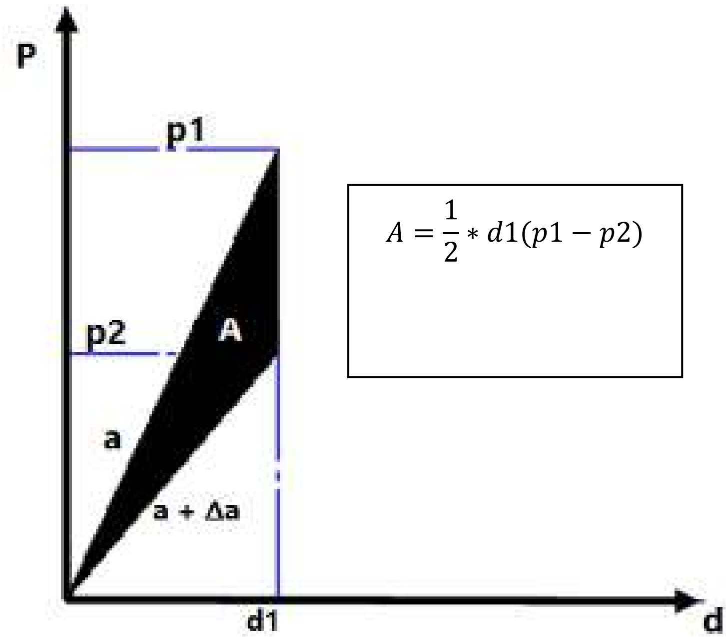


Figure3. 3: Load vs displacement curve of area method

the ratio of deformation to applied load [33].

Where p1 is load 1 at displacement 1 and p2 is load 2 at displacement 2.

$$C = \frac{\delta}{p} \quad \text{..... ....} \quad (3.8)$$

The total strain energy U can be written in terms of this compliance as:

$$U = \frac{1}{2} p\delta = \frac{1}{2} Cp^2 \quad \text{...} (3.9)$$

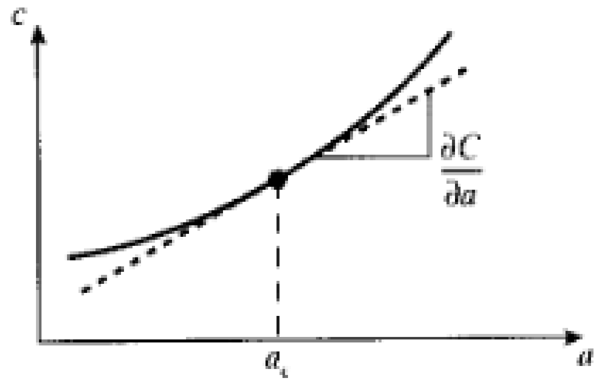


Figure3. 4: compliance as a function of crack length [33]

The strain energy release rate can then be determined by differentiating the curve of compliance versus length:

$$Gi = \frac{\partial U}{\partial a} \quad \text{.......... (3.10)}$$

As Anderson, the critical strain energy release rate can be calculated using the change in compliance, C.

$$G_{IC} = \frac{p_c^2}{2B} * \frac{\partial C}{\partial a} \quad \text{.......... (3.11)}$$

Where p_c is the critical load associated with a given crack length and B is the thickness of the specimen. The experimental Cvs. a data needs to be plotted and the best-fit function should be found. And then, C is calculated by using:

$$C(a) = c_1.x^3 + c_2.x^2 + c_3.x + c_4 \quad \text{.......... (3.12)}$$

Where:c_1, c_2, c_3 and $c_4$are the best fit coefficients. These coefficients were c_1= 2497*10^{-7}, c_2 = -1736*10^{-5}, c_3 = 4244*10^{-4}, c4 = -3143*10-3

J-Integral method

For a linear orthotropic material under mode-I loading the G_{IC} can be equated with the J-Integral proposed by Rice.

ASTM D E399

The ASTM E399 testing standard valid for isotropic materials gives the critical stress intensity factor for CT specimen by:

$$K_{IC} = \frac{p_c}{h\sqrt{w}} f\left(a/w\right) \quad \text{……………………………………………………………… (3.13)}$$

Where $f(a/w)$ is the geometric correction function given by:

$$f\left(a/w\right) = \frac{2 + a/w}{(1 - a/w)^{1.5}}\left[0.886 + 6.64\left(a/w\right) - 13.32\left(a/w\right)^2 + 14.72\left(a/w\right)^3 - 5.6\left(a/w\right)^4\right] \quad \text{………… (3.14)}$$

But, for this thesis work we are going to use the compliance calibration method.

Chapter four
Experimental Methods and Conditions

4.2 Materials

Best reinforcement and matrix materials are chosen based on different parameters material properties such as strength and stiffness.

4.2.1 Matrix

A. Hardener

Hardener is one of the matrix element used as a catalyst to cure the epoxy resin. This catalyst initiates the chemical reaction of the epoxy resin and monomer ingredient from liquid to solid state. As a result, the curing agent and/or hardener used for this research work is hardener with trade name HY-915 hardener, which is purchased from local market.

B. Epoxy resin

The resins used (act) as the matrix of the composite to bind the composite materials together and transfer the component stresses that may act on the part to the fibers in the composite. The fibers are designed and selected to handle the designed stresses imposed. In this experiment, a general purpose epoxy resin will be used. This is purchased from the local fiber glass production industries in Addis Ababa, Ethiopia.

4.2.2 Reinforcement

Woven glass fiber is used as reinforcing material. It has 40% higher strength, better retention of properties at elevated temperatures. The glass fiber with required quantity and type is purchased from local market.

4.2.3 Release agent (wax)

A Release agent must be applied onto the mold surface to prevent the part from bonding to the mold surface. It prevents resins from sticking on the mold. The type of release agent used for this thesis work is Wax-based release agent

Ensure that the selected release system is compatible with the selected materials. It is best to perform tests before using new materials. When tests are performed, the same materials, application processes, and environmental conditions should be simulated in the test in order to provide reliable results. Take care when new molds are used for the first time. A special procedure is normally required to prepare the mold for the very first usage. In this experiment, the tabletop will be covered waxes to act as the release agent.

4.2.3 Mold

Generally, two layers of flat plates are used to hold the flat shape of the layup.

4.3 Dimension

4.3.1 Specimen Dimension

A compact tension (CT) specimen's dimension for fracture experiments on bidirectional woven glass fiber reinforced epoxy composite materials is chosen based on ASTM standard D E399 and reported using figure 4.1.

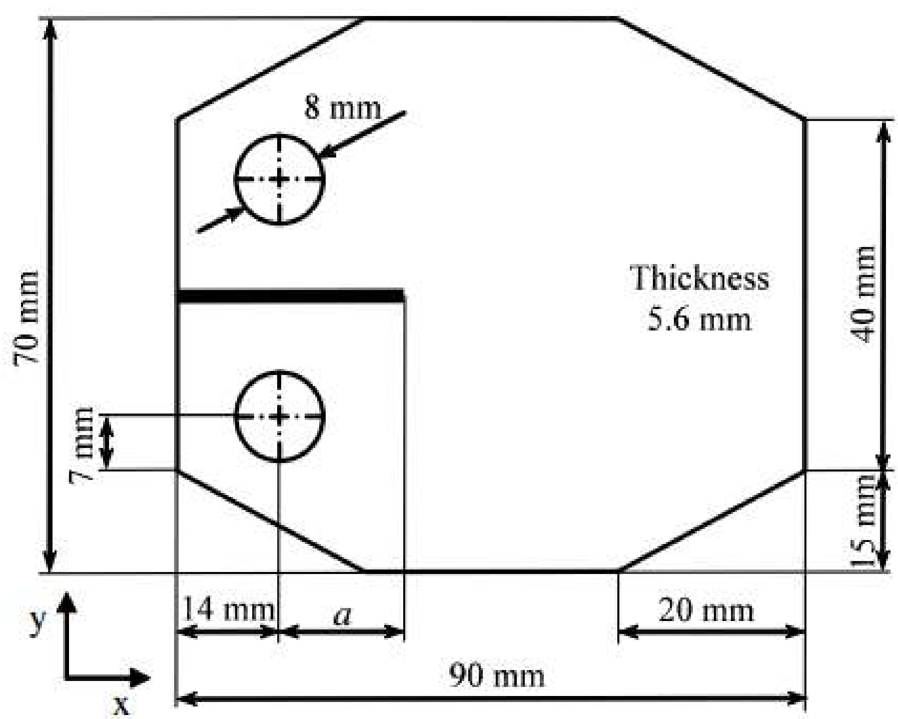


Figure4. 1: doubly tapered compact tension [specimen [34].

