



Addis Ababa University
College of Technology and Built Environment
(CTBE)
School of Mechanical and Industrial Engineering
Mechanical Design Stream

**Investigation of the Intralaminar fracture toughness of jute and
jute-glass hybridized reinforced plastic composite**

By: Biruk Degefu

September, 2026 Addis Ababa, Ethiopia



Addis Ababa University

College of Technology and Built Environment
(CTBE)

School of Mechanical and Industrial Engineering

Mechanical Design Stream

*Investigation of the Intralaminar fracture toughness of jute and jute-glass
hybridized reinforced plastic composites*

A thesis submitted to the School of Mechanical and Industrial Engineering in partial
fulfillment of the Degree of Master of Science in Mechanical Engineering (Mechanical
Design)

By
Biruk Degefu

Approved by the Board of examiners

1. <u>Dr. Mulugeta H.</u> Advisor	_____ Signature	_____ Date
2. _____ Internal Examiner	_____ Signature	_____ Date
3. _____ External Examiner	_____ Signature	_____ Date
4. _____ Chair or School Dean	_____ Signature	_____ Date
5. _____ Office of Vice Executive dean For Academic Affairs	_____ Signature	_____ Date

Declaration

I hereby confirm that this research work, titled "Investigation of the Intralaminar fracture toughness of jute-glass hybridized reinforced plastic composite" represents my own independent efforts. This work has not been submitted previously to any other academic institution for the award of any degree, and all material sources utilized throughout this study have been fully acknowledged.

Biruk Degefu

Date

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

Dr. Mulugeta Habtemariam (Advisor)

Date

Acknowledgment

I would like to thank God for giving me the strength, perseverance, wisdom and health to complete this thesis. I would like to express my indebtedness to my advisor Dr. Mulugeta H. for his expert guidance, technical inputs and unstinting support throughout the course of this research work. Special thanks are extended to Dr. Hairedin I. Head of the Workshop, for his generous advice, contribution of the necessary equipment during composite fabrication and providing much support during material testing. I also thank Dr. Araya A. for his valuable feedback and suggestions.

I am particularly thankful to the hands-on support given by the technical staff in the execution of the experiments: Mr. Anteneh in the workshop for manufacturing and Mr. Mikiyas and Mr. Afework of Addis Ababa Science and Technology University for the technical assistance in material testing and fractography procedures. Thanks to G-seven Trading and Industrial PLC (Ethio Fiber) for providing the raw jute fibers and showing how jute is being manufactured industrially. I would also like to thank Mr. Abadi Zinabu, my colleague, and classmate, for his continuous support and encouragement during our thesis process.

Last but not least, I am very grateful to my dear family. Their love, prayers, sacrifices and moral support without any conditions, during my entire academic journey, has been my strength, foundation and motivation.

ABSTRACT

Fiber-reinforced polymer (FRP) composites are used extensively in the structural industry because of their excellent specific strength and stiffness properties. But, with the concerns about environment related to synthetic fibers, there is now an interest in natural fiber-reinforced polymer composites (NFRPCs). Although jute fibers have a low density, renewability, and cost, their low strength and hydrophilic nature restrict their use in building structures alone. A combination of natural and synthetic reinforcement, e.g. E-glass, gives a good compromise between mechanical properties and ecological advantages. The tensile, flexural and impact properties of jute-glass hybrids are reported, however, a lack of quantification of their intralaminar fracture toughness, crack propagation resistance (R-curve behavior) and the underlying micro-scale failure mechanisms

The study aims to explore the Mode I intralaminar fracture properties of woven jute and E-glass fiber unsaturated polyester composites treated with alkali (5 wt% NaOH). Laminates were produced by controlled hand layup process with three different variations in laminate construction, all having identical total fiber volume fraction (V_f) of 30%, namely a pure jute control laminate “J”, a sandwich-like hybrid laminate “H_1”, and an interleaved hybrid laminate “H_2”. Doubly-tapered compact tension (2TCT) specimens were tested for Mode I fracture in a universal testing machine. Considering the critical energy release rate (G_{IC}) and crack-growth resistance (R-curves) parameters, a two-stage compliance calibration procedure was performed in Abaqus/CAE 2020 software package along with Python scripting and a polynomial data-reduction was obtained to carry out the analysis. In addition, macro-fractography, optical microscopy and X-ray radiographical analysis were employed to establish the progression of damage inside the specimen.

Experimental and numerical results show that hybridization has a significant effect on the crack-growth resistance. The critical energy release rate (G_{IC}) for the pure jute composite increased from 2.887 kJ/m² to 20.74 kJ/m² (86.08% higher) for H_1 and 25.03 kJ/m² (88.46% higher) for H_2. The propagation values ($G_{IC-PROG}$) reached 4.133 kJ/m², 25.809 kJ/m², and 33.645 kJ/m² for J, H_1, and H_2, respectively. It was found that results of the FE-based reduction method are more accurate for estimating orthotropic fracture toughness than isotropic approximations, a finding that was confirmed by comparison with conventional ASTM D5045 formulations, which underestimated orthotropic fracture toughness by 37%-41%. Progressive damage stabilization was observed from the initial appearance of the cracks up to a crack length of 40 mm, followed by the emergence of the multi-interface fiber bridging, tow splitting and delamination phenomena. Interleaver of glass plies (H_2) gave the best toughest value due to the multiple interlaminar shear stresses. These results provide quantitative design recommendations for designing lightweight, environmentally friendly and damage-tolerant hybrid structural composites.

Table of Contents

Acknowledgment	iii
ABSTRACT.....	iv
List of Tables	vii
List of Figures	ix
CHAPTER ONE	1
INTRODUCTION	1
1.1 Background of the Study	1
1.2 Statement of the Problem	9
1.3 Objectives	10
1.3.1 Main Objective.....	10
1.3.2 Specific Objectives.....	10
1.4 Methodology.....	10
1.5 Significance of the Research	13
1.6 Scope and Limitations of the Research	13
1.7 Organization of the thesis	14
CHAPTER TWO	15
LITERATURE REVIEW	15
2.1 Overview of Fiber-Reinforced Polymer Composites	15
2.1.1 Classification and Constituents of FRP Composites.....	15
2.1.2 Role of Reinforcement and Matrix in Structural Performance	15
2.1.3 Engineering Applications of FRP Composites	15
2.2 Natural Fiber-Reinforced Polymer Composites (NFRPCs)	16
2.2.1 Types and Properties of Natural Fibers.....	16
2.2.2 Jute Fiber: Structure, Chemical Composition, and Mechanical Properties.....	16
2.2.3 <i>Advantages and Limitations of Natural Fiber Composites</i>	17
2.2.4 Sustainability and Environmental Considerations	18
2.3 Fiber Surface Treatment and Interfacial Modification	18
2.3.1 Alkali (NaOH) Treatment of Jute Fiber	18
2.3.2 Other Chemical and Physical Treatment Methods.....	20
2.3.3 Effect of Treatment on Fiber-Matrix Adhesion and Mechanical Properties.....	20
2.4 Hybrid Composites: Concept and Design	20
2.4.1 Principles of Fiber Hybridization and the “Hybrid Effect”.....	20
2.4.2 Stacking Sequence and Laminate Architecture Effects	21
2.4.3 Review of Jute-Glass and Related Natural/Synthetic Hybrid Composite Studies	22
2.5 Polymer Matrix Systems for Hybrid Composites.....	23

2.5.1 Matrix Selection Criteria for Jute-Glass Hybrids.....	23
2.5.2 Thermoset Matrices: Epoxy versus Polyester	23
2.5.2 Unsaturated Polyester Resin: Properties, Curing, and Compatibility	23
2.6 Composite Fabrication Techniques	24
2.6.1 Hand Layup Method.....	24
2.6.2 Comparative Overview of Other Fabrication Techniques	24
2.6.3 Curing and Quality/Void-Content Considerations	25
2.7 Fundamentals of Fracture Mechanics in Composites.....	25
2.7.1 Linear Elastic Fracture Mechanics (LEFM) Overview	25
2.7.2 Interlaminar versus Intralaminar Fracture.....	25
2.8 Intralaminar Fracture Toughness Characterization	26
2.8.1 Compact Tension (CT) Specimen Geometry and Test Procedure	26
2.8.2 Data Reduction Techniques and Compliance Calibration	27
2.8.3 R-Curve Behavior and Crack-Growth Resistance	27
2.8.4 Intralaminar Fracture Studies on Synthetic-Fiber Composites	28
2.8.5 Fracture Toughness Studies on Hybrid/Natural-Fiber Composites	28
2.9 Finite Element Modeling of Fracture in Composites	28
2.9.1 Numerical Approaches to Fracture Simulation (VCCT, CZM, XFEM).....	28
2.9.2 Use of Abaqus in Composite Fracture Simulation.....	29
2.10 Fractographic Analysis of Composite Failure	29
2.10.1 Fractography Techniques	29
2.10.2 Failure Mechanisms in Hybrid Composites	29
2.11 Summary and Research Gap.....	31
2.11.1 Synthesis of Reviewed Literature	31
2.11.2 Identified Research Gap	31
2.11.3 Positioning of the Current Study.....	31
CHAPTER THREE	32
MATERIALS AND METHODS	32
3.1 Research Design Overview	32
3.2 Materials	33
3.2.1 Jute Fiber	33
3.2.2 Glass Fiber.....	34
3.2.3 Unsaturated Polyester Resin and Curing System.....	34
3.2.4 Chemicals and Auxiliary Materials	35
3.3 Laminate Design and Stacking Sequence.....	36
3.4 Composite Fabrication.....	37
3.4.1 Preparation of Woven Jute	37

3.4.2 Alkali (NaOH) Treatment Procedure	38
3.4.3 Hand Lay-up Procedure	39
3.4.4 Curing.....	41
3.5 Specimen Preparation	41
3.5.1 Doubly-Tapered Compact Tension (2TCT) Specimen Design.....	41
3.5.2 Specimen Cutting and Precracking	43
3.6 Experimental Testing Procedure	46
3.6.1 Universal Testing Machine Setup	46
3.6.2 Mode I Intralaminar Fracture Test Procedure	47
3.7 Modeling and Numerical Analysis	47
3.7.1 Data Reduction.....	47
3.7.2 Finite Element/VCCT Procedure for Determining Data-Reduction Coefficients	49
CHAPTER FOUR	53
RESULT AND DISCUSSION	53
4.1 Experimental Load-Displacement Curve	53
4.2 Polynomial Data-Reduction Coefficients	56
4.3 Critical Energy Release Rate Values (G_{IC}).....	58
4.4 Resistance Curves (R-Curves).....	60
4.5 Fractographic and Damage Mechanism Analysis	64
4.5.1 Fractographic Analysis of Pure Jute Composite Laminate	64
4.5.2 Fractographic Analysis of Hybrid 1 (H_1) Composite Laminate	68
4.5.3 Fractographic Analysis of Hybrid 2 (H_2) Composite Laminate	72
Chapter Five	77
Conclusion and recommendation	77
5.1 Conclusion	77
5.2 Recommendations Future Work.....	78
5.3 Future Work.....	78
Reference	79
APPENDIXES	88

List of Tables

Table 1 Mechanical Properties of jute fiber [107]	33
Table 2 Mechanical Properties of jute fiber [110]	34
Table 3 Mechanical Property of Unsaturated Polyester resin [108], [109]	35
Table 4 Summary of raw materials used for laminate fabrication in this study	35

Table 5 Stacking sequence and relative percentage of constituent of the composites.....	37
Table 6 Summary of the intralaminar fracture toughness test matrix used in this study...	47
Table 7 mesh refinement data for convergence check.....	50
Table 8 Elastic properties of composite laminae of Jute/Glass-Polyester [112-116]	52
Table 9 Elastic properties of composite laminates used	52
Table 10 Values of polynomial coefficients for the four composite laminates	58
Table 11 Critical Energy Release rate value and standard deviation.....	59
Table 12 stating the difference in critical energy reales rate obtained in data reduction formula and ASTM D5045 standard.....	60
Table 13 the average critical energy release rate for crack propagation (G_{IC_PRO}).....	63

List of Figures

Figure 1 (a) Sustainability of NFRPCS and (b) Advantages of utilizing natural fibers as reinforcement in NFRPCS [1],[5]	2
Figure 2(a) Jute plant, (b) jute fiber after retting and drying, (c) jute yarns after spinning and (d) jute fabric [7]	3
Figure 3 Interlaminar and Intralaminar fracture [28]	6
Figure 4 Structure of jute plant [46]	17
Figure 5 Tensile strength variation for 5% NaOH treated and 10% NaOH treated jute reinforced composites [62]	19
Figure 6 different ways of making stacking sequence	21
Figure 7 Hand lay-up method composite preparation method	24
Figure 8 (a) Interlaminar fracture (delamination) and (b) Intralaminar fracture [84]	26
Figure 9 determination of C and the critical load [40]	27
Figure 10 Overall research methodology flowchart followed in this study	32
Figure 11 Raw Jute fiber bundle	33
Figure 12 Glass fiber	34
Figure 13 other chemicals and auxiliary materials used.....	36
Figure 14 Laminate design and Stacking sequence.....	37
Figure 15 Preparation of woven jute	38
Figure 16 Chemical (NaOH) treatment procedure	39
Figure 17 Hand lay-up procedure.....	40
Figure 18 curing process of the laminates	41
Figure 19 doubly tapered compact specimen configuration.....	42
Figure 20 modeling the 2TCT on the laminates	43
Figure 21 specimen cutting and pre-crack initiation	46
Figure 22 experimental setup	47
Figure 23 Half crack model of 2TCT	49
Figure 24 the different level of mesh (a-Course mesh, b-Intermediate mesh and c-Fine mesh)....	50
Figure 25 Mesh convergence graph	51
Figure 26 Mesh of the selected refinement level.....	51
Figure 27 Load-Displacement Curve (a-pure jute, b-Hybrid 1 and c-Hybrid 2).....	54
Figure 28 stress distribution of 2TCT (a-Von Miss and b-In-plane principal stresses)	56
Figure 29 close-up view of the crack tip	57
Figure 30 critical energy release rate (G_{IC}) and SD.....	59
Figure 31 31 R-curve (G_{IC} vs a)	61
Figure 32 32 graph of G_{IC_PRO}	63

Figure 33 X-ray Imaging and Fractography of pure Jute laminate	64
Figure 34 (a) surface profilometry of jute surface, (b) 2-D and 3-D Morphology of the surface ..	66
Figure 35 (a) top crack surface profilometry of jute , (b) 2-D and 3-D Morphology of the surface	67
Figure 36 (a) bottom crack surface profilometry of jute, (b) 2-D and 3-D Morphology of the surface	68
Figure 37 X-ray Imaging and Fractography of pure Hybrid 1 laminate.....	69
Figure 38(a) surface profilometry of H-1 surface, (b) 2-D and 3-D Morphology of the surface ...	70
Figure 39 (a) 2-D and 3-D Morphology of the Top crack surface of H1, (b) profilometry graph .	71
Figure 40 (a) bottom crack surface profilometry of H_1, (b) 2-D and 3-D Morphology of the surface	72
Figure 41 X-ray Imaging and Fractography of pure Hybrid 2 laminate.....	73
Figure 42 (a) surface profilometry of H-2 surface, (b) 2-D and 3-D Morphology of the surface ..	74
Figure 43 (a) top crack surface profilometry of H_2 , (b) 2-D and 3-D Morphology of the surface	75
Figure 44 (a) bottom crack surface profilometry of H_2, (b) 2-D and 3-D Morphology of the surface	76

List of abbreviations

ASTM	American Society for Testing and Materials
CBBM	Compliance-Based Beam Method
CFRP	Carbon Fiber-Reinforced Polymer
CT	Compact Tension (specimen)
2TCT	Doubly-Tapered Compact Tension (specimen)
CZM	Cohesive Zone Modeling
DIC	Digital Image Correlation
ECT	Extended Compact Tension (specimen)
FE / FEA / FEM	Finite Element / Finite Element Analysis / Finite Element Method
GFRP	Glass Fiber-Reinforced Plastic (Polymer)
HDPE	High-Density Polyethylene
LEFM	Linear Elastic Fracture Mechanics
MEKP	Methyl Ethyl Ketone Peroxide
NaOH	Sodium Hydroxide
NFRPC	Natural Fiber-Reinforced Polymer Composite
PEEK	Polyether Ether Ketone
RTM	Resin Transfer Moulding
SD	Standard Deviation
SEM	Scanning Electron Microscopy
TCT	Tapered Compact Tension (specimen)
UD	Unidirectional
UPR	Unsaturated Polyester Resin
UTM	Universal Testing Machine
VCCT	Virtual Crack Closure Technique
WCT	Widened Compact Tension (specimen)
XFEM	Extended Finite Element Method
J	Pure Jute laminate configuration
H1	Hybrid laminate configuration 1,
H2	Hybrid laminate configuration 2,
R_a	Arithmetic average of deviations from the mean
R_q	Root mean squared value of deviations
R_p	Maximum peak height
R_v	Maximum valley depth

Nomenclature

Symbol	Description
a	Crack length
a_0	Initial (precrack) crack length
B, t	Specimen thickness
c_0, c_1, c_2, c_3	Polynomial data-reduction coefficients
d	Loading-hole diameter
e	Vertical distance from hole center to specimen edge
E_1, E_{xx}	Longitudinal (fill-direction) modulus
E_2, E_{yy}	Transverse (warp-direction) modulus
f, g	Taper horizontal and vertical dimensions (2TCT specimen)
$f(a)$	Normalized energy release rate as a function of crack length
G	Strain energy release rate
G_{IC}	Critical (Mode I) strain energy release rate - fracture toughness
G_{IC_PRO}	Critical energy release rate for crack propagation (R-curve plateau)
G_{IIC}	Mode II critical strain energy release rate
G_{12}, G_{xy}	In-plane shear modulus
h, H	Specimen height
h_1	Untapered center height of the 2TCT specimen
K_{IC}	Critical (Mode I) stress intensity factor
P, P_c	Applied load, critical (fracture) load
V_f	Fiber volume fraction
w, W	Specimen width
$wt\%$	Weight fraction
x	Load-line offset from specimen edge
Δa	Crack extension
ν_{12}, ν_{xy}	In-plane Poisson's ratio
σ	Stress

CHAPTER ONE

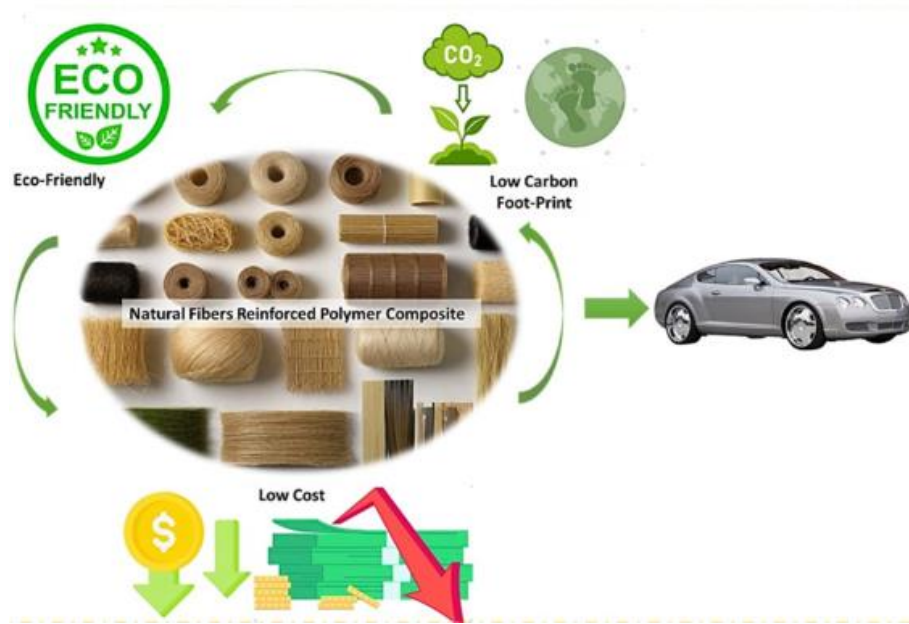
INTRODUCTION

1.1 Background of the Study

Conventional metallic materials are difficult to match fiber-reinforced polymer (FRP) composites in terms of their low density and high specific strength and stiffness, and thus FRP materials have been widely used in various fields such as the aerospace industry, the automotive industry, the marine industry, the wind-energy industry, and the civil-infrastructure industry. The synthetic reinforcements which dominate this class of materials [1], [2]. However, especially those based on glass and carbon fiber, have a significant environmental impact; the cradle-to-gate life cycle assessment of glass-fiber fabric production has reported that the fiber-manufacturing stage itself dominated the non-renewable resource use and greenhouse-gas emissions of the natural fiber [3]. The studies of polypropylene composites using cotton, jute and kenaf fibers also demonstrate that the use of any proportion of one or more natural fiber results in a significant reduction in carbon and eco footprint of the composites compared to the unmodification of polypropylene [4].



(a)



(b)

Figure 1 (a) Sustainability of NFRPCS and (b) Advantages of utilizing natural fibers as reinforcement in NFRPCs [1],[5]

The aforementioned sustainability challenges have spurred the rapid development of natural fiber reinforced polymer composite (NFRPC) research in the last ten years. Recent thorough reviews highlight NFRPCs as an emerging family of engineering materials with the characteristics of renewability, biodegradability, low processing energy, and increasingly higher mechanical strength, and outline the technical challenges, especially the lack of fiber-matrix adhesion due to the hydrophilicity of plant fibers, that remain today [1], [6]. The result of sector-specific reviews is the same: the automotive sector has been identified as one of the industries that has been early in adopting NFRPCs for eco-friendly light-weighting, both because of regulatory pressures for decarbonization, and due to the beneficial strength-to-weight ratio that NFRPCs can provide if the fiber-matrix bonding is optimized [5].

Jute is one of the natural fibers that have been studied with special interest as a structural material due to its low cost, high production and its ability to be used as a structural material after overcoming its main limitation, which is the lack of adhesion to polymer matrices [7]. The chemical treatments developed to enhance this interfacial bonding are generally listed

in reviews of jute fiber-reinforced polymer composites, most frequently the alkali (NaOH) treatment that cleans the surface of the fiber from pectin, wax and hemicellulose, and roughens the surface of the fiber which helps to provide mechanical interlocking with the resin [8]. The results of hot-alkali treatment studies further corroborate the fact that this process is capable of measurably increasing the crystallinity of cellulose in jute fiber and reducing the amount of fiber pull-out at the fracture surface, thus, truly enhancing the interfacial compatibility rather than simply roughening the surface [9]. Similar improvements have been reported using acid pretreatment and combined alkali/silane treatments and both have been demonstrated by scanning electron microscopy to decrease the interfacial gaps between the jute fiber and adjoining matrix in both epoxy and rubber-matrix composites [10], [11].

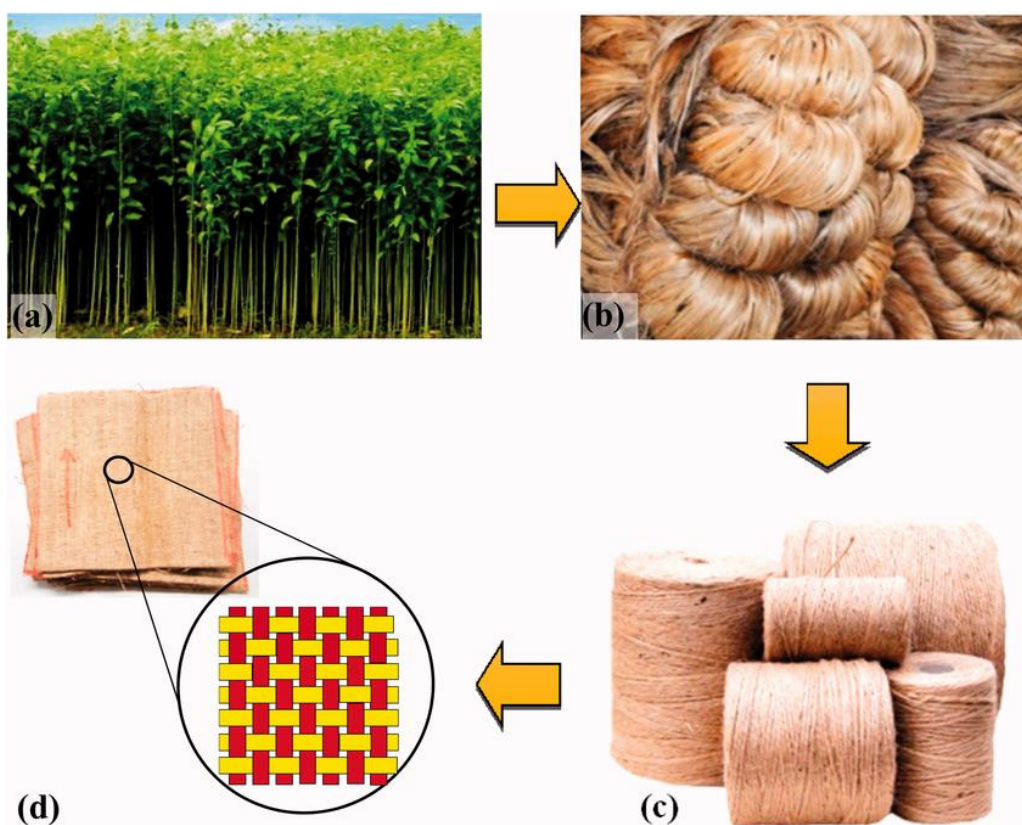


Figure 2(a) Jute plant, (b) jute fiber after retting and drying, (c) jute yarns after spinning and (d) jute fabric [7]

Further systematic studies with varying alkali concentrations also reveal that mechanical properties like flexural and impact strength usually increase to an optimum treatment concentration and then decrease, suggesting that treatment with alkali must be carefully optimized and not just maximized, taking into account the fiber [12]. Similar interfacial gains are seen not just in polymer matrices; alkali-treated jute fiber has also been reported

to significantly enhance the flexural strength and stiffness of fiber-metal laminate sandwich composites compared to untreated fiber, indicating that the chemistry treatment developed for jute-polymer systems is applicable to other combinations of fibers and matrix materials [13].