Where a is extension and is equal to 30 mm. ply thickness=8 plies or 5 mm.

4.3.2 Fixture Dimension

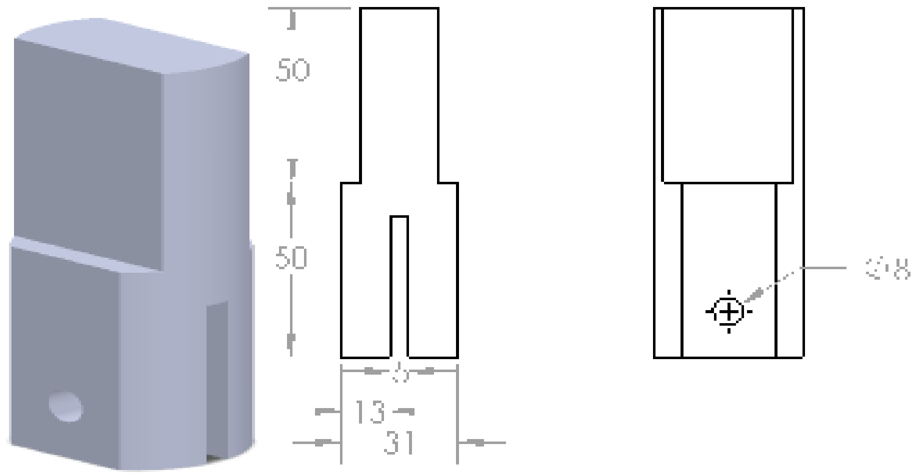


Figure4. 2: Fixture dimension

4.4 Sample preparation

4.4.1 Composition

To obtain the best strength and stiffness properties fiber volume has to be as high as 60 to 70 percent. Therefore, for this thesis work volume fraction of fiber is 60% per specimen. Matrix materials composition, General purpose epoxy resin and hardener HY-951 is in 99:1in ratio[35].

The materials used to prepare composite is reported using table 4.1

Table4. 1: Detail of materials used

Constituent/ parameter	Specification/ detail
Reinforcement	Woven glass fiber (E-glass)
Epoxy	General purpose epoxy
Hardener	HY- 951

Table4. 2: Mechanical property of materials used [36]

Materials	Density	E (Gpa)	Tensile strength
Woven glass fiber	2.45	89	4.69
Epoxy	1.54	3.5	0.06

The volume of the composite material is defined by the length, width and depth of the mold. Equation 4.1 provides the total volume of the composite.

V= L*W*B…………………………………………………………………………… (4.1)

Volume of composite material is calculated using equation 4.2.

V_{cp}= V_{ep}+V_{gf}……………………………………………………..……………………(4.2)

Where: V_{cp} is volume of the composite materials, V_{ep} is volume of epoxy resin, V_{gf} is volume of glass fiber, L is length of mold, W is width of mold and B is thickness of mold.

During specimen preparation, the mass of each material used is as follows:

M_{gf}=4434.8gm

M_{ep}= 2926.968gm

M_h=29.565gmand then,

mass of matrix is:

M_{mat}= M_{ep}+ M_h = 2956.533gm…………………………………………………………… (4.3)

Where: M_{gf} is mass of glass fiber, M_{ep} is mass of epoxy resin, M_h is mass of hardener and M_{mat} is mass of matrix.

Mass fraction of woven glass fiver with epoxy:

$$\frac{Mgf}{Mep} = \frac{\rho gf*Vgf}{\rho ep*Vep} \quad \text{…………………………………………....... (4.4)}$$

$$\frac{4434.8gm}{2956.533gm} = \frac{2.45 * Vgf}{1.54 * Vep}$$

$$1.5 = 1.591 * \frac{Vgf}{Vep}$$

$$\underline{\underline{Vgf = 0.9\ Vep}}$$

$M_{cp}= M_{gf}+ M_{mat}$…………………………………………………………………………..….. (4.5)

$V_{cp}= V_{ep}+V_{gf}$

$V_{cp}= V_{ep}+0.9V_{ep}$

$V_{cp}= 1.9\ V_{ep}$, where: $V_{ep}=\frac{Mep}{\rho ep}$

$V_{cp}= 1.9\left[\frac{Mep}{\rho ep}\right]$

$V_{cp}= 1.9\left[\frac{2956.533gm}{1.54}\right] = 1.9*1919.927$

V_{cp}=$\underline{\underline{3647.671cm^3}}$= volume of die or composite

Table4. 3: Compact tension specimen with different orientation

Specimen Code	Fiber Orientation	Composition %		**No. of specimens**
		Epoxy	**Woven glass fiber**	
CT0	0^o	40	60	3
CT30	30^o	40	60	3
CT45	45^o	40	60	3
CT60	60^o	40	60	3

Hand tools used:

Equipment and supplies needed in composite materials hand lay-up are listed for the specific application. These are:

1. Cutting of fibers

- Scissors
- Roller blade cutters
- Blades

2. Mixing of epoxy and glass fiber

- Mixing containers
- Weighing scale or epoxy dispensers
- Mixing sticks or electric mixers
- Cups
- Meter tape

3. Impregnation

- Brushes
- Rollers
- Squeegees

4. Cleaning

- Solvents (acetone)
- Paper towel or cloths
- Jugs

5. Safety wears (equipment)

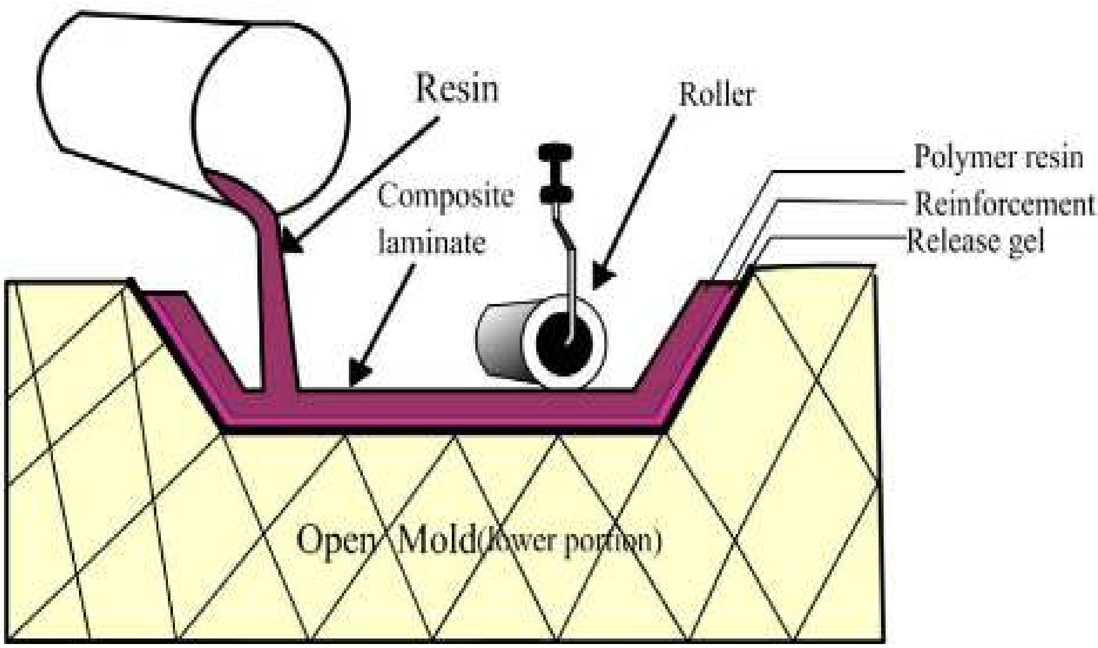
- Lab coat
- Gloves
- safety goggle
- safety shoe

4.4.2 Epoxy and hardener preparation

Epoxy of HY-951, mixed with general purpose hardener, is used to prepare the composite plate. The weight ratio for mixing epoxy and hardener is 99:1. This ratio is chosen for the sake of safe curing of composite material at room temperature. Hardeners include anhydrides (acids), amines, polyamides, dicyandiamide etc. The mixer, strewed with stirrer for about two minutes continuously. The mixing performed in the mixing containers (Bowl). The bowl is made of Nickel to prevent melting of the Bowl during the exothermic reaction with the tongue depressor the mix is done slowly so as to not entrain any excess air bubbles in the resin.