On the basis of this fiber level knowledge, a significant amount of work has been carried out to directly characterise the jute-glass hybrid composites. Initial research found that the basic hybridization rule is, when mixed together in proportions (weight fractions) of jute and glass fiber in an epoxy matrix, composites become denser, more impact resistant, higher in tensile strength and flexural strength than jute composites, and lower in moisture absorption than jute laminates. This indicates that the addition of glass fiber offsets jute's main mechanical weaknesses [14]. The glass to jute ratio (GJR) has been systematically varied and it has been found that tensile, flexural and impact properties of the jute-glass hybrid materials are significantly dependent on GJR and hence it is treated as the main design variable for engineering a hybrid material with desired properties [15]. As early as 2017, it was found that jute-glass hybrids could be a basic engineering viable material for structural application through the use of the traditional hand layup technique [16].

Recent investigations have built upon this work with the development of more sophisticated and advanced fabrication and characterization methods. A study of woven glass-jute epoxy laminates was performed using the vacuum-assisted resin infusion method (VARI), and further finite element (FE) simulation in the software package ANSYS was used to identify an optimal laminate configuration which resulted in a significant improvement in tensile and flexural strength compared to lower ply count laminates; it was concluded that laminate architecture is a first-order design variable, and not just fiber ratio as originally thought [17]. The flexural and drop weight impact load tests were conducted on compression-molded glass-jute hybrid composites and the results revealed that the area of damages after the impact reduced with an increase in jute content of the hybrid, although jute provides greater stiffness than glass fiber does, but it is evident from the results that jute fiber provides better impact energy absorption among the two fibers [18].

Hybrids made of jute and glass with biodegradable matrix of polybutylene succinate (PBS) have also demonstrated that the stacking sequence plays a significant role in the tensile, flexural and moisture-absorption properties, and the hybrid concept has been extended from thermosetting to biodegradable thermoplastic matrices [19]. Recently, a novel composite

architecture based on a nanomaterial-assisted interface engineering has been investigated, in which a structural core of glass fiber is wrapped by graphene-oxide treated jute fiber, which resulted in a significantly superior tensile strength, flexural modulus and impact resistance to standard laminated jute-glass composites with reduced water absorption, thus suggesting that the new development of jute-glass hybrid architectures through nanomaterial assisted interface engineering is still alive and productive [20]. The tensile properties of jute/carbon fiber-reinforced epoxy composites have been found to be amenable to both experimental and predictive design methods, with good agreement between the two methods for the jute/carbon fiber hybridization system, which is consistent with the overall finding that jute-based hybrids can be designed both ways [21].

Another similar design variable that is not fiber-type ratio is the arrangement of the fibers in the laminate, called the stacking or layering sequence of the fibers in the laminate. It has been demonstrated in the studies on jute/glass/polyester laminates that a neat glass/polyester laminate is superior in raw mechanical performance as compared to a neat jute laminate and a few jute/glass-ply composite stackings with the same total amount of fiber content, but the balance of tensile, bending and thermomechanical properties depend on the specific arrangement of jute and glass plies [22]. Similar stacking-sequence fatigue tests were conducted on banana-glass hybrid laminates designed for use in automotive shell applications, and the mechanical performance and moisture resistance was optimised by examining certain stacking-sequences, while fractographic examination of the failure surfaces indicated that fiber pull-out, matrix cracking, and delamination were the more prevalent, sequence-dependent failure modes [23]. In basalt/ramie hybrid laminates, tensile, flexural and impact properties could be optimized by using a specific (7 layers) stacking sequence [24], in multi-natural-fiber systems with nanofillers and steel mesh, both stacking sequence and nanofillers addition were found to affect tensile, flexural and tribological properties [25]. Combined, these studies show that the fiber-type ratio and stacking sequence can more or less be designed independently from each other, both of which should be optimized for a desired mechanical response of a hybrid laminate.

The above studies have focused on the tensile, flexural and impact properties of jute-glass and related hybrid composites, but the durability of a structural composite under service depends more on the ability of the material to resist crack initiation and propagation, and its fracture toughness, which is a property that is controlled by different physical mechanisms than monotonic strength. Laminated composites are distinguished between

two types of fracture: interlaminar fracture in which a crack extends between two adjacent plies (delamination) and intralaminar fracture in which a crack extends through a ply (interply or interfiber fracture). Intralaminar cracking directly involves fiber breakage and fiber bridging; it is measured using specimen geometries different from that of interlaminar delamination, most commonly with a compact tension (CT) specimen, and is now known to require dedicated characterization, not just based on the interlaminar delamination results [26], [27].

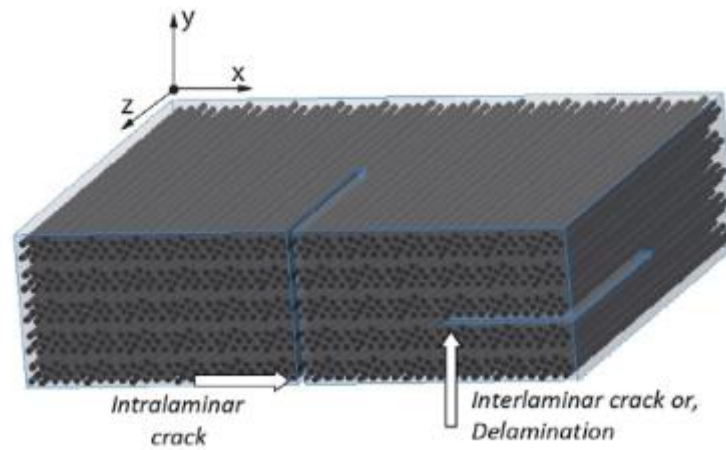


Figure 3 Interlaminar and Intralaminar fracture [28]

Comparative testing of unidirectional carbon/epoxy laminates with compact tension and double cantilever beam specimens has yielded results that the intralaminar and interlaminar initiation toughness values are similar when specimens are prepared with sharp fatigue precracks instead of blunt film inserts, yet the two modes differ significantly during propagation because of the additional fiber-bridging mechanisms associated with intralaminar cracking [28]. Systematic comparisons of stable (compact) and unstable (tension-loaded notch) test techniques for measuring the intralaminar fracture toughness of woven carbon fiber composites have been performed, and it has been found that both test techniques provide comparable values of fracture toughness, provided that the precrack geometry is controlled, and that the use of stable tests as a standard measure for intralaminar characterization is now more reliable [29]. Finally, a wide variety of test geometries, e.g., the modified compact tension test that is used to measure fracture toughness in tri-axial braided composites, have demonstrated that intralaminar fracture toughness can be one to two orders of magnitude greater than interlaminar fracture toughness precisely because the intralaminar propagation requires breaking individual fibers, not just separating plies along a resin-rich interlayer [26]. Intralaminar fracture characterization is still an active

experimental field for well-known synthetic-fiber composite materials, as was shown in the case of high strength carbon-fiber laminates, where special fixtures had to be designed to ensure that the laminate did not fail before the crack tip [27].

Specific fracture toughness issues in hybrid and hybrid with natural fibers have been studied to a lesser extent, and the results reported are generally consistent, highlighting the importance of hybridization, fiber type, and layer sequence as primary factors affecting the toughening of composites. Studies on interlaminar fracture of carbon-fiber laminates hybridized with natural fibers like jute and kenaf have indicated that the introduction of a natural fiber layer is able to retard the growth of cracks and increase the mode I and mode II propagation toughness when compared to non-hybrid carbon fiber laminate structures, which is believed to be due to an increase in fiber bridging at the crack front [30].

This evidence is summarized in reviews of fracture behavior in hybrid natural-fiber-reinforced composites, where it is concluded that in general, stress concentration at a crack tip is lowered and fracture toughness is increased due to hybridization, as the initiation of failure is delayed because dissimilar fibers with different failure strains interact to distribute load more evenly across the process zone at a crack tip [20]. The same shear-fracture-energy mechanism has been used to improve Mode II fracture energy for adhesively bonded natural/synthetic hybrid composites as compared to purely synthetic-fiber composites [31]. Results from complementary tests based on starch bio composites impregnated with hybrid natural fibers and Nano clay indicates that fracture toughness of these composites are sensitive to the weight fraction of natural fibers and in a broad sense similar to those reported for jute-glass bio composites [31] giving reinforcement of the generality of fiber-content-dependent fracture behavior in different classes of natural fiber hybrid composites [32].

Similarly, other measurable improvements and in some cases, improvements, in Mode I fracture toughness and flexural strength when compared to non-hybrid carbon laminates has been seen in carbon-fiber hybrids which replace the natural or semi-natural secondary fiber with carbon fibers, such as silk-fiber and silk-fabric hybrids, and thus the toughening or weakening effect of a secondary fiber is not necessarily assumed a priori, but rather depends on its mechanical character [33], [34]. Fracture toughness of woven carbon-fiber composites reinforced with nanomaterials has been tuned further independently of fiber

architecture by modifying the matrix; this means that fiber-content, stacking-sequence, and matrix-modification are complementary ways of influencing fracture toughness [35].

These publications together show two uniform statements. Secondly, the concept of jute/glass fiber hybrid composites is a mechanically viable and established approach to the development of lower impact structural composites where jute fiber ratio, stacking sequence, fiber treatment at interface and even textile architecture are significant and mostly independent variables to design the tensile, flexural and impact properties [17], [18], [20], [15], [19], [22–25]. Secondly, the effect of hybridization and fiber content on fracture toughness of composite materials is generally accepted in the literature [30–34] [34], [35] and although rigorous intralaminar fracture-toughness testing methods are now well established for synthetic-fiber laminates [26–29], but no studies were found that investigated the relationship between fiber content and the intralaminar fracture toughness, R-curve and the associated micro-scale failure mechanisms of a jute-hybridized glass-fiber-reinforced plastic (GFRP) composite in particular. The few existing jute-glass fracture studies are on the lower end of the spectrum when compared to the large number of tensile/flexural/impact tests, and the fracture literature of hybrid-composites has been limited to carbon-fiber-based hybrids or interlaminar, rather than intralaminar, fracture. This results in a significant lack of understanding in the quantitative sense of designing jute-hybridized GFRP composite to be damage-tolerant for structural applications.

This research gap is important from a practical engineering point of view. Due to the continued advancement of jute-glass hybrid composites from laboratory testing to be used in a variety of applications including in the automotive, marine, and construction sectors, understanding the behavior of such composites during damage and crack growth conditions is becoming increasingly important. Industries where natural fibers are already suggested to replace the part of the conventional reinforcement materials are identified [2–5]. Although many studies have reported the mechanical properties of jute-glass composites, information on how the amount of jute fiber affects intralaminar fracture toughness and the mechanisms responsible for failure is still limited. However, the knowledge of these factors is needed to find out whether the decrease in the amount of glass-fiber can be achieved without giving the composite a significantly decreased capacity to resist and control the propagation of crack. This information would be useful in the development of structural composite materials that would be more conducive to utilizing more jute fibers that are

made from renewable sources and relatively low costs, yet maintain a degree of damage resistance.

Thus, a set of experiments is conducted to study the intralaminar fracture toughness of the jute-glass fiber-reinforced polymer composites in this thesis. The influence of jute fiber content and the orientation of jute fibers on the fracture toughness and the R-curve behavior of the laminate is of particular interest. The failure mechanisms of crack initiation and propagation for the various composite configurations are also studied. The experimental procedure is inspired by the numerous studies on jute-glass hybrid composites [1], [2], [5], [6], [8–21] and fracture-testing methods that have been developed and used for synthetic-fiber-reinforced composites [26–29], [34], [35] [36–40]. The study will deliver relevant experimental data regarding the fracture characteristics of hybrid jute-glass composites and may help to enhance the development of composite materials that can provide a practical compromise of sustainability, cost, fracture resistance, and crack growth resistance.

1.2 Statement of the Problem

The use of light and sustainable material for engineering applications is growing and there is a growing interest on the use of hybrid composite, a composite obtained by association of natural fibers with synthetic reinforcement fibers [1], [2], [5], [6]. This interest developed mainly because of environmental impact created due to synthetic materials and the need for light weight material having good strength to replace those materials. In order to overcome this problem new materials must be explored and studied for their properties and must be characterized.

Thus jute fiber, important for its biodegradability, low density, low cost and availability can be successfully used to improve the sustainability features of Fiber Reinforced Plastic (FRP) composites, without compromising the mechanical performance, by using an adequate interface treatment, and engineering the fiber ratio and stacking sequence [8], [12], [22]. But, the intralaminar fracture toughness of the jute and it's hybridized GFRP composites, the associated resistance-curve behaviour and damage mechanisms are poorly understood. And determining these properties are crucial in the presence manufacturing defects or in-service damage [26], [30], [34].

Therefore, characterisation of fracture behaviour and fracture mechanisms of jute and jute-hybridized GFRP composites is important for the environment for using it as alternative to

synthetic materials and design optimisation for structural applications as the fracture testing directly assess the resistance to crack propagation, which is the most important property in determining the safe service life and durability of a composite structure. This study attempts to address these deficiencies by systematically characterising jute for intralaminar fracture toughness and its damage characteristics which give quantitative information to develop efficient and environmental friendly structural materials.

1.3 Objectives

1.3.1 Main Objective

The primary objective of this research is to investigate the Mode I intralaminar fracture behavior and failure mechanisms of jute fiber composites and their hybrid configurations.

1.3.2 Specific Objectives

- To investigate the force-displacement response of jute and jute-hybridized GFRP composites under intralaminar fracture loading.
- To determine the critical energy release rate value of the composites (fracture toughness, G_{IC})
- To construct the crack-growth resistance curve (R-curve) of the composites
- To evaluate the microstructural failure mechanisms of the composite laminates (Fractography)

1.4 Methodology

The methodology adopted for this research is of experimental type which is used to investigate the intralaminar fracture toughness of jute-hybridized glass fiber reinforced plastic (GFRP) composite. Several phases were employed in the study, which were:

I. Literature review

- ❖ Reviewed and synthesized literature (journal articles, conference papers, books) to develop background knowledge on natural-synthetic hybrid composites, chemical surface treatments and fracture mechanics characterization.

II. Material Preparation

- ❖ The following are the reasons for importing jute from Bangladesh for use as packaging material and some jute used for this study was extracted from the jute plant in Ethiopia: Jute Fiber and Glass Fiber. Then it is prepared and treated with chemical to enhance adhesion. Glass fibers was bought from Ethio-fiber.
- ❖ For the making of composite, a suitable unsaturated polyester was bought from Ethio-Fiber PLC, to be compatible with jute and glass fiber.

III Composite Fabrication

- ❖ Layering Design: Composite laminates that are made with different amounts of jute fiber but the same amount of glass fiber.
- ❖ Controlled hand layup: Manufacturing process used to produce composite laminates. This process will involve putting the fibers in the desired orientation and spreading the polyester resin over the fibers to a uniform thickness. The fabricated laminates were then cured at room temperature, which results in maximum bond between the fibers and the matrix.
- ❖ Sample Preparation: Three materials prepared each having five sample using ASTM standards for the compact tension specimen test.

IV. Experimental Testing

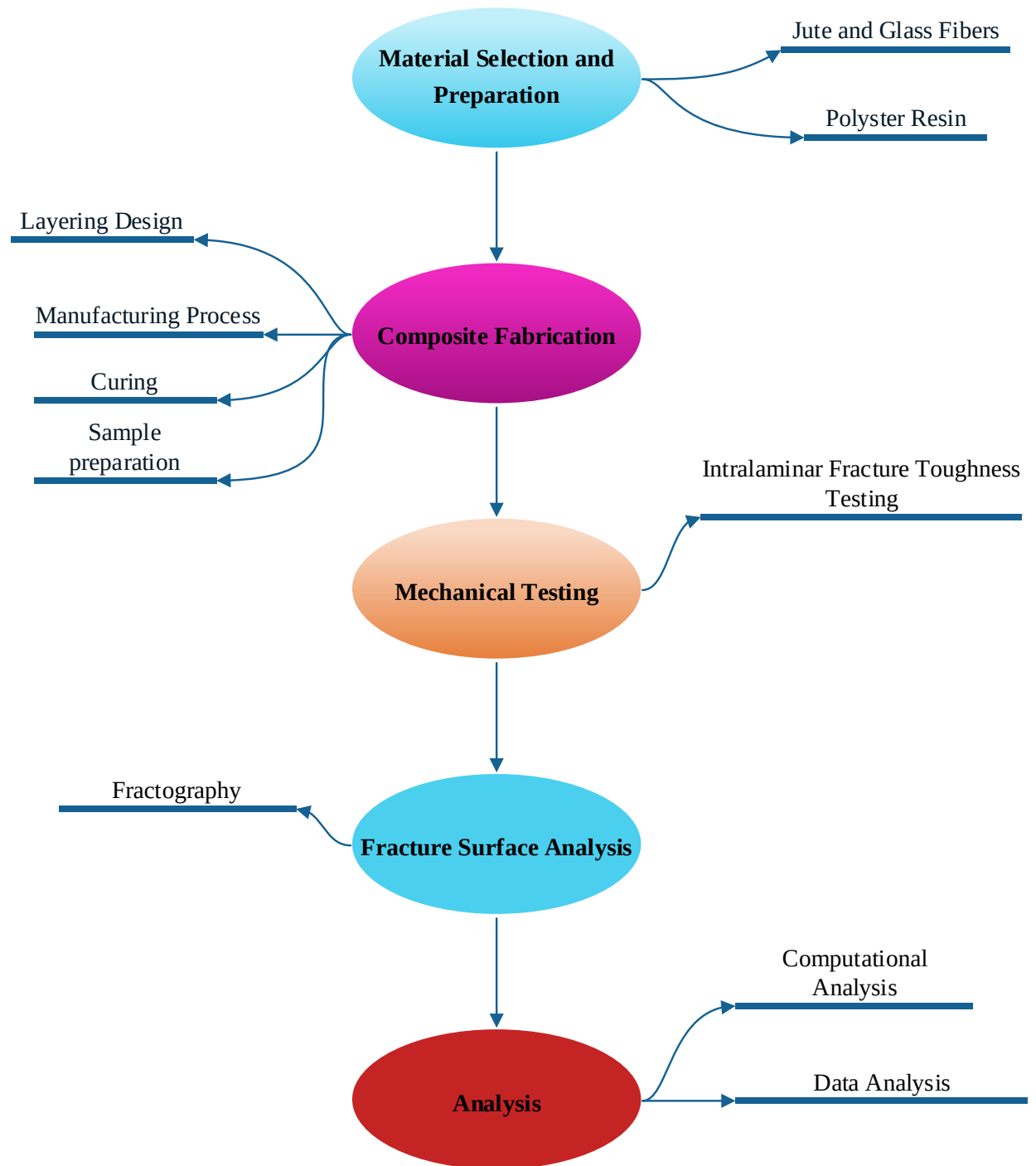
- ❖ Intralaminar Fracture Toughness Testing: using doubly-tapered compact tension specimen, tensile mode I intralaminar fracture test done on universal testing machine.

V. Analysis

- ❖ The FEA analysis was performed using computational software: Abaqus 2020, while Matlab was used to perform the curve fitting and to determine the polynomial coefficient for the data reduction technique.
- ❖ Data Analysis: From the experimental result and computational analysis critical energy release rate was determined and R-curve plotted.

VI. Fracture Surface Analysis

- ❖ Fractography of each material discussed.



1.5 Significance of the Research

This study is important as it explores the intralaminar fracture toughness of jute-hybridized glass fiber-reinforced plastic (GFRP) composites, which are not adequately addressed in the vast amount of available literature on various tensile, flexural and impact properties [1], [8]-[12]. This study investigates the effect of different fiber content of jute/fiberglass composites on fracture resistance and provide quantitative understanding of fracture behavior and failure mechanisms that will help in designing guidelines for optimizing the structure behavior of hybrid composites.

The results of this study are hoped to assist in developing sustainable, high performance material for use in engineering applications based on use of renewable resources like jute as per the literature on sustainability and LCA in composite materials [4]-[6], [28], [29]. The findings may be particularly relevant for industries like automotive, aerospace, marine and construction, which are looking to replace materials for structural applications with increasingly sustainable and cost-effective composites.

1.6 Scope and Limitations of the Research

The study aims to investigate the intralaminar fracture toughness of the jute-hybridized glass fiber reinforced plastic (GFRP) composites. It studies the performance of these materials with respect to the influence of varying jute fiber content on the mechanical performance. Controlled hand layup technique and standard curing processes will be used to fabricate composite laminate. The compact tension specimen will be employed to assess intralaminar fracture toughness under universal testing machine and fracture surfaces will be analysed by scanning electron microscopy (SEM) to understand the failure mechanism.

The study will only be conducted on certain fiber orientations (woven) and proportions. The study's results are expected to help fill the knowledge void regarding the fracture behaviour of jute-hybridized GFRP composite and offer valuable insights for design of sustainable high-performance materials to be used in automotive, aerospace, marine and structural applications.

1.7 Organization of the thesis

The thesis comprises of five main chapters. Chapter 1 presents the background of the research and sets out the main problem and core objectives, methodology, scope and engineering significance of the research. The literature review described in Chapter 2 provides a comprehensive overview of the literature, lays the foundations for a theoretical framework and assesses current advances in the field. The experimental and numerical procedures are described in Chapter 3 such as material selection, chemical treatment, fabrication of the specimens, testing setups and finite element modeling in Abaqus software. Experimental data and numerical results are reported and analyzed in chapter 4, where fracture toughness parameters, R-curve and fractographic analysis are covered. Finally, Chapter 5 summarizes the findings, point out important contributions, and suggest future areas of research.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview of Fiber-Reinforced Polymer Composites

2.1.1 Classification and Constituents of FRP Composites

Fiber reinforced polymer (FRP) composites are composite materials that are created by continuous or discontinuous fibers embedded in a polymer matrix, and their mechanical properties are superior to those of any of their components [41], [42]. The reinforcing phase, which is usually glass, carbon, aramid or a natural fiber, has the highest applied load, and determines stiffness and strength properties, while the polymer matrix distributes load between fibers, maintains fiber alignment and protects the fibers from environmental degradation [43]. According to matrix type, the FRP composites can be classified as thermoset-based and thermoplastic-based, which include various implications for processing, mechanical performance and cost, according to type of fiber, they can be classified as synthetic fiber or natural fiber, with implications for processing, mechanical performance and cost, and according to the architecture of the reinforcement, they can be classified as unidirectional, woven, chopped or hybrid, with implications for mechanical performance and cost [42], [44].

2.1.2 Role of Reinforcement and Matrix in Structural Performance

The mechanical properties of an FRP composite depend on both the intrinsic properties of the fiber and the intrinsic properties of the matrix, and the quality of the interfacial bond between them [43]. If the bond between the matrix and the fiber is strong, load can be transferred from the matrix to the fiber, whereas, if the bond is weak, it will result in premature debonding, fiber pull out and a lowering of the composite strength even if individual fibers are strong [41]. This interface-dependence is a recurring theme throughout the literature reviewed in this chapter and is a primary motivation for the fiber-treatment strategies discussed in Section 2.3.

2.1.3 Engineering Applications of FRP Composites

Because of their high specific strength and stiffness compared with traditional metallic materials [42], [44], FRP composites are widely applied in various industries, such as aerospace, automotive, marine, wind energy, and civil infrastructure. Carbon fiber or aramid fiber composite has a higher price tag than glass fiber composite; however, when

structural performance, corrosion resistance, and cost are considered, glass fiber provides a more favorable combination than either carbon fiber or aramid fiber, and thus dominates applications like boat hulls, storage tanks, automotive body panels, and pipe systems for which cost is a major factor [41], [43]. This composite of performance and affordability is one of the major factors that make GFRP the synthetic-fiber portion of the hybrid composite being researched in this thesis.

2.2 Natural Fiber-Reinforced Polymer Composites (NFRPCs)

2.2.1 Types and Properties of Natural Fibers

Because they are locally available in many production areas, inexpensive and renewable, and biodegradable, natural plant-based fibers like jute, sisal, hemp, kenaf and flax have become the focus of ongoing research as reinforcements, due to their relatively good specific mechanical properties and low density [45], [46]. From these, the jute fiber is one of the most extensively studied bast fiber due to its some level of strength, high availability and very low cost compared to the synthetic fiber, it is a natural fiber fiber that is suitable for being used in part to replace the glass fiber in the structural composites [45].

2.2.2 Jute Fiber: Structure, Chemical Composition, and Mechanical Properties

The structure, chemical composition and mechanical properties of jute fiber will be discussed. Jute fiber is a lignocellulosic bast fiber from the stem of *Corchorus capsularis* and *Corchorus olitorius* plants containing cellulose, hemicellulose, lignin, some pectin, wax and extractives [46], [47]. The composition can vary slightly depending on the cultivar and growing conditions and the retting process, but it is generally summarised as 70-75% cellulose, 15-20% hemicellulose, with a small amount of lignin, pectin, wax and mineral matter in total (see figure 4) [47], [48]. Cellulose, which crystallizes into microfibrils, provides load-bearing properties to the fiber; hemicellulose and lignin, which are both amorphous, adhere the microfibrils together and, besides, lignin imparts stiffness and resistance to microbial attack. The individual jute fiber cell is spindle-shaped, ranging between 1.5 mm and 5 mm in length and 15-25 μm in width, and is naturally bound in a natural system to form the technical fiber [46], [49].

In addition to composition, morphological variation also affects the properties of jute fiber; the nominal diameter is a less significant factor than the actual fiber cross sectional area in the determination of tensile strength, and the Weibull analysis indicates that the jute fiber

has a lower modulus than glass fiber, meaning that there is greater fiber strength scatter [50]. In addition to this, there is an additional degree of scatter in measured diameter coefficients of variance that are > 20% within a single fiber batch, and strength and modulus that vary with gauge length and harvest position along the stem [51], [52]. At the composite scale, this type of variability manifests as deviations between the experiments and the simulations for jute-glass composites and the improvement of accuracy obtained when the rule-of-mixtures uses the irregular fiber cross-sectional area in lieu of a circular one [53], [54].