4.4.3 Hand lay- up process

The first step is to mix the resin and the hardener. The proportions are usually given by the supplier and can be found on the containers of the hardener or resin. The portions can be either measured by weight or by volume but it is important to follow these proportions exactly as this is a complete chemical reaction and all components must react completely for maximum strength of the matrix. It is easiest to measure proportions using the volume method and a screw in pump that inserts into the cans of resin and hardener. These pumps purchased along with the containers of resin and hardener. Make sure to keep the resin pump and container top separate from the pump and container top of the hardener because any contamination will initiate the chemical reaction and cause the resulting blend to harden. The mixing is performed in the mixing containers with the mixing stick and should be done slowly to not entrain any excess air bubbles in the resin. Be careful to mix completely and deliberately for a full two minutes before applying. It is best to use a "flat" stick- such as tongue depressor; a round stick does not work well as it does not 'paddle' the mixture to blend it properly. Note: Plastic mixing containers may melt during the exothermic reaction, so it is best to use containers that are specifically made for the purpose of mixing epoxy resin. These are typically available from the resin vendor. Next an adequate quantity of mixed resin & hardener is deposited in the mold and a brush or roller is used to spread it around all surface. It is important not to add too much resin, which will cause too thick of a layer, nor to add less than the necessary amount, which will cause holes in the surface of the part when it is cured. An estimate of the amount of resin needed based on weight of glass fiber cloth. One can assume 50 volume% resin/50% volume% fiber and then use the density of the reinforcement to arrive at the weight of the resin. But according to literatures and for this thesis work, the composition is 60% glass fiber and 40% is epoxy. It is good to then add a small safety factor so that enough resin is mixed for the layup. The first layer of fiber reinforcement then lay. This layer must be wetted with resin and then softly pressing using a brush or a roller make the resin that added in the previous step wick up through the fiberglass cloth. If the fiber is not completely wet, more resin can added over the top and spread around. At this stage a second layer of glass fiber is added and special care must be taken to eliminate all air bubbles possible. This can be accomplished by either rolling any air bubbles out with a small hand rolling tool or brushing out the air bubbles with a paintbrush. This step repeated until the desired thickness obtained. As the glass fiber layers are added to build laminates and total part thickness the individual layers may be oriented at varying angles to accomplish specific strength in the direction of the reinforcement weave. This called ‘clocking’. Sometimes during the buildup of successive layers of reinforcement; a cover sheet of plastic can be temporarily put over the layup and rolled together with the layers underneath to reduce the mess and squeeze out excess resin. It is important when the proper amount of resin has been used for the layup that any excess resin in the cup is placed on and in an area that does not have any flammable material, such as a concrete sink or slab.



(a) [35]

(b)

Figure4. 3: hand lay-up process: (a) hand lay-up method pictures from lecture (b) picture in AAIT mechanical workshop

Final layer:

After the final layer of fiber has been applied a layer of peel ply is applied on the surface. This layer does not bond with the epoxy system being used and will ensure a good finish of the component as well as protection from the effects of air during curing. The peel ply should have a trace lining to make it easy to detect when the layup procedure is completed.

4.4.4 Curing

The part can be cured at elevated temperatures using an oven (usually somewhere around 160 degrees F) or at room temperature. The laminate will be allowed to cure for about 24 hours. Generally, the proper curing time of each type of resin-hardener, as well as the working time, is given by the supplier on the back of the containers. If the part is left on plastic sheeting be sure to use proper plastic sheet that will survive the elevated temperature. Most plastic sheet available from hardware stores (polyethylene) may melt. If planning the layup part is going to be moved to a curing oven, then layup should be done on a caul plate- generally a sheet of aluminum or steel

>1/8” thick. For the purposes of this experiment and using an epoxy resin system, room temperature curing is adequate.

4.4.5 Cleaning

Tools are cleaned after lay-up using an appropriate solvent. Normally acetone works well for cleaning epoxy tainted tools. Cleaning must be performed before the resin starts curing. Once the part is ready to be cured, it must be moved to an adequate location. In this case it can be moved to a curing oven or simply left to cure in place until the next day. Then a cleanup must be done before leaving the class. All the materials used (brushes, rollers, mixing tools, scissor), including the table, must be cleaned using acetone and cloth. Also, the rest of the fiberglass woven reinforcement must be collected from the table and floor.

Cleaning of brushes:

- Wipe off excess epoxy with paper towel.
- Use a small quantity of acetone (20ml) and work it through the brush thoroughly with a dabbing motion.
- Dry the brush by it against paper towel or with a swinging action.
- Repeat the above procedure twice, each time with fresh acetone.
- Store the clean brush in a closed acetone container. (This container should only contain enough acetone to cover the brush hairs.) Replace the acetone in this container weekly to remove the build-up of epoxy in the container.

Cleaning of tools:

- First, take cloth (paper) and remove excessive resin.
- Decant the required amount of acetone into a cup or similar holder.
- Close storage container properly.
- Clean tool thoroughly.
- If required, apply fresh acetone to tool.
- Dump contaminated acetone into a dedicated waste container.

Warning:

Acetone is extremely flammable with a low flash point. Containers for acetone, especially when open may NOT under any circumstances be placed or stored near open flames, where welding or grinding is in progress, smoking areas or electrical switches. How to dispose of acetone: Soap and water can be used on skin if exposed. Some shop hand cleaners work well also. Any excess acetone should be properly disposed of, it is a good idea to put it in a proper disposal can with lid and disposed of correctly.

De-molding:

After the part has cured sufficiently, it can be de-molded. Care must be taken to ensure the curing process has completed, as de-molding forces may cause damage to parts when the resin is still in a soft, semi-cured phase.

Prepared sample:

Now here, woven glass fiber reinforced epoxy resin composite material with different fiber orientation is ready for test and typical view of some composite board is show below.

Figure4. 4: prepared Sample

4.4.6 Cutting

After curing the laminate for about 24 hours at room temperature, it is cut to obtain test specimens with 4 different orientations of glass fiber (0°, 30º, 45° and 60°). The cutting process will be done according to the designed procedures.

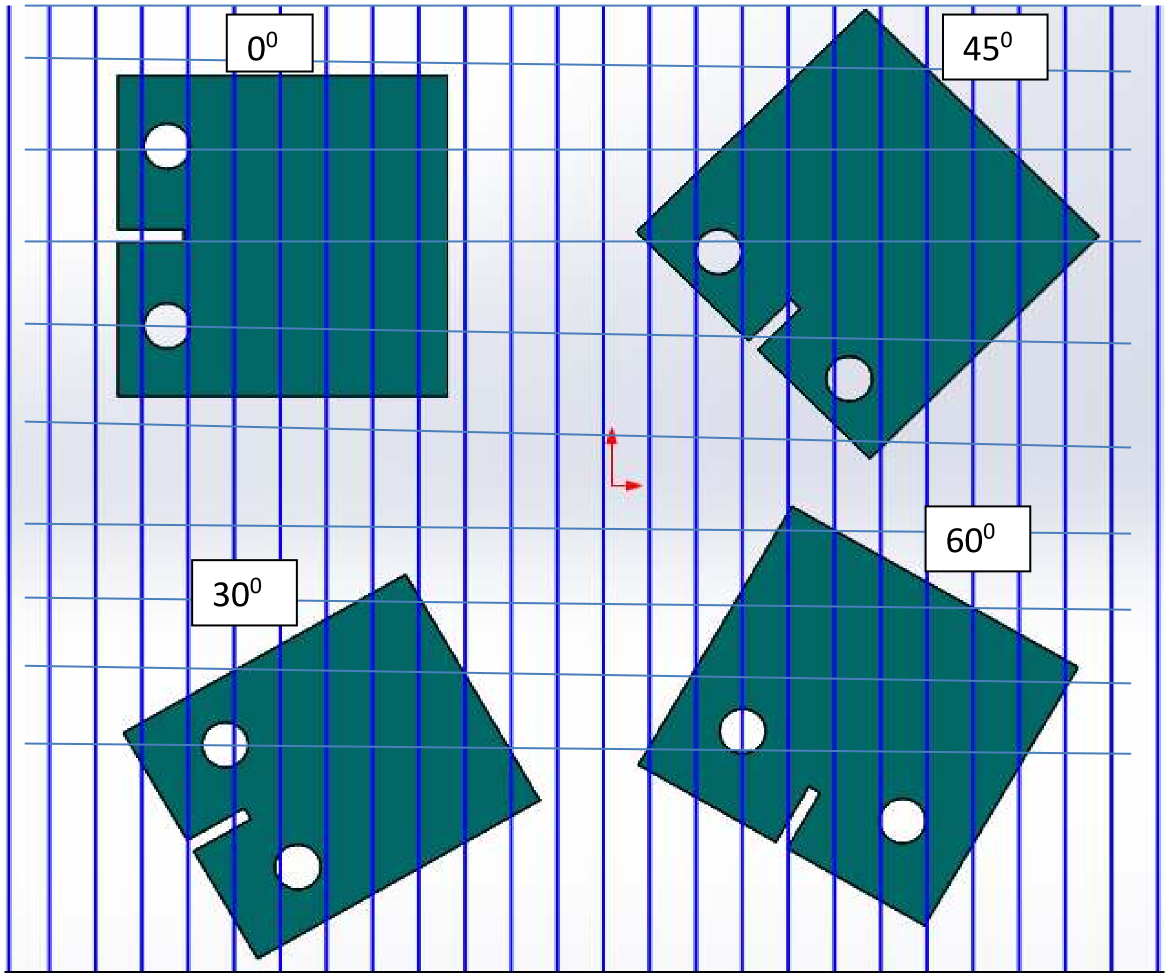


Figure4. 5: Fiber orientation of test specimen

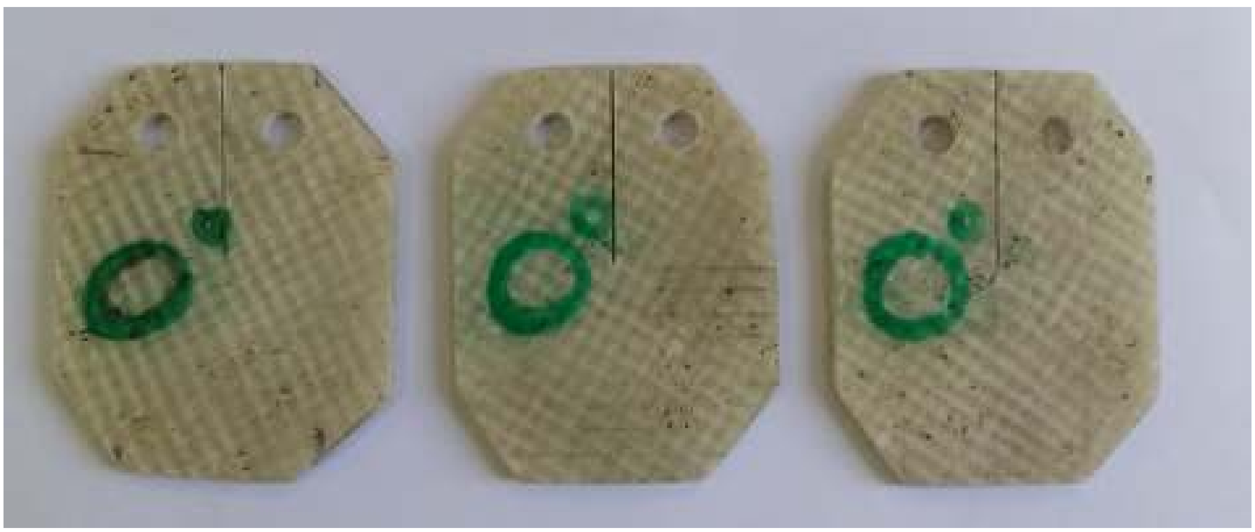
Prepared samples

Now here, laminated glass fiber reinforced epoxy resin composite material with different fiber orientation is ready for test and typical view of some compact tension specimen is shown below.

(a)

(b)

(c)



(d)

Figure4. 6: prepared Sample with different fiber orientation.

4.6 Test Method and Experimental setups

To study and evaluate the fracture behavior of bidirectional glass fiber/ epoxy composite materials with different orientations; 0^0, 30^0, 45^0 and 60^0, compact tension specimen sample will be developed using ASTM standard ASTM E399. For each orientation a total number of 3specimensare needed.

The CT specimen will be tested using UTM machine, model wp 310, equipped with a 50KN load cell.

4.7 Test apparatus

Universal Testing Machine (UTM): Universal Testing Machine testing system is integrated testing packages that can be configured to meet different testing needs. Each includes a load unit with integrally mounted actuator and servo valves, a hydraulic power unit, and the control system. The control system has three major parts: the system software running on a personal computer, the digital controller, and a remote station control panel. These functions work together to provide fully automated test control. Optional application software packages let you further tailor the system to automate most any standard or custom test procedure.

(a)

(b)

Figure4. 7: Universal Testing Machine in Defense University, Engineering College which is found in Bishoftu, Ethiopia.

Fracture Toughness Test for Mode one Fracture using Compact tension test (ASTM D E399)

Here compact tension sample was prepared for 0.3 ratio value between crack length, ‘a’ and crack width, ‘w’ $(\frac{a}{w} = 0.3)$. For each sample, 3 specimens were tested in the UTM machine and these CT specimens were clamped with UTM machine by the help of clevis fixture, which is made in Addis Ababa Institute of Technology mechanical work shop. The cross head speed will be used is0.2mm/min. The region in front of the crack tip was black painted. Then, strips patterns were streaked perpendicularly to the crack tip with 1mm spacing to form a 20mm scale rule for the crack length monitoring. A stationery camera will be used to view a magnified image of the area of the specimen containing the crack length. Load and load line displacement (elongation) were recorded from the given test and stress intensity factor including critical one for the recorded loads. The experimental setup for measuring the fracture toughness using CT specimen is shown in the figure 4.8.

(a)

Figure4. 8: Experimental Setup for CT Specimen: (a) machine setup and (b) specimen setup.

Chapter five

Result and Discussion

5.1 Experimental Result

5. 2 Compact Tension Test Result

3 (three) test samples were prepared for each orientation (0^0, 30^0, 45^0, 60^0) of fiber for Compact Tension test. And experimental result of these specific tests have been summarized using graphs, which can relate different material properties that are used in fracture mechanics to show fracture resistant of a given composite material, including critical strain energy release rate (Kc), strain energy release rate (G_C) , and R-curve (resistance curve)

Prepared samples after test

(a)

(b)

(c)

(d)

Figure5. 1: Four groups of samples after test: (a) 0^0 oriented sample fracture, (b) 30^0 oriented sample fracture, (c) 45^0 -oriented sample fracture, and (d) 60^0 oriented sample fracture

5.2.1 Standard deviation of test specimens

$$\overline{X} = \frac{\sum_{n=1}^{n}(x_1 + x_2 + x_3 + x_4 + x_5 ....+ x_n)}{n} \quad (5.1)$$

$$\overline{X} = \frac{\sum_{1}^{3}(x_1 + x_2 + x_3)}{3} \quad (5.2)$$

$$\delta^2 = \frac{\sum_{1}^{5}(x_1 - \overline{x})^2 + (x_2 - \overline{x})^2 + (x_3 - \overline{x})^2}{3} \quad (5.3)$$