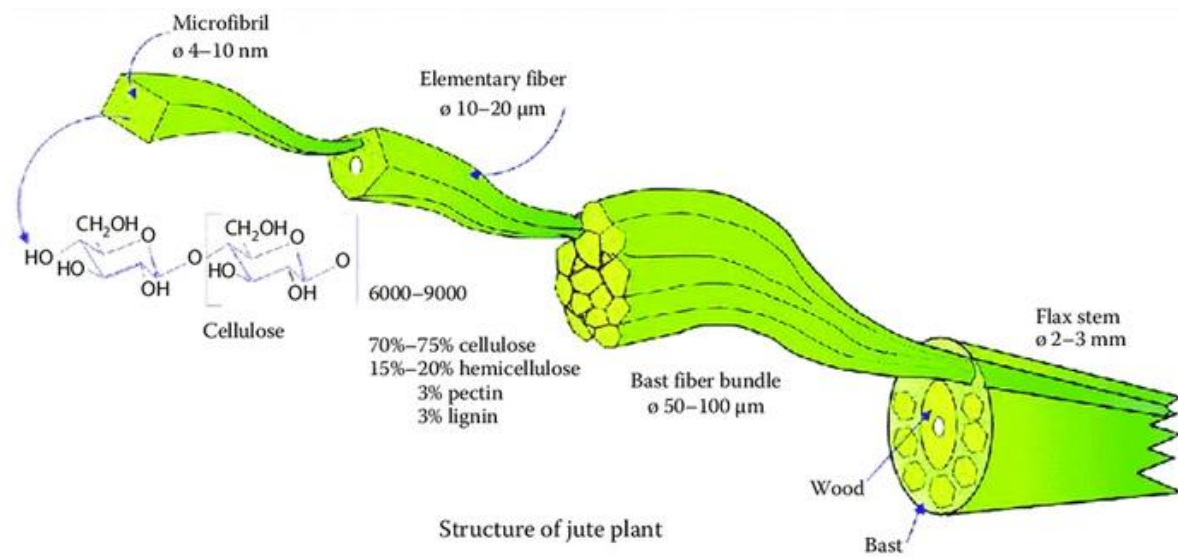


Figure 4 Structure of jute plant [46]

2.2.3 Advantages and Limitations of Natural Fiber Composites

The key benefits of jute and other natural composites are its low density, low cost, renewability and biodegradability, making it suitable for possible application as partial replacement of glass fiber in non-critical or hybrid structural applications [45]. Due to the inherent hydrophilic nature of cellulose, natural fiber composites typically exhibit moisture absorption, dimensional changes, and inconsistent and incomplete bonding with hydrophobic polymer matrices unless the fiber surface is chemically modified [55], [56]. The property variability of natural fiber composites is another challenge due to natural variation in fiber diameter and cellulose crystallinity and defect density along the fiber length and for this reason the treatment of fibers (Section 2.3) and hybrid of natural fibers with a synthetic fiber (Section 2.4) are the two predominant methods cited in the literature to overcome these limitations[45], [56].

2.2.4 Sustainability and Environmental Considerations

The environmental benefit of replacing natural fiber with GFRP is well established: the use of natural fiber lowers the energy use, carbon footprint, and non-renewable resource use of the composite, and even partial replacement of the glass fiber with natural fiber reduces [41], [44]. The mechanical case discussed below is another factor underlying the current research interest in jute-glass hybrid composites, in addition to this sustainability motivation.

2.3 Fiber Surface Treatment and Interfacial Modification

2.3.1 Alkali (NaOH) Treatment of Jute Fiber

Most important chemical process done to jute and other bast fiber is the alkali (NaOH) treatment, to remove the pectin, wax and some hemicellulose on surface exposing cellulose microfibrils and roughen surface as shown in a schematic manner in Figure 2 [49], [55]. The roughness of the resulting fiber allows another mode of fiber-matrix interlocking and removes weak boundary layers where concentration of stresses could occur and alkali treatment has also been shown to increase the relative crystallinity of the cellulose fraction by selectively removing amorphous non-celluloseic material [55].

There is a phenomenon worthy of attention: to improve the mechanical properties of materials, the effect is highly dependent on the concentration of NaOH. The changes in the two are not unidirectional; they will not continue along a single trend indefinitely, and will only reach the optimal effect within a specific concentration range. It is not that the higher the NaOH concentration, the material's properties will keep improving. Once the most suitable concentration is exceeded, the properties can no longer continue to be enhanced. A comprehensive review of alkali treatment effects on different natural-fiber-reinforced polymer systems has been conducted, and it is concluded that the mechanical properties of the treated composite compared to the untreated base composite depend on the concentration, exposure time and washing protocol after the treatment, and most fiber systems have a clear optimum concentration range of 4-6 wt% NaOH [57].

For kenaf/polyamide composites, 6 wt% NaOH gave the best results. The flexural strength was the highest, and the void content was the lowest at this level. When the NaOH level was increased or reduced from 6 wt%, the flexural strength dropped. At the same time, void content went up in the composites [58]. In bamboo fiber-reinforced epoxy composites, the

optimum concentration of NaOH solution that leads to the maximum tensile strength and Mode-I fracture toughness of the composites was determined using Box–Behnken response surface optimization, showing that the optimization of NaOH concentration can be correlated with the outcome of fracture toughness [59].

This is not to say that alkaline concentrations of 4-5 wt% are optimal for bast fibers in general: Soaking a new bast fiber for 30 minutes at 4 wt% NaOH was reported to increase tensile strength by 50% [59] and further increases in concentration were reported to progressively weaken the fibers by excessive delignification and scission of the cellulose chains. Similar results have been obtained for banana fiber-epoxy composites [60]. a 5 wt% NaOH treatment resulted in an enhancement in tensile, flexural, and impact properties of the composites by about 15%, 9%, and 30%, respectively, and it has been shown that the preparation method (hand layup versus hydraulic press) affects the mechanical properties of the composites in combination with the NaOH concentration used in the treatment [61],[62].

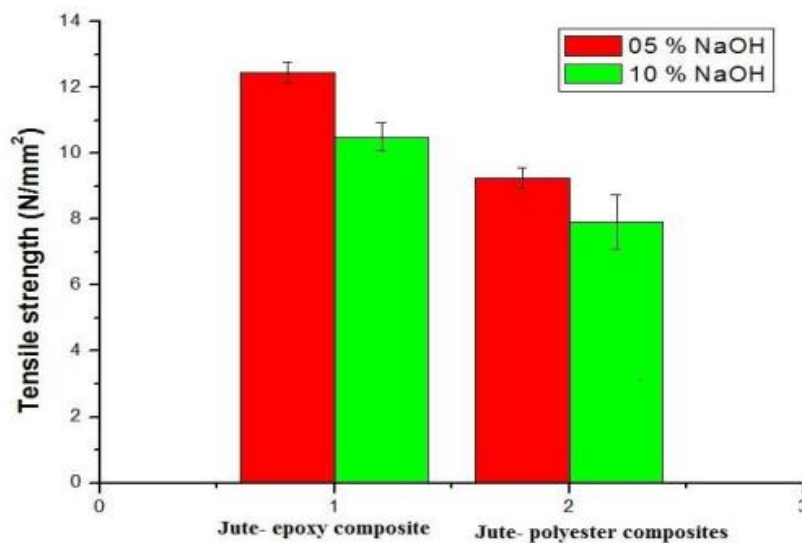


Figure 5 Tensile strength variation for 5% NaOH treated and 10% NaOH treated jute reinforced composites [62]

The overall results indicate that, rather than being a binary treated/untreated variable, concentration is really a process parameter that needs to be optimized when using jute fiber and the polyester matrix system for the purpose of this thesis.

2.3.2 Other Chemical and Physical Treatment Methods

Besides the alkali step, papers also describe other ways to change the surface. One method uses silane coupling agents. In that case, the hydroxyl groups on cellulose bond to the polymer network through covalent links. Other work looks at acetylation and benzylation of cellulose. There is one note about polyester-matrix systems, though. In those cases, methacrylic-silane treatment is used instead [63]. For jute-polyester composites, some studies report that gamma radiation at moderate levels can improve tensile strength. They link this to more crosslinking at the fiber-matrix boundary. But when the radiation dose gets too high, the strength drops. The reason given is that heavy exposure degrades the cellulose backbone [64].

2.3.3 Effect of Treatment on Fiber-Matrix Adhesion and Mechanical Properties

Across the reviewed treatment studies, the top tensile, flexural, and impact results showed up at a specific treatment level or time. After that point, extra treatment can strip more non-cellulosic matter. That removal can weaken the fiber. In some cases, the treated fiber properties even get worse. Because of this, treatment settings have to be tuned with care. It is not a matter of pushing those property values to the highest possible level [49], [64]. A key design point for the fiber preparation stage in the present invention is this same idea. The link between interfacial modification and mechanical performance is treatment dependent and not monotonic.

2.4 Hybrid Composites: Concept and Design

2.4.1 Principles of Fiber Hybridization and the “Hybrid Effect”

In the case of a hybrid fiber with more than one kind of reinforcement fibers in a polymer matrix, the process is called fiber hybridization and the aim is to achieve a fiber composite with properties lying between the two non-hybrid fiber composites. A large number of papers describe systematic deviations from the rule of mixtures, which are known as the hybrid effect, or positive hybrid effect and negative hybrid effect, respectively, with respect to the properties of the hybrid laminate and its constituent fibers [65], [66]. A positive hybrid effect is when the measured property is greater than the rule-of-mixtures prediction, which is typically explained by the synergistic load sharing between the two types of fibers, whereas a negative hybrid effect, usually reported for fracture-related properties, is

believed to be due to the effect of the interfaces and/or strains incompatibility between two types of fibers [65].

2.4.2 Stacking Sequence and Laminate Architecture Effects

The performance of a hybrid laminate is also known to vary with the order of the plies and not only as a function of the fiber-type ratio; for example, the four representative jute-glass stacking sequences compared in Figure 3 have been shown to have a significant influence on the laminate performance [67], [68]. Research with kenaf/E-glass/hemp and similar three-fiber hybrids has indicated that, at a fixed total fiber content, the relative position of the synthetic fiber (core versus skin) significantly affects the laminate's tensile and flexural responses, due to the fact that the bending stresses are the highest in the outer layers of the laminate, and thus they have the greatest impact on flexural properties [69], [70]. In the same way, twill-weave kenaf/Kevlar/polyester hybrid has been demonstrated that the sequence of the layers in a laminate and the direction of the fibers within each layer are independent design variables and can be optimized together for a given application to achieve either the highest tensile strength, the highest flexural strength, or the highest hardness [64].

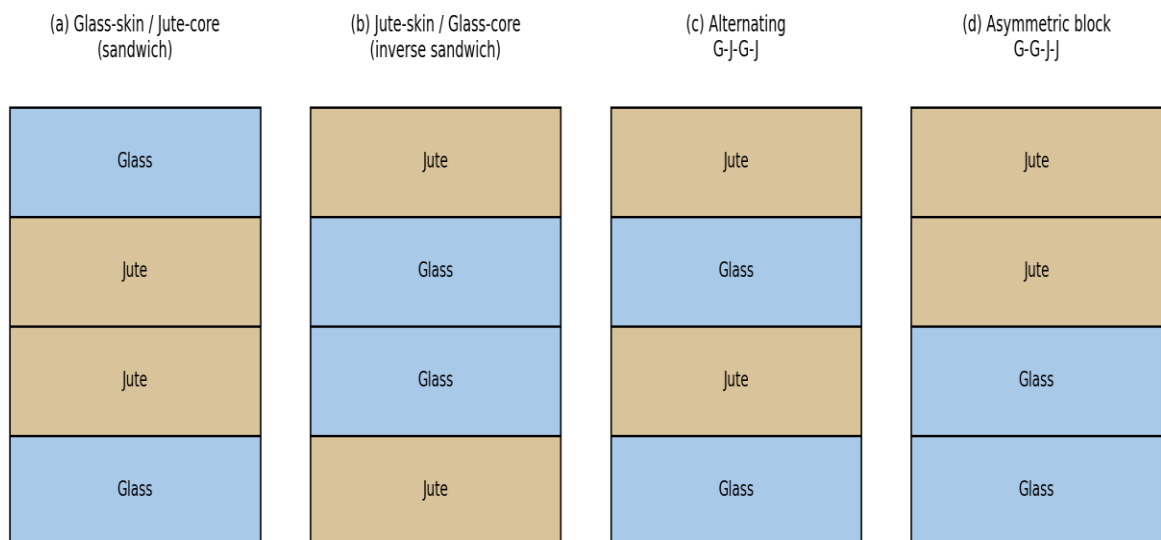


Figure 6 different ways of making stacking sequence

Figure 6 shows four examples of stacking sequence that are frequently discussed in the jute-glass hybrid literature and representative of the configuration space investigated in this thesis. The configuration shown in (a) is a glass-skin/jute-core sandwich: flexural stresses are highest in the skin (typically, the flexural strength and stiffness are maximized); the jute

core provides toughness, reduces areal density and cost. This configuration is typically reported to be the best performing for flexure dominated loading [69], [70]. In configuration (b), the jute is placed on the outside and the glass is placed on the inside, with the result that the flexural strength is generally decreased compared to configuration (a), but in some studies, both impact energy absorption and moisture-barrier behavior of the exterior surface is improved due to the use of jute, which is a more compliant outer material being used to absorb energy through fiber pull-out and matrix cracking before the load reaches the stiffer glass core [69].