$$\delta = \sqrt{\delta^2} \quad (5.4)$$

where = $\bar{x}$ = Mean

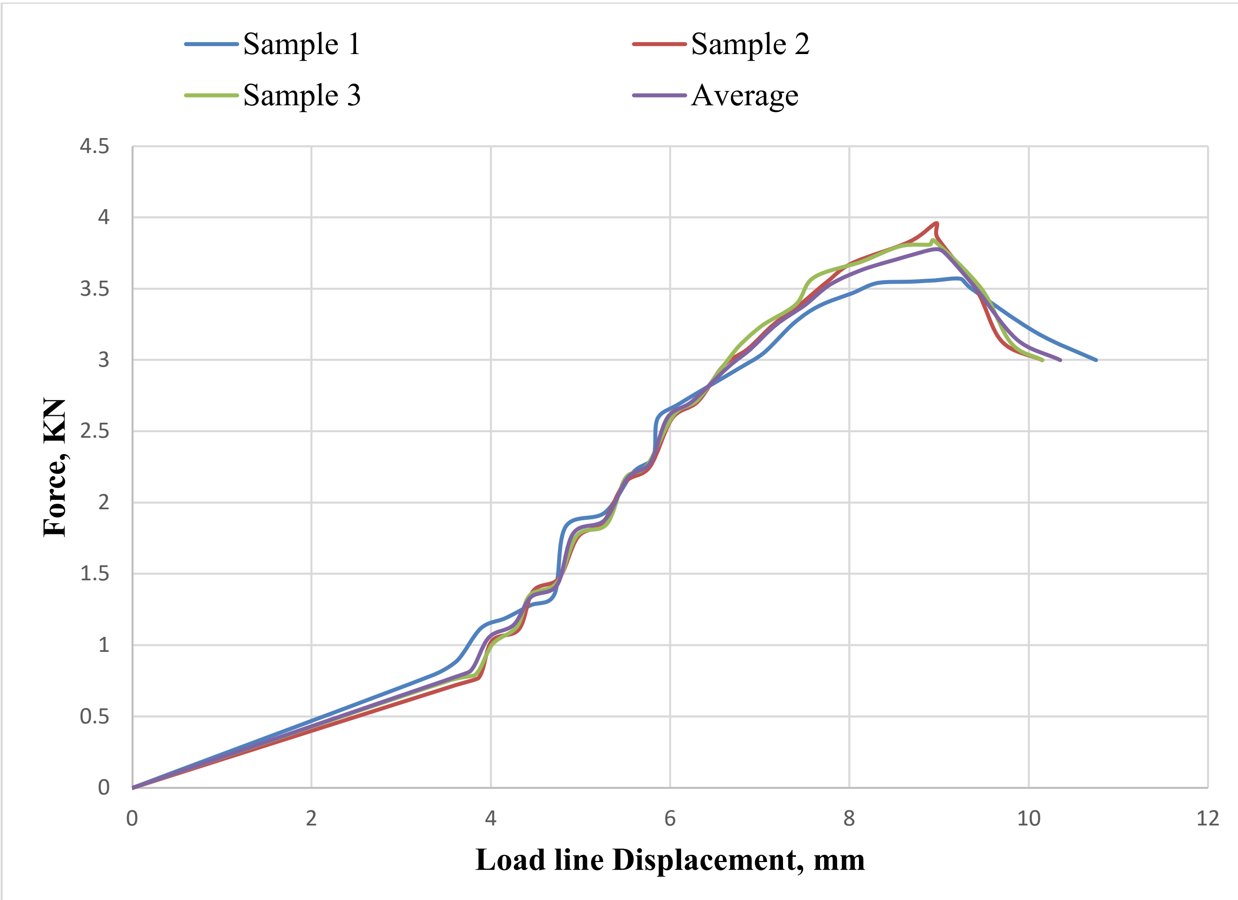
$\delta^2 = Variance$

$\delta = Standard\ devation$

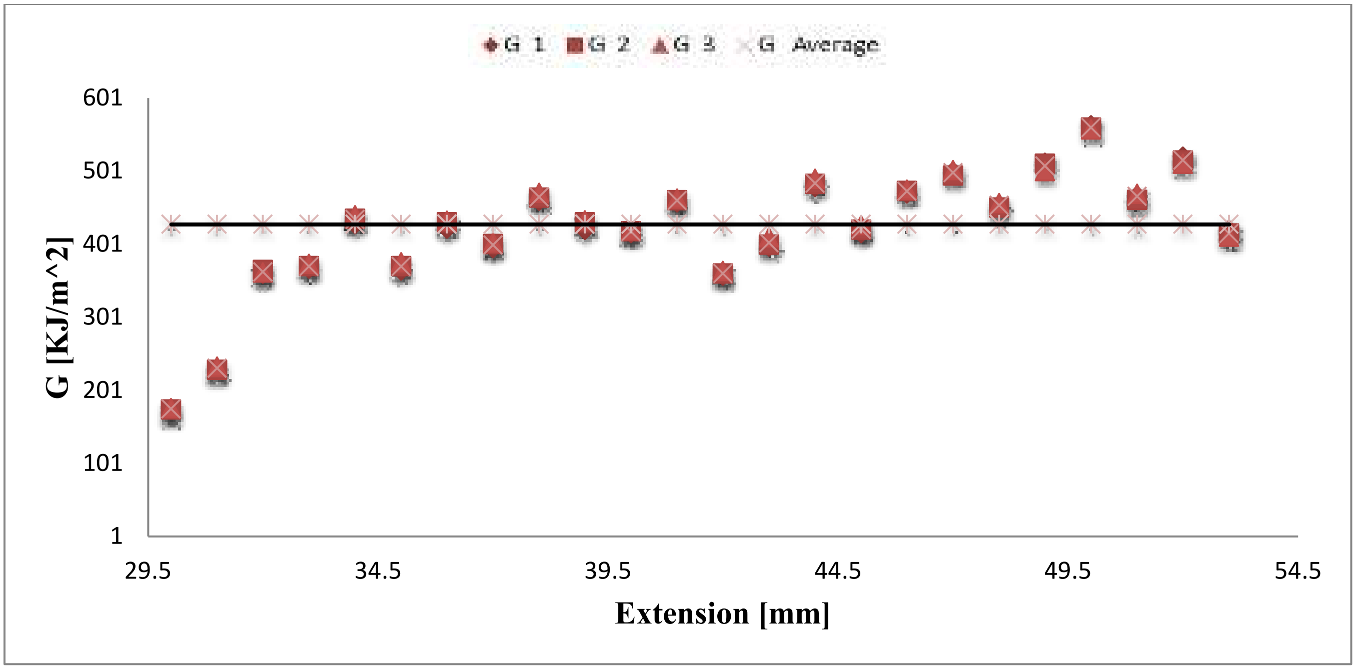
Table5. 1: Standard Deviation

Samples	**Maximum force (KN)**	**Standard Deviation**	**Energy release rate (KJ/m^2)**	**Standard Deviation**
CTS 0^0	**3.59**	**0.654**	**198.66**	**2.25**
CTS 30^0	**3.87**	**0.959**	**229.22**	**3.51**
CTS 45^0	**4.19**	**0.816**	**268.64**	**2.53**
CTS 60^0	**3.87**	**0.78**	**232.98**	**1.72**

5.2.2 Force and displacement graph of CT specimens

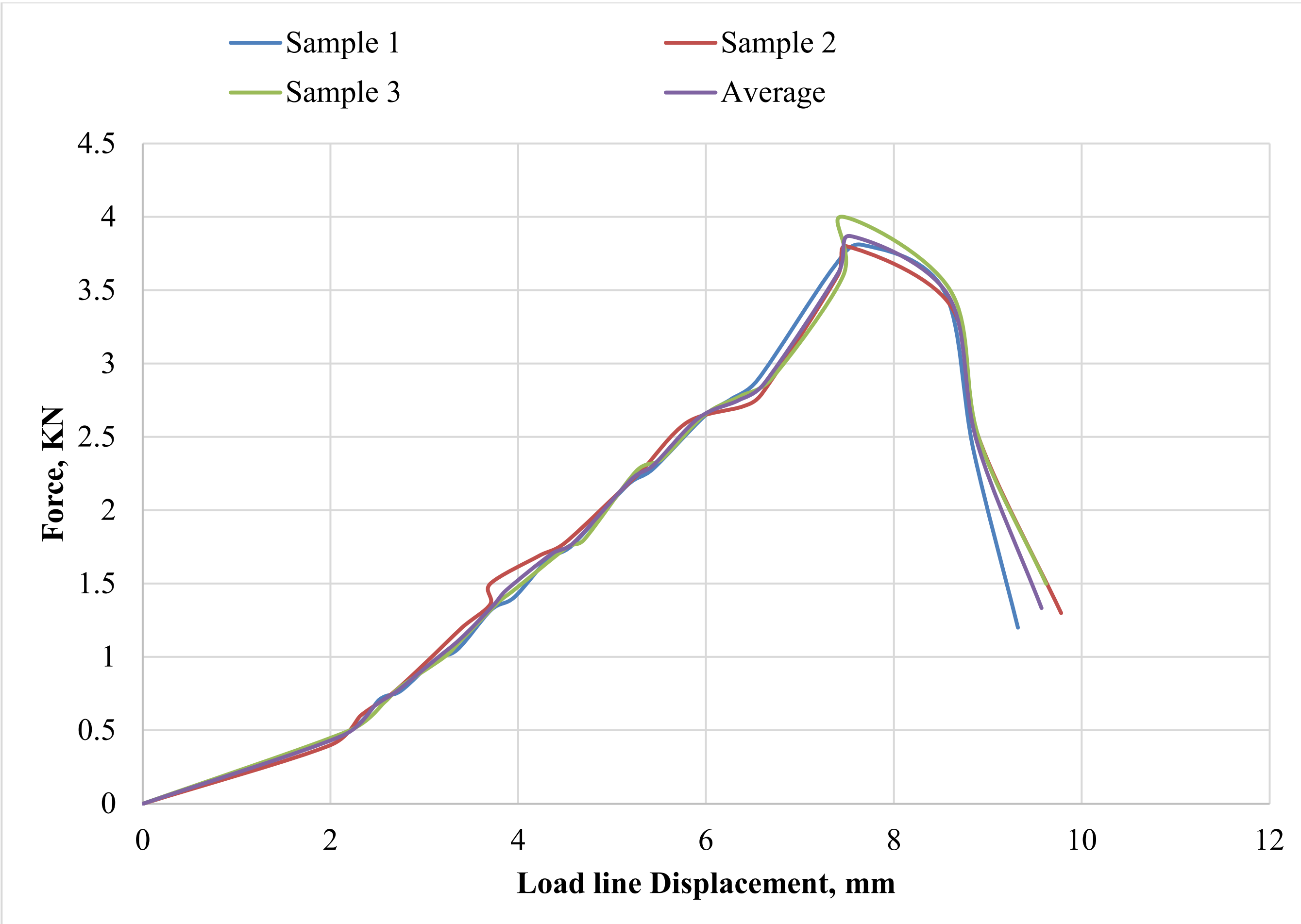


(a)



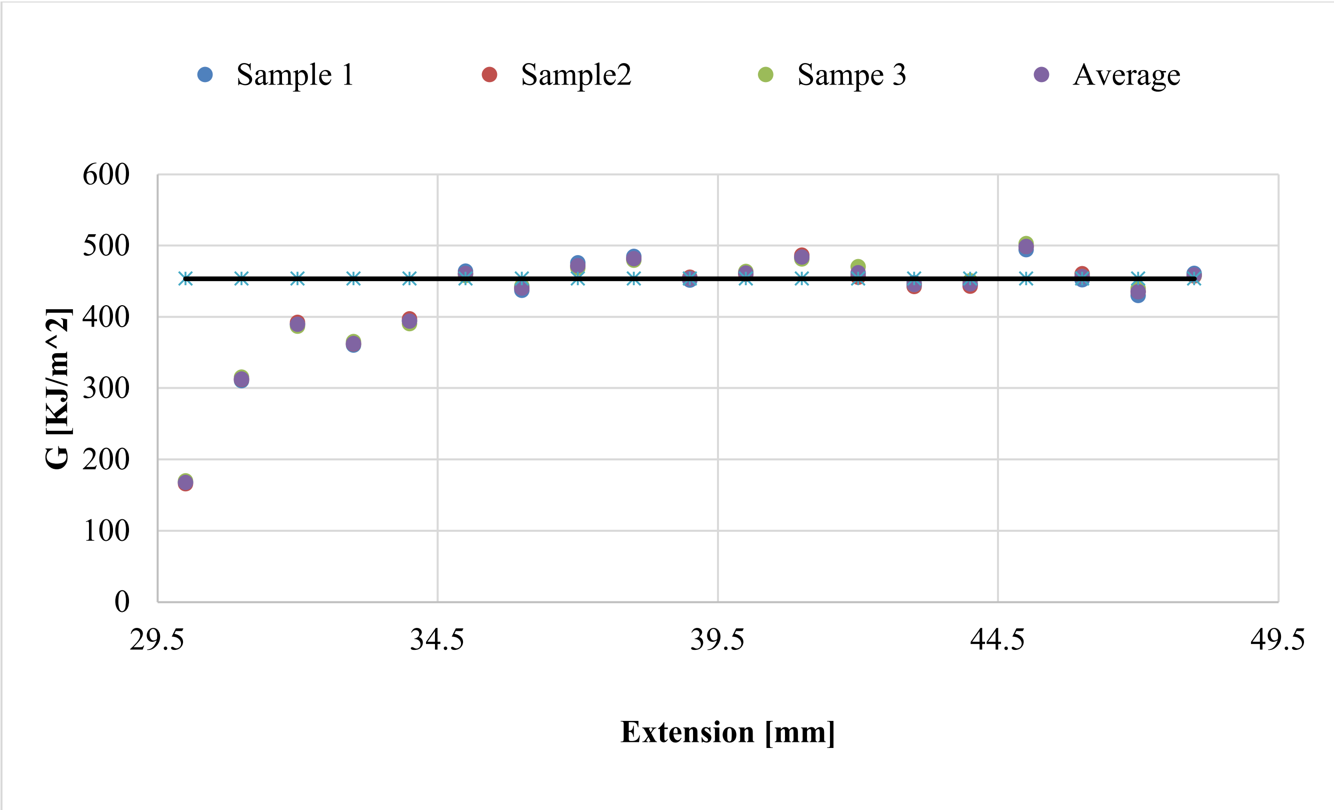
(b)

Figure5. 2: Compact Tension Test result for 0^0orientations, (a) force Vs Load line displacement, (b) energy release rate Vs Load line displacement



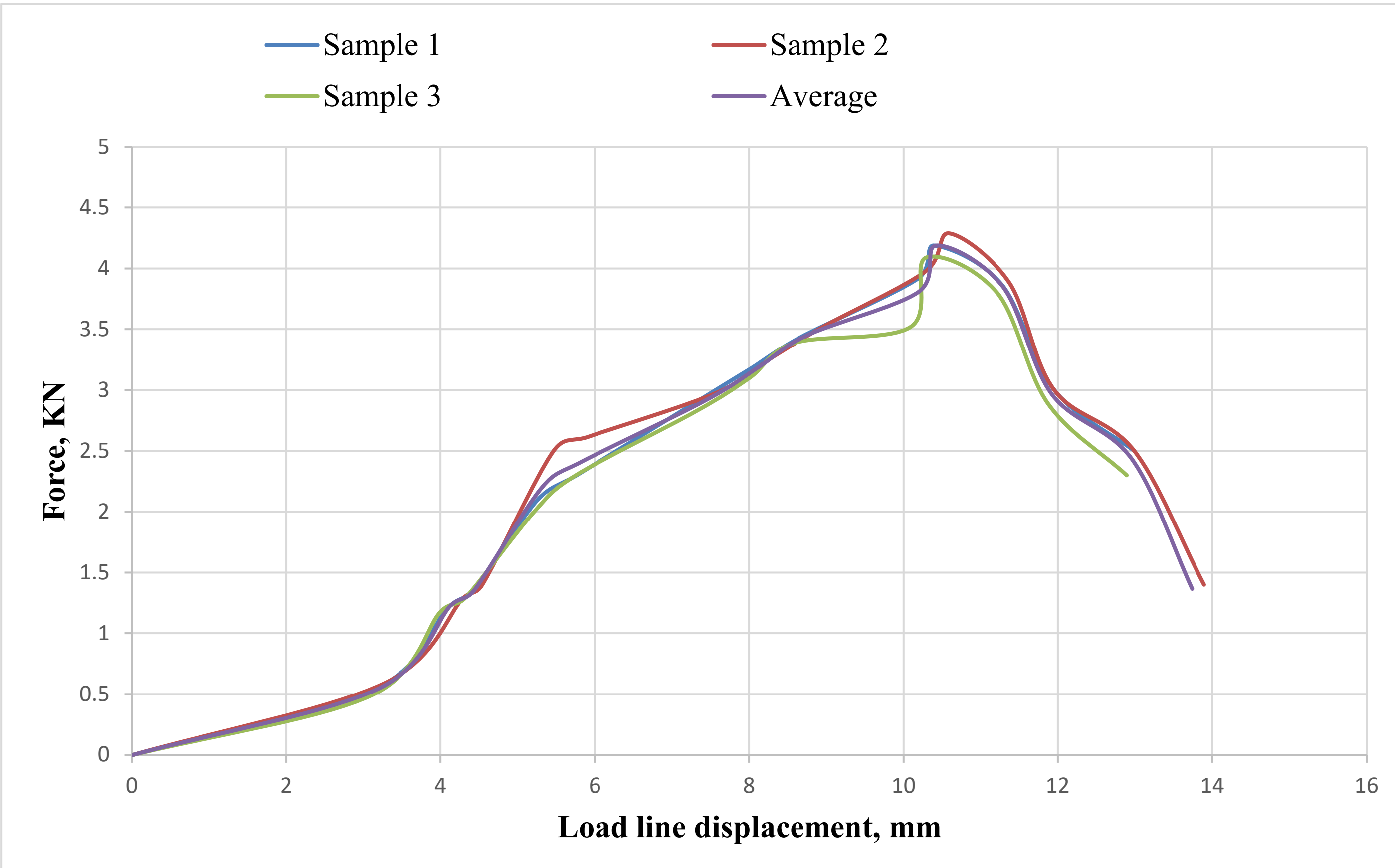
Sample 1
Sample 2
Sample 3
Average
Force, KN
Load line Displacement, mm
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
2
4
6
8
10
12

(a)