The alternating sequence of glass-jute-glass-jute in configuration (c) results in an even distribution of the two fiber types in the thickness direction and tends to have intermediate fiber properties between (a) and (b), a more even stress distribution through the thickness, and, in some studies, more gradual progressive failure than the abrupt failure found in (a) with a skin-dominated failure [67], [68]. It is the least advantageous of the four block configurations, due to the absence of mid-plane symmetry, and the laminate thus obtained may exhibit unwanted bending-extension coupling effects and residual curvature during cure, this is often used intentionally in the literature to study the bending-extension coupling effect, or to tailor one face of a component for a particular environmental exposure [67], [70].

2.4.3 Review of Jute-Glass and Related Natural/Synthetic Hybrid Composite Studies

The use of jute-glass materials led to the development of studies that incorporated natural fibers and glass in mechanical systems, with a large volume of literature available to give context to the specific studies of jute-glass mechanics reviewed in Chapter One. Hybridization has been reported to improve the tribological and mechanical properties of kenaf/glass composites by optimizing the stacking sequence, addition of fillers, and treatment of kenaf fibers, compared to unhybridized composites entirely made of kenaf fiber [68]. Results from testing under a standard ASTM protocol have revealed that tensile strength, wear resistance, and water-absorption resistance for all hybrid systems of hemp, kenaf, flax and sisal fibers and glass fiber have been consistently enhanced, to varying degrees, with the natural-fiber composites than the corresponding non-hybrid natural-fiber composites [69]. The results obtained with chemically similar bast and leaf fibers further support the mechanical basis for the jute-glass hybridization in particular.

2.5 Polymer Matrix Systems for Hybrid Composites

2.5.1 Matrix Selection Criteria for Jute-Glass Hybrids

The selection criteria for jute-glass hybrids is presented in the form of a matrix. The use of an unsaturated polyester matrix for a jute-glass hybrid composite represents a conscious choice because unsaturated polyester is less expensive and is easier to process than epoxy, and, as such, it is a material that is more likely to be used for reasons of cost than for mechanical performance, therefore placing emphasis on appropriate fiber treatment and quality control during fabrication to ensure acceptable composite performance [71], [72]. Many mechanical tests done on jute-polyester have proved that if treated and fiber loaded properly, jute-polyester laminate can have tensile and flexural properties similar to jute-epoxy laminate with much lower material costs [73], [74].

2.5.2 Thermoset Matrices: Epoxy versus Polyester

In jute and jute-glass hybrid composite researches, epoxy and unsaturated polyester resin are the most frequently used thermoset matrices. Epoxy, in general, has better mechanical properties, lower cure shrinkage, and better fiber wet-out, but is also much more expensive than the unsaturated polyester resin (UPR) which is significantly cheaper, cures rapidly at room temperature, and is the primary matrix material used in large volume, cost-sensitive structural applications like boat hulls and storage tanks [71], [72]. This cost benefit is one of the reasons that polyester resin is used as the matrix system for the present study as opposed to epoxy.

2.5.2 Unsaturated Polyester Resin: Properties, Curing, and Compatibility

A free radical copolymerization reaction between unsaturated polyester resin and a reactive diluent, most often styrene, is the mechanism of cure, with an accelerator that allows cure at room temperature, and a peroxide catalyst [75], [76]. One of the major technical challenges with UPR is the relatively high cure shrinkage, if not managed properly by cure temperature, catalyst ratio and post-cure profile, it can lead to generation of internal stresses, fiber–matrix debonding and micro-voids [71], [77]. UPR is also highly hydrophobic compared to the cellulose and it is difficult to wet-out and to provide good bonding at the interface between the untreated jute fiber and the UPR, which is another reason why alkali treatment (as described in Section 2.3) is required if UPR rather than epoxy is used as matrix [63], [78].

2.6 Composite Fabrication Techniques

2.6.1 Hand Layup Method

The hand layup technique is the most popular fabrication process reported in the literature for jute and jute-glass hybrid polyester composites as it involves less capital equipment, it can be used to fabricate woven natural fiber fabrics which are difficult to be processed by automated processes and it gives the ability to control the ply stacking sequence precisely [73], [74], [79]. During this process, fiber layers are first placed in an open mold and then coated with the resin, which is impregnated into the fibers with a resin roller or brush, and the laminate is cured, generally at room temperature followed by a post cure step, and, in many of the studies, subjected to light compression molding to establish the final thickness and fiber volume fraction of the laminate [74], [80].

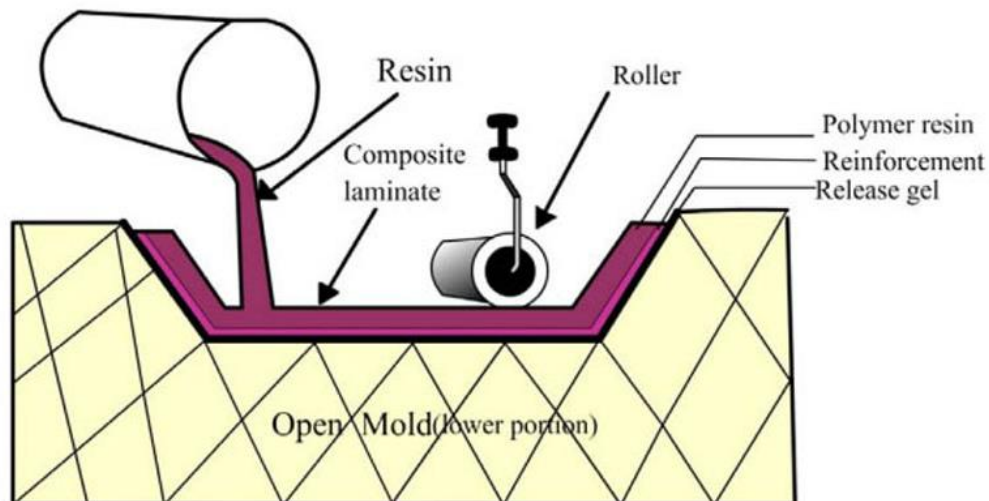


Figure 7 Hand lay-up method composite preparation method

2.6.2 Comparative Overview of Other Fabrication Techniques

In addition to hand layup, jute reinforced composites have also been manufactured by compression molding, vacuum assisted resin infusion, injection molding and pultrusion with varying levels of fiber volume fraction, void content, surface finish and production rate [45]. Comparative SWOT-style reviews of these techniques conclude that simpler techniques like hand layup have a bit lower mechanical properties because of the uneven distribution of fibers and higher void content, while more capital-intensive techniques like resin infusion or compression molding are able to get higher fiber volume fraction and more consistent fiber quality, with a higher degree of processing complexity [45].

2.6.3 Curing and Quality/Void-Content Considerations

Whatever fabrication method is employed, control of the resin curing cycle with regards to gel time, exotherm temperature, and post-cure schedule can be shown to directly impact the distribution of voids, interlaminar bond quality, and final mechanical properties of polyester-matrix composites [75], [77]. Careful control of resin viscosity and layup pressure is especially important for hand-layup jute-glass hybrid laminates because of the significant differences between the surface roughness and moisture sensitivity of jute compared to glass fibers, which can result in resin-starved regions and trapped voids if layup is not carefully performed, as summarized in Table 1 [45], [74].

2.7 Fundamentals of Fracture Mechanics in Composites

2.7.1 Linear Elastic Fracture Mechanics (LEFM) Overview

The mathematical basis for linear elastic fracture mechanics (LEFM) is used to describe the stress field near a crack tip, characterized by a stress intensity factor, K , which is a function of applied load, crack length and specimen geometry, as shown in Figure 4 [81]. Outside a small process zone at the crack tip, LEFM assumes that the material is linear elastic, which is generally a good approximation for the matrix-dominated and fiber-dominated fracture behavior of FRP laminates in which the process zone is small compared to the specimen size [82].

2.7.2 Interlaminar versus Intralaminar Fracture

A major difference between laminated composite fracture mechanics is the difference between interlaminar fracture commonly called delamination which is the propagation of a crack between adjacent plies and intralaminar fracture which is the propagation of a crack within a ply cutting across the reinforcing fibers themselves [83], [84]. Intralaminar (translaminar) fracture toughness testing, which is most relevant to the present study, has been standardized for damage-initiation toughness only, for several decades, and various less standardized methods exist for crack-growth (R-curve) behavior [82], [83].

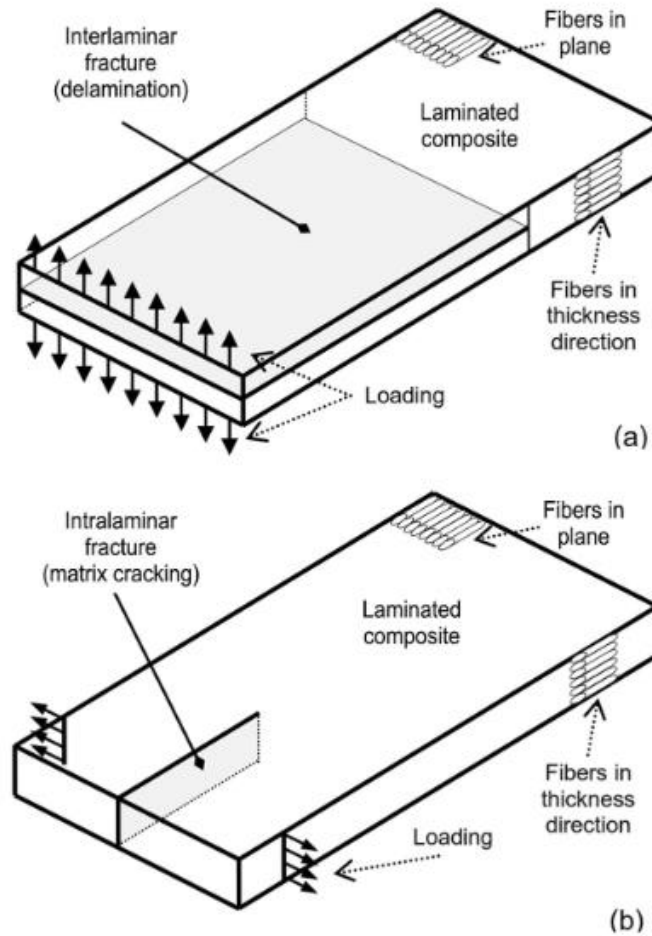


Figure 8 (a) Interlaminar fracture (delamination) and (b) Intralaminar fracture [84]

2.8 Intralaminar Fracture Toughness Characterization

2.8.1 Compact Tension (CT) Specimen Geometry and Test Procedure

The compact tension (CT) specimen is widely used for intralaminar (translaminar) fracture toughness characterization of polymer matrix composites and is designed from the ASTM E399 standard for metallic-materials fracture toughness testing, and is a rectangular, or doubly-tapered, plate specimen on which a notch has been cut and two symmetric loading holes have been drilled; the specimen is loaded in tension through the two loading holes to drive crack propagation across the specimen width [82], [85]. A preexisting fatigue or razor-sharpened precrack is usually created in front of the tip of the machined notch before testing to provide a sharp crack initiation site that is reproducible and consistent with sharp precracks, as blunt notches have been found to overestimate the measured fracture toughness compared to sharp precracks [85].

2.8.2 Data Reduction Techniques and Compliance Calibration

As per ASTM D5045, the critical load for the crack initiation is determined by drawing a straight line AB from the load-displacement curve and the compliance will be determined then another line AB' will be drawn which having 5% greater compliance as shown in figure 9, by relating these lines the peak load will be determined [40]. Since the CT test data are obtained without using an optical crack length measurement at each load increment, the energy release rate can be extracted from the load-displacement record using compliance based data reduction method. The most widely used method in compliance based data reduction from CT test data is the compliance calibration (CC) method, which relates the compliance of the specimen (displacement per unit load) empirically or analytically to the instantaneous crack length, thereby enabling the energy release rate to be calculated directly from the measured load-displacement record [86], [87]. Comparative testing of compliance calibration to modified beam theory has demonstrated that, when the crack length-compliance relationship is calibrated for the particular material and geometry, both of those methods provide consistent and repeatable toughness values [87], [88].

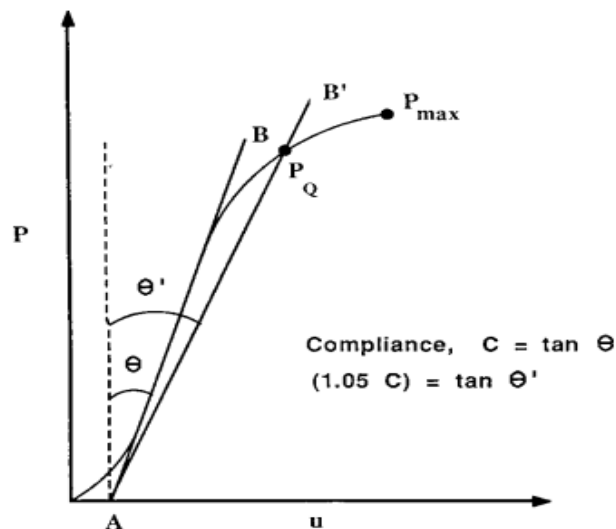


Figure 9 determination of C and the critical load [40]

2.8.3 R-Curve Behavior and Crack-Growth Resistance

The apparent fracture toughness changes with the progression of crack propagation; it is known as the resistance curve (R-curve) and shows a rising trend from an initial value to a plateau value where a zone of fiber bridge has formed behind the advancing crack tip [89], [90]. This rising R-curve behavior, which is well established for interlaminar delamination and is now showing up to an increasing degree for intralaminar and translaminar cracking,

is known to be geometry and specimen-size-dependent and not strictly a material property [91], [92].