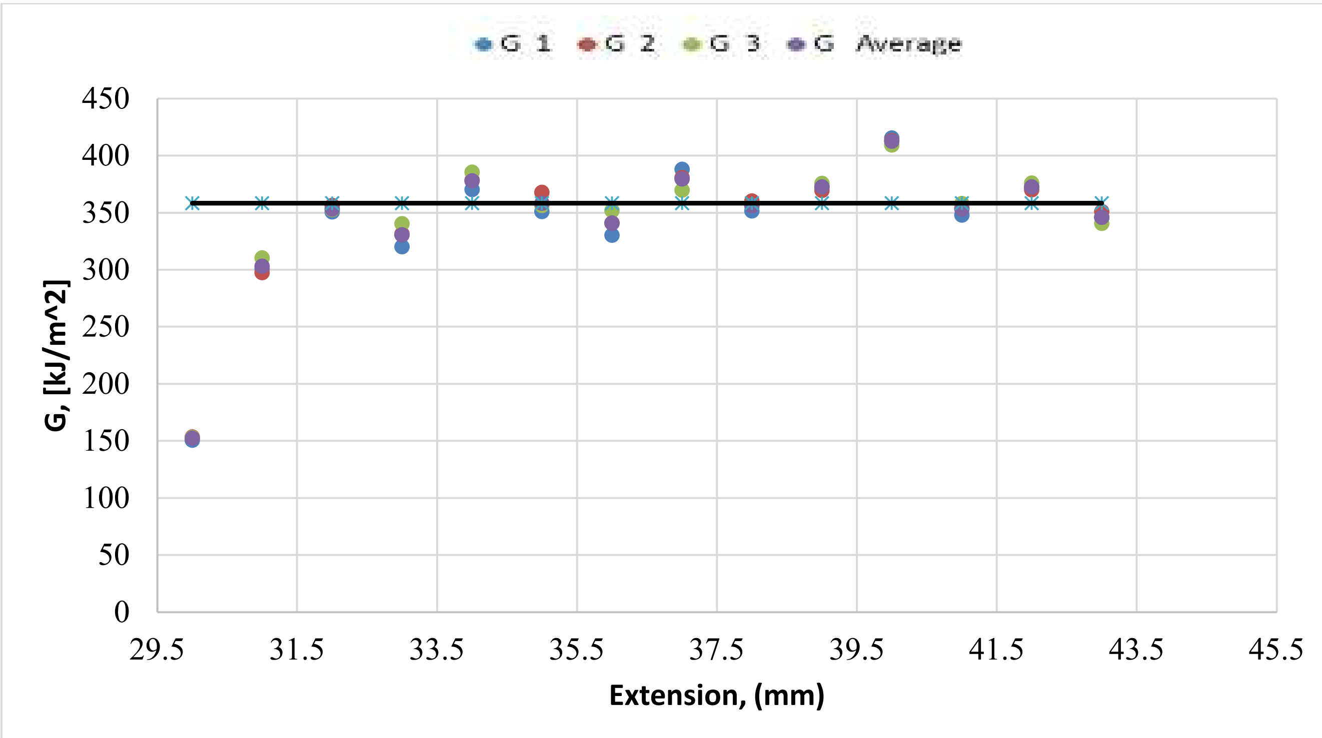


(b)

Figure5. 3: Compact Tension Test result for 30^0 orientations. (a) Force Vs Load line displacement, (b) energy release rate

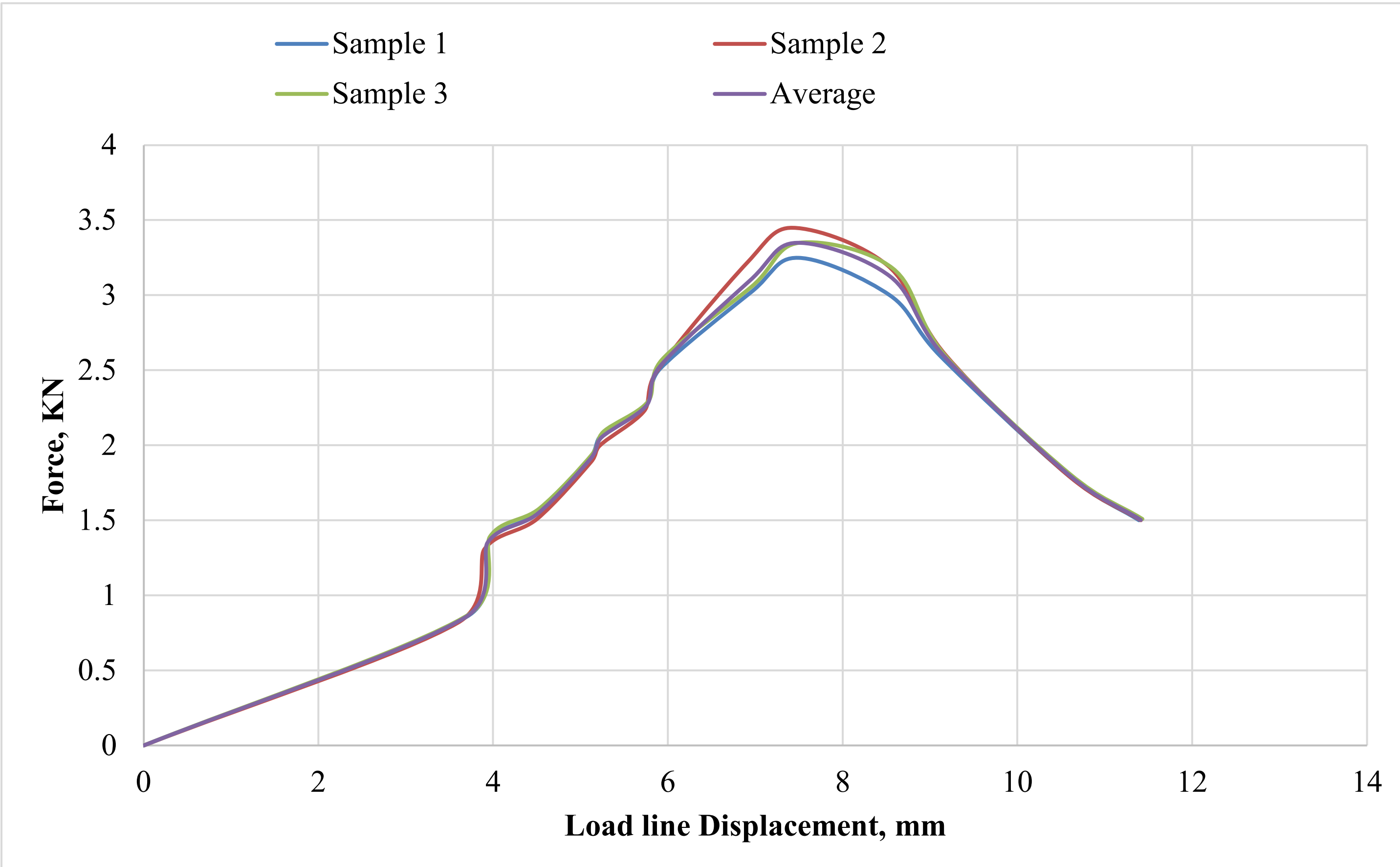

Sample 1
Sample 2
Sample 3
Average
Force, KN
Load line displacement, mm
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
2
4
6
8
10
12
14
16

(a)



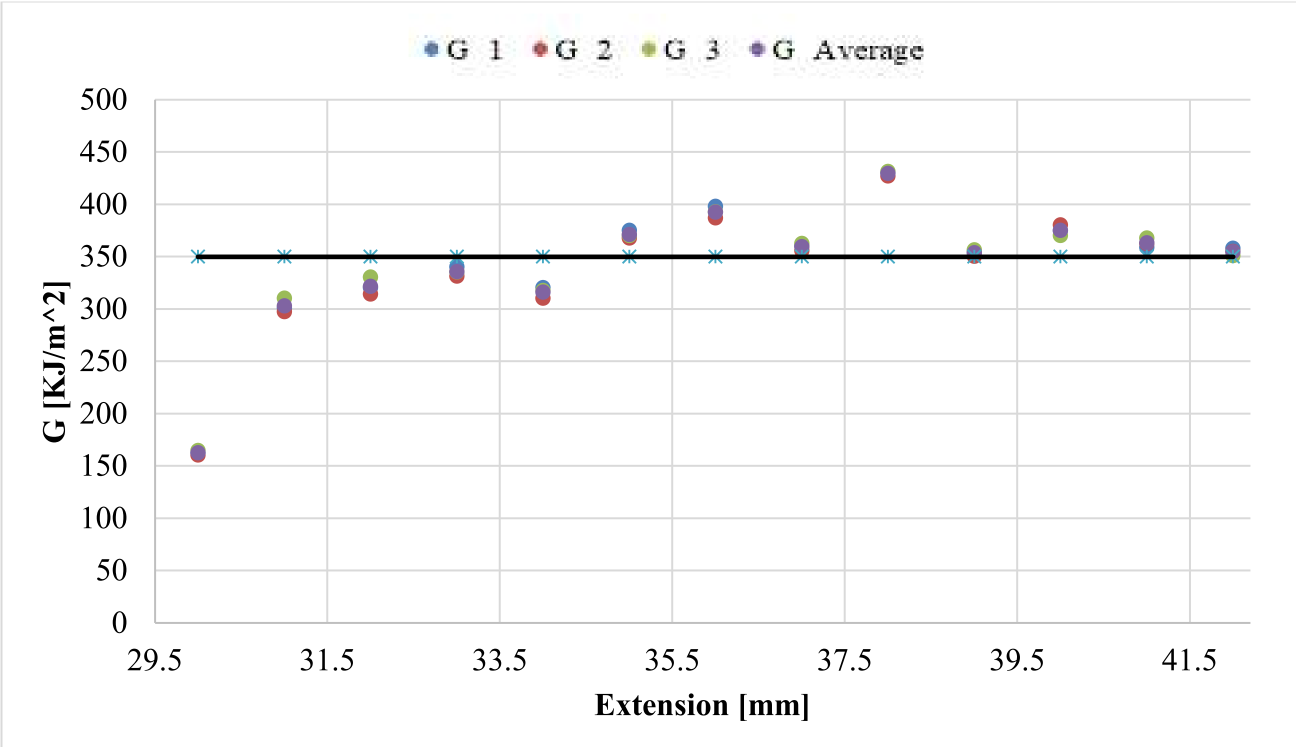
(b)