2.8.4 Intralaminar Fracture Studies on Synthetic-Fiber Composites

Studies of intralaminar fracture of synthetic-fiber composite materials. Most severe intralaminar and translaminar fracture toughness characterization has been performed on carbon fiber and glass fiber based composite systems, and these principles have been extended to natural fiber and hybrid fiber laminate systems in the compact-tension and single-edge-notch-tension methods, respectively. Those studies show the translaminar fracture toughness results change a lot with specimen thickness. They also depend on ply orientation and how sharp the precrack is. Over time, the papers added ways to reduce data and suggestions for building the specimens. That work supports the testing method used in this thesis for the jute hybrid GFRP composite [82], [85], [93], [94].

2.8.5 Fracture Toughness Studies on Hybrid/Natural-Fiber Composites

In addition to the fiber-bridging and R-curve mechanisms presented in this section, it is evident that hybridization, fiber content and interfacial treatment control the intralaminar fracture resistance in a similar manner to the synthetic-fiber composites of which they are a part, as presented in Chapter One and reviewed here [91], [92]. This is the theoretical underpinnings required for comparing the rigorous test and data reduction methodology traditionally used for synthetic fiber systems with the composite system of jute fiber and GFRP, studied in this research.

2.9 Finite Element Modeling of Fracture in Composites

2.9.1 Numerical Approaches to Fracture Simulation (VCCT, CZM, XFEM)

The virtual crack closure technique (VCCT), cohesive zone modeling (CZM), and extended finite element method (XFEM) are the three numerical techniques that have been most widely used for the finite-element simulation of crack propagation in composite laminates [95]. VCCT, based on LEFM principles, calculates the energy release rate directly from the nodal force and displacement in front of and behind a user defined crack tips rather than the crack length, but will need a pre-existing crack and a very fine, often re-meshed, mesh in front of and behind the crack tips [96]. CZM, on the other hand, describes fracture under a traction-separation law at a cohesive interface, does not require any pre-existing crack to exist, and does not require any modification of the mesh domain as damage progresses;

hence, it is of a relatively simple implementation for cases of delamination and translaminar crack propagation in commercial finite element codes [96], [97].

2.9.2 Use of Abaqus in Composite Fracture Simulation

Abaqus is one of the most popular commercial finite-element packages for fracture simulation in composite laminates, and is readily capable of simulating debonding in composites using a VCCT methodology, and naturally also provides support for various cohesive-element and cohesive-contact models for composites fracture (CZM), as well as enhanced support for XFEM-VCCT hybrid methods since recent upgrades [97], [98]. Applications of cohesive zone formulations to a variety of fracture problems, including delamination in laminated composites, fracture at interfaces in bonded joints, fracture of cementitious materials, and fracture of metals, have been made using cohesive elements included in the Abaqus material models, or through user-defined cohesive UEL/UMAT subroutines, and have proven to be both versatile and reliable for problems involving a variety of material systems [97], [99].

2.10 Fractographic Analysis of Composite Failure

2.10.1 Fractography Techniques

At the microstructural level, the main instrument used to analyse composite fracture surfaces is the scanning electron microscope (SEM), which allows the various failure modes to be identified that were involved in crack propagation, such as fiber breakage, fiber pull-out, fiber-matrix debonding and matrix cracking [58], [100]. In general SEM fractography is carried out on the fracture surface sections after mechanical testing and micrographs are analyzed at different magnifications to differentiate the zones of the fracture surface that fail in fibers, matrix and interfacial ways [100]. Some of the alternative to analyze the damage mechanism are digital image correlation (DIC), X-Ray and C-scan.

2.10.2 Failure Mechanisms in Hybrid Composites

The failure mechanisms found from fractographic examination of natural and hybrid fiber composite structures are all similar: fiber pull-out (where the fiber-matrix interface has poor bonding or load transfer at a specific location); fiber-matrix debonding (where cracks form in the matrix, with gaps or smooth fiber surfaces that do not contain resin); matrix cracking and micro-void coalescence; and, when hybrid laminates are considered, crack deflection at the interface between dissimilar fiber plies, which has been suggested as a toughening

mechanism similar to fiber bridging [60], [100], [101]. One parameter of particular diagnostic value is the length of fiber pull-out, where a short pull-out length with uniform pull-out lengths are normally indicative of good fiber-matrix interface bonding, and a long pull-out length and non-uniform pull-out lengths are normally indicative of poor fiber-matrix interface bonding or weak fiber-matrix interface bonding [57], [61].

The mechanics of fiber pull-out has been extensively studied in the general composites literature. pull-out is known to involve two previous, sequential failure events, first debonding the fiber from the matrix ahead of the crack tip, and then frictional sliding of the debonded fiber as it is pulled from the matrix, and the energy dissipated during this frictional sliding stage is recognized as the primary toughening contribution of the pull-out mechanism [102], [103]. A detailed examination of the pull-out mechanism in brittle-matrix fiber-reinforced composites once again showed that failure of the fibers is preferentially triggered by flaws on the surface of the fibers present at the interface rather than by the fibers' nominal strength, as is well known in the case of observed pull-out lengths in a real composite fracture surface being distributed rather than uniform even for nominally the same strength of the fibers [104]. Jute fiber has natural surface irregularities and cell-wall defects (Section 2.2.2) which are likely to give a correspondingly wide distribution of pull-out length on the fracture surfaces investigated in this study.

Inplane fracture analyses of fiber-reinforced composites have demonstrated that cracking usually initiates at the matrix ahead of the crack tip, loading the remaining intact fibers, which fail subsequently either on the matrix crack plane, resulting in a sudden loss of load bearing capacity of the fibers, or at a weak spot within the still-intact matrix, which leads to fiber pullout and provides bridging traction along the crack wake [105]. Acoustic-emission-based studies, correlating the acoustic signature (signals generated by the growing crack) with the associated fracture mechanism, have demonstrated that matrix cracking, fibre breakage, fibre-matrix debonding and delamination all possess statistically distinct acoustic signatures that can also be used to track the sequence in which the various mechanisms occur during loading, in addition to the post mortem SEM fractography used in this study [106]. These studies confirm that fiber pull-out, interfacial debonding and matrix cracking do not occur independent of each other, but are rather sequential failure modes whose relative dominance on the fracture surface corresponds to the quality of interfacial bond and distribution of fiber strength at that location. The current study is summarized and a research gap is identified.

2.11 Summary and Research Gap

2.11.1 Synthesis of Reviewed Literature

The literature reviewed in this chapter covers the fundamentals of FRP composites, the properties and treatments of jute fibres, the principles of hybrid composite design, polyester matrix systems, methods for fabricating composites, fractography using SEM and theory of fracture mechanics; intralaminar fracture toughness characterization and finite element fracture modeling. This body of literature is sufficient to conclude that jute composite and jute-glass hybridization is a mechanically and economically viable approach, that treatment of the fibers and stacking sequence are important design variables that are largely independent from each other, that the intralaminar fracture toughness testing methodology in synthetic fiber-based composites is well established in the ASTM E399 and ASTM D5045 compact-tension/ESE(T) framework, and that cohesive zone modeling with Abaqus is a validated method for numerically predicting the propagation of cracks after a test to the R-curve data.

2.11.2 Identified Research Gap

To the authors' knowledge, there is no cited study that has undertaken a comprehensive investigation of the intralaminar (translaminar) fracture toughness properties of a jute-hybridized glass-fiber-reinforced polyester composite specific to this material, incorporating rigorous, standards-based testing, R-curve characterization by compliance calibration, finite element correlation with Abaqus, and fractographic analysis via SEM. The studies that have been performed on jute-glass and jute-polyester materials have all focused on tensile, flexural, and impact properties, and the literature of intralaminar fracture toughness have devoted their attention to carbon and glass-fiber-only systems, with no attention given to the examined combination of materials.

2.11.3 Positioning of the Current Study

This thesis has the potential to fill this void directly because it utilizes methodologies not previously seen working together but, in each case, applied previously to different, non-hybrid or synthetic-fiber-only composite systems: hand layup fabrication of jute-hybridized GFRP polyester laminates, testing of doubly-tapered compact tension specimens according to Intralaminar fracture toughness principles, the extraction of R-curve behavior, and the interpretation of the resulting fracture surfaces by using X-Ray and 3D Optical surface profiler microscope (model:zeta20).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Research Design Overview

The chapter outlines the materials, manufacturing processes, specimen design, experimental testing procedure, data-reduction method and finite element modeling method, and fractographic analysis method employed to study intralaminar fracture toughness of jute-hybridized glass-fiber-reinforced polyester (GFRP) composites. The overall research design is based on 9 sequential phases, starting from literature review, moving on to a fractographic analysis and concluding with the solution.

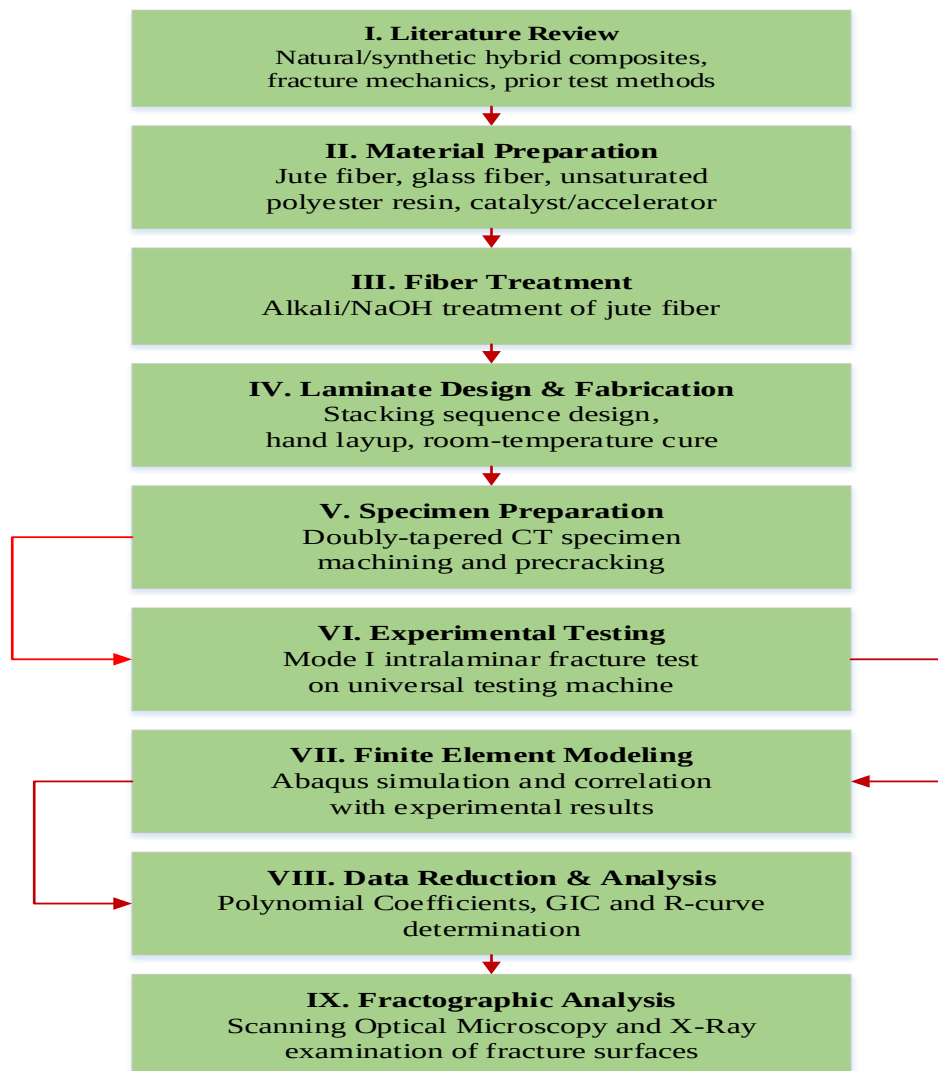


Figure 10 Overall research methodology flowchart followed in this study

3.2 Materials

3.2.1 Jute Fiber

In this study, the natural fiber reinforcement was used in the form of raw jute fiber. Jute fiber bundles for this investigation were raw fiber bundles obtained from Bangladesh for industrial packing application, because jute is not commercially grown in Ethiopia in sufficient quantity for making composites as reinforcement. Then, it is passed through a number of machine operations to get the fine jute fibers. Samples are taken prior to the fibers being chemically treated by the company. The fine fibers were observed and trimmed to the required size of the ply and were stored at room temperature for a week to normalize the moisture content of the fiber plies and to minimize the property scatter that inherent to jute due to its hydrophilic nature [8], [79].