Figure5. 4: Compact Tension Test result for 45^0 orientations. (a) Force Vs Load line displacement, (b) energy release rate



Sample 1
Sample 2
Sample 3
Average
Force, KN
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
Load line Displacement, mm

(a)



(b)

Figure5. 5: Compact Tension Test results for 60^0 orientations. (a) Force Vs Load line displacement, (b) Resistance- curve for the tensile fracture toughness tests

Where G1 energy release rate which stand for sample1, G2 energy release rate which stand for sample1, G3 energy release rate which stand for sample1, and G is the average energy release rate of the three samples of 60^0.

5.2.3 Strain energy release rate

The critical strain energy release rates of the CT specimen were computed with compliance calibration method, which is one of the data reduction scheme. The results are shown in figure 5.6.

5.2.4 Critical strain energy, G_C

The critical value, G_C of K_C is then found by measuring the critical load P_c needed to fracture a specimen containing a crack length of a_c, and using the slope of the compliance curve at this same value of a.

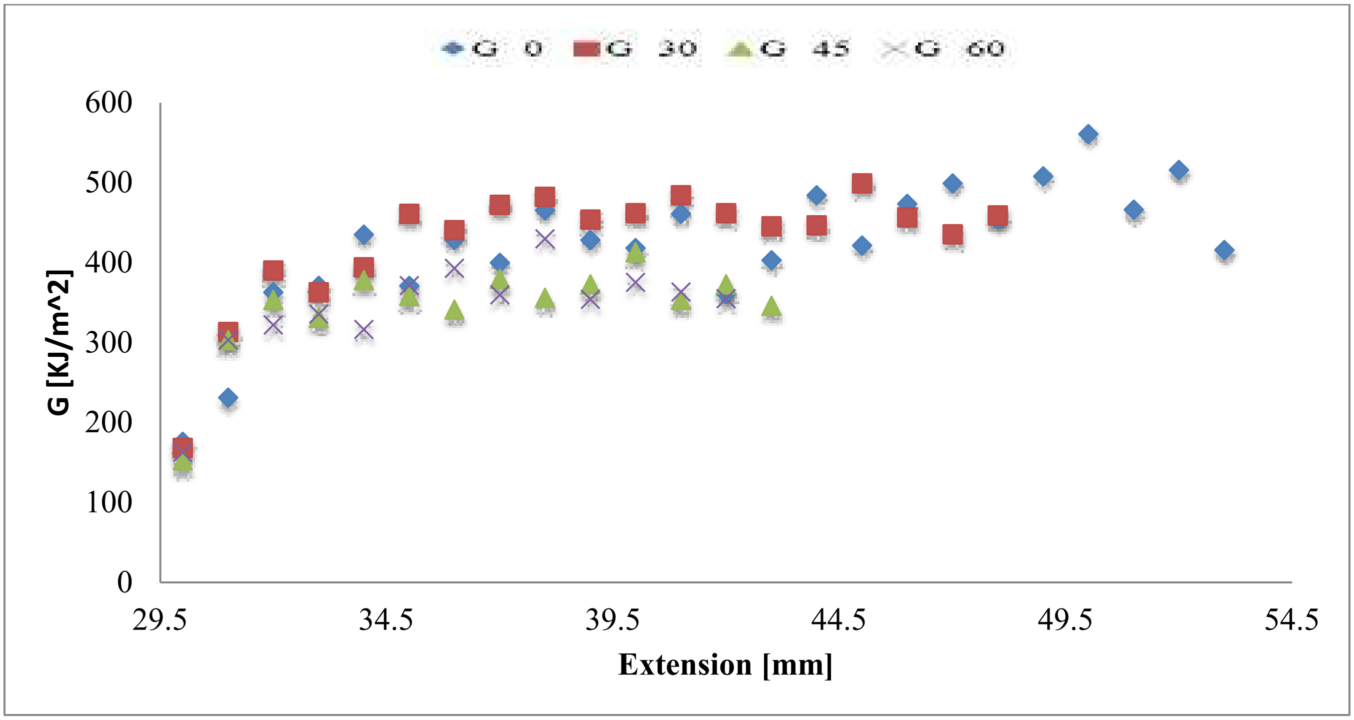


Figure5. 6: Resistance- curve for the tensile fracture toughness tests: each symbol type corresponds

5.3 Discussion

Table5. 2: Strain energy release rate

Specimen	Gc	Percent variation
	KJ/m^2	%
CTS 0	198.66	Reference
CTS 30	229.22	15.38
CTS 60	232.98	17.27
CTS 45	268.64	35.22

The fracture behavior of all the four samples is investigated. The crack propagated in the direction of fiber lay-up.

Gayatri Vineela et al [27] studied fracture behavior of fiber reinforced composites with change in fiber orientation. In this research, three types (45/90, 0/90, and 30/60) of glass/epoxy composite were investigated analytically and experimentally. 30/60 composite material has 239.9 KJm^{-2} energy release rate. From the results, it is concluded that 30/60 composite material has more damaged resistance than the other orientations.

Carlson, L et al 2000 [23] Fracture experiments were carried out on compact tension specimens of cross-ply S-glass/epoxy with 0 and 90 degree orientations. Fracture toughness values were determined by the compliance calibration technique and by measuring the area under the load-displacement curve. Tests on cross-ply S-glass specimens were valid although the cracks propagated were not always straight and other damage mechanisms were also present. 0 degree oriented composite material has best fracture toughness properties with energy release rate value 178 KJm^{-2}.

Depending on the literature, the result from this thesis work is acceptable.

Chapter Six

Conclusion, Recommendation and Future work

6.1 Conclusion

The experimental investigation of fracture behavior of bidirectional woven glass fiber reinforced epoxy composite materials leads to the following conclusions. A woven glass fiber reinforced epoxy composites with fiber orientation (0^0, 30^0, 45^0, and 60^0) are made by hand layup technique. Mechanical property of composites such as fracture toughness is obtained for the above woven glass fiber reinforced epoxy composite system. The average value fracture toughness for each of the test varies within 15.38-35.22% from the corresponding specific test specimens.

From experimental data, the strain energy release rate of CTS 0 was calculated to be 198.66 KJ/m^2. Overall, these results show an improvement 22.62% strain energy release rate over that of CTS 30, CTS 45 and CTS 60. The difference in this case is mostly due to fiber orientation and/ or fiber layup angle.

6.2 Recommendation

Nowadays, many structures are made from composite materials. Glass fiber reinforced epoxy composite materials are manufactured for different applications. To manufacture woven glass fiber reinforced epoxy composite material, manufacturers have to use the right fiber layup orientation. The best fiber la up orientation is important to manufacture a composite material with desired toughness.

Then in order to manufacture laminated composite material, zero (0) degree fiber layup orientation is highly recommended.

6.3 Future work

This thesis work mainly addresses the effect of fiber orientation on fracture behavior of bidirectional woven glass fiber reinforced epoxy composite material. However, there are many different related research areas which are highly important to improve the fracture property of woven glass fiber reinforced epoxy composite materials. Here the following topics are suggested for further studies. These are:

- ✓ Effect of fiber ply thickness on fracture property
- ✓ Effect of woven glass fiber reinforced epoxy laminated composite material manufacturing process on fracture property.
- ✓ Reinforcement and matrix volume ratio difference and its significance on fracture property of woven glass fiber reinforced epoxy laminated composite material.

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