Figure 11 Raw Jute fiber bundle

Table 1 Mechanical Properties of jute fiber [107]

Properties	Amount
Moisture content (%)	1.1
Tensile strength (MPa)	393–773
Pectin (%)	0.2
Diameter of fiber (μm)	5–25
Density (g/cm^3)	1.46
Hemi-cellulose (%)	12
Elongation (%)	1.16–1.5
Micro-fibrillar angle ($^\circ$)	8.0
Cellulose (%)	64.4

Young modulus (GPa)	13–26.5
Fiber length (mm)	0.8–6
Lignin (%)	11.8
Waxes (%)	0.5

3.2.2 Glass Fiber

The synthetic-fiber reinforcement was woven E-glass fabric, which was obtained from World-Fiber PLC. For the reasons mentioned above, the use of E-glass fiber in this study is found to be well suited since it could provide a high specific strength and stiffness at a comparatively low material cost, is locally available, and is compatible with ambient-cure unsaturated polyester resin systems, which makes it a practical and economically viable synthetic reinforcement for a jute-hybridized structural GFRP composite [108–110].

Table 2 Mechanical Properties of jute fiber [110]

Property	E-Glass fiber
Density (g/cm ³)	2.54
Young's modulus (GPa)	76
Poisson's ratio	0.22
Shear modulus (GPa)	33
Elongation (%)	1.8–3.2
Tensile strength (MPa)	3400



Figure 12 Glass fiber

3.2.3 Unsaturated Polyester Resin and Curing System

An unsaturated polyester resin (UPR) and hardener for the curing was bought from World-Fiber PLC Addis Ababa, Ethiopia. This system was used for all the laminates produced in this study. UPR is a thermosetting resin with good fiber wet-out, moderate mechanical properties and low viscosity that makes it suitable for hand-layup fabrication of glass and

natural-fiber-reinforced laminates, such as boat hulls, storage tanks, automotive body panels, and pipe systems [24], [30].

Table 3 Mechanical Property of Unsaturated Polyester resin [108], [109]

Property	Value
Density (g/cm ³)	1.2
Tensile strength (MPa)	50
Young's modulus (GPa)	3
Shear Modulus (GPa)	1.13
Poisson's Ratio	0.31
Elongation (%)	2.5

Table 4 Summary of raw materials used for laminate fabrication in this study

Material	Type / Grade	Source	Role in Laminate
Jute fiber	Woven fabric,	Ethio-Fiber PLC	Natural-fiber reinforcement
Glass fiber	Woven E-glass fabric	World-Fiber PLC	Synthetic-fiber reinforcement
Polyester resin	Unsaturated polyester resin	World-Fiber PLC	Polymer matrix
Catalyst	Hardener (MEKP)	World Fiber PLC	Room-temperature curing agent

3.2.4 Chemicals and Auxiliary Materials

Key chemicals and processing tools were used during the fabrication of the composite laminates for surface modification, sample washing and mold release. In order to get better interfacial adhesion between the natural fibres and the matrix, alkaline surface treatment of the raw jute fibre was used with sodium hydroxide (NaOH). The treated fibres were then washed with distilled water to remove all the chemical reagents and impurities from the fibres before drying. Moreover, the commercial honey wax was used as a good release agent on the mold surfaces, so that the cured laminates can be successfully demolded without breaking the composite laminate. The processing materials and chemicals were sourced locally.



Figure 13 other chemicals and auxiliary materials used

3.3 Laminate Design and Stacking Sequence

An experimental program was designed and conducted to isolate the effect of jute fiber content on intralaminar fracture toughness while maintaining the same number of plies and laminate thickness. A jute fiber only control laminate and two jute-glass hybrid laminates are increasing jute content were used as shown in Figure 14. This design was based on stacking-sequence design principles, in which the outer plies have been used in the form of glass fibre to maintain the flexural load-bearing capacity and moisture resistance, with the core plies being gradually replaced by jute fibre to assess its impact on fracture resistance [17], [20], [22].

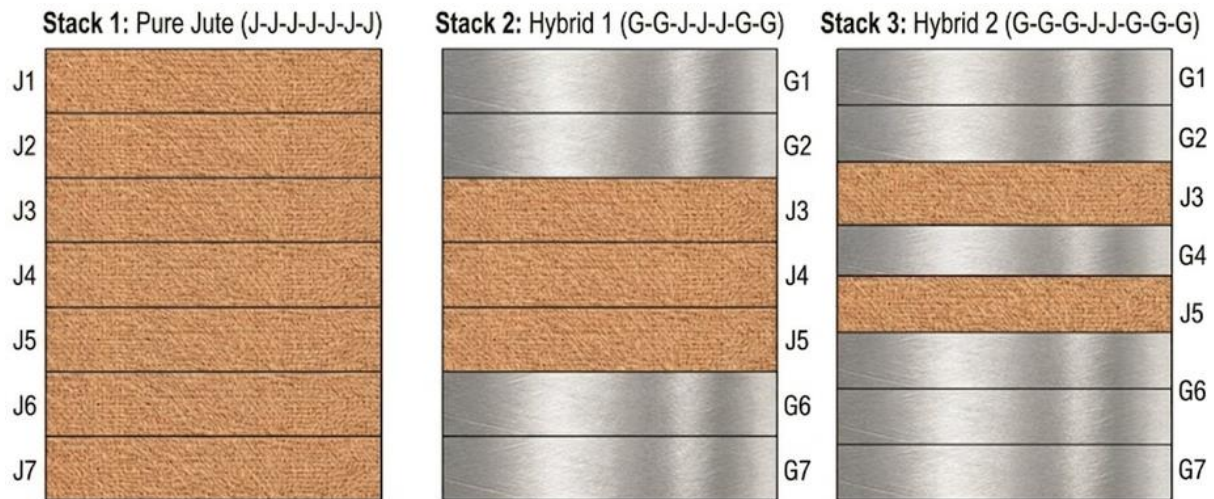


Figure 14 Laminate design and Stacking sequence

Table 5 Stacking sequence and relative percentage of constituent of the composites

Laminates	Stacking Sequence	Fiber Volume Fraction (V_f)		Fiber weight Fraction (wt%)	
		Jute	Glass	Jute	Glass
Pure jute	J-J-J-J-J-J-J	30	0	34.27	0
Hybrid 1	G-G-J-J-J-G-G	13	17	12.99	29.54
Hybrid 2	G-G-J-G-J-G-G	8.5	21.5	8.22	36.16

3.4 Composite Fabrication

3.4.1 Preparation of Woven Jute

The raw jute bundles were collected from Ethio Fiber and processed into fine hair-like fiber filaments for uniformity and softness to fabricate plain woven jute cloth. A custom rectangular wooden frame loom of size 230 mm* 550 mm was made with the same nails evenly spaced at 5mm along all four edges of the loom, which was used as the structural loom anchor.

The processed fine jute fibres were longitudinal warped between the top end nail and bottom end nail under uniform tension to create the warp bed and the side nails were used to create structural boundary alignment. The fine continuous jute yarn was hand- woven by plain weave technique (1/1 over under interlacing) across the warp threads to form a dense and uniform natural fiber mat using a manual, which would be suitable for composite

fabrication and mechanical testing.



Figure 15 Preparation of woven jute

3.4.2 Alkali (NaOH) Treatment Procedure

Prior to lamination chemically treated Woven Jute was roughened and treated with sodium hydroxide (NaOH) solution to remove surface pectin, wax and hemicellulose and to increase mechanical interlocking and adhesion with the polyester matrix [8], [13]. The study utilized an alkali treatment of 5 wt% NaOH for 24 hours in a protected container, an optimal concentration and immersion time known to enhance tensile and flexural properties while preventing excessive cellulose degradation [62], [67], [70], [72]. To prevent any interference in the curing reaction of the polyester with the NaOH present in the fabric after alkali immersion, the treated fabric was first rinsed with distilled water until neutral pH was reached, and then air-dried in sun light before lamination [69], [71].





Figure 16 Chemical (NaOH) treatment procedure

3.4.3 Hand Lay-up Procedure

The hand layup method was used for all laminates which is the most widely used fabrication technique for jute and jute-glass hybrid polyester composites [31], [32]. The raw fibers were subjected to chemical surface treatment before being sun dried for two days and the sun dried woven fabrics were then cut into plies of 200 mm x 250 mm. A rectangular steel frame mold, same size as these dimensions with a uniform thickness of 5.6 mm was used to control the thickness of laminate. The matrix was prepared by weighing polyester resin on a digital analytical balance and then mixing it together in a certain weight ratio of 10:1 with MEKP hardener and mixing it thoroughly. The stacking sequences were made up of seven layer of three different laminate configurations, one control laminate made from jute (J) and two hybrid jute/glass (H_1 and H_2) laminate as shown in Table 2. In both types of hybrid structures, the glass fiber plies were intentionally placed at the surface layers (top and bottom) to ensure excellent moisture resistance and jute fiber plies were used in the core layers.

To assure easy removal from the mold cavity a thin, uniform coating of honey wax was applied to the mold cavity surfaces before lay-up. The initial process involved in the fabrication was to wet the bottom mold surface with a layer of polyester resin. The first woven glass ply was installed and a substantial amount of resin was added. After each layer was applied a hand roller and brush were continually used to impregnate the matrix, drive out entrapped air bubbles and obtain an even distribution of resin between plies. This was done in turn according to the sequence of glasses to be stacked, until the last top glass ply was stacked and completely filled with resin.



Figure 17 Hand lay-up procedure

3.4.4 Curing

After layup, laminates were cured at room temperature for 24 hours under the flat plate load 50 ton press machine which corresponds to the ambient-cure ability of unsaturated polyester resin system [25], [27]. Laminated edges were trimmed after the cure and each panel was visually and dimensionally checked before the specimens were machined.



Figure 18 curing process of the laminates

3.5 Specimen Preparation

3.5.1 Doubly-Tapered Compact Tension (2TCT) Specimen Design

The geometry of intralaminar fracture toughness specimens was developed and validated by Blanco et al. for woven composite laminates and used to machine the specimens in the doubly-tapered compact tension (2TCT) configuration shown in Figure 19 [38], [39]. Blanco et al. performed a parametric finite element study with the virtual crack closure technique (VCCT) to identify the failure index (FI1, defined as the maximum longitudinal compressive stress at the right edge of the specimen) for the various specimen configurations and found that the unmodified CT geometry is not suitable for woven composite laminates, as the associated failure index exceeded five, which indicates that these geometries failed by edge compression well before the crack propagated far enough for a valid fracture toughness measurement, according to ASTM E399 [36], [39].

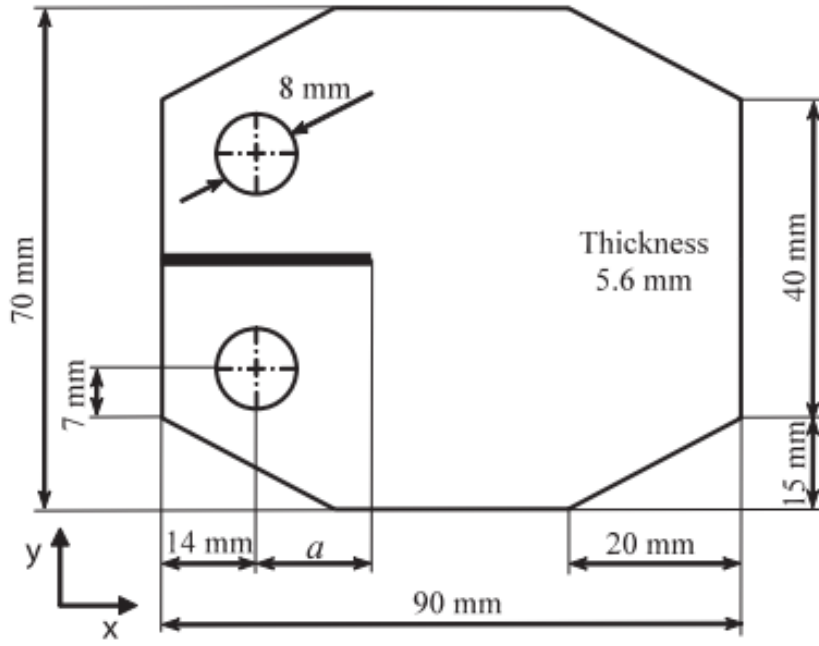


Figure 19 doubly tapered compact specimen configuration

To overcome this, Blanco et al. developed a doubly-tapered compact tension (2TCT) specimen, in which tapers are made in the top and bottom corners of the edge being loaded on the specimen. The 2TCT configuration minimized overall failure indices, with the critical edge-compression failure index reduced by about 60% compared to the standard CT specimen, while the other failure indices (matrix cracking, bearing failure, shear-out, and buckling) were close to or below the acceptable limit as long as the specimen was manufactured to a thickness that was adequate to prevent global instability [39]. From this, the 2TCT geometry was chosen for the present study as it is suitable to ensure stable crack propagation through the laminate within the matrix, and not through the fibers, in a woven jute/glass hybrid laminate.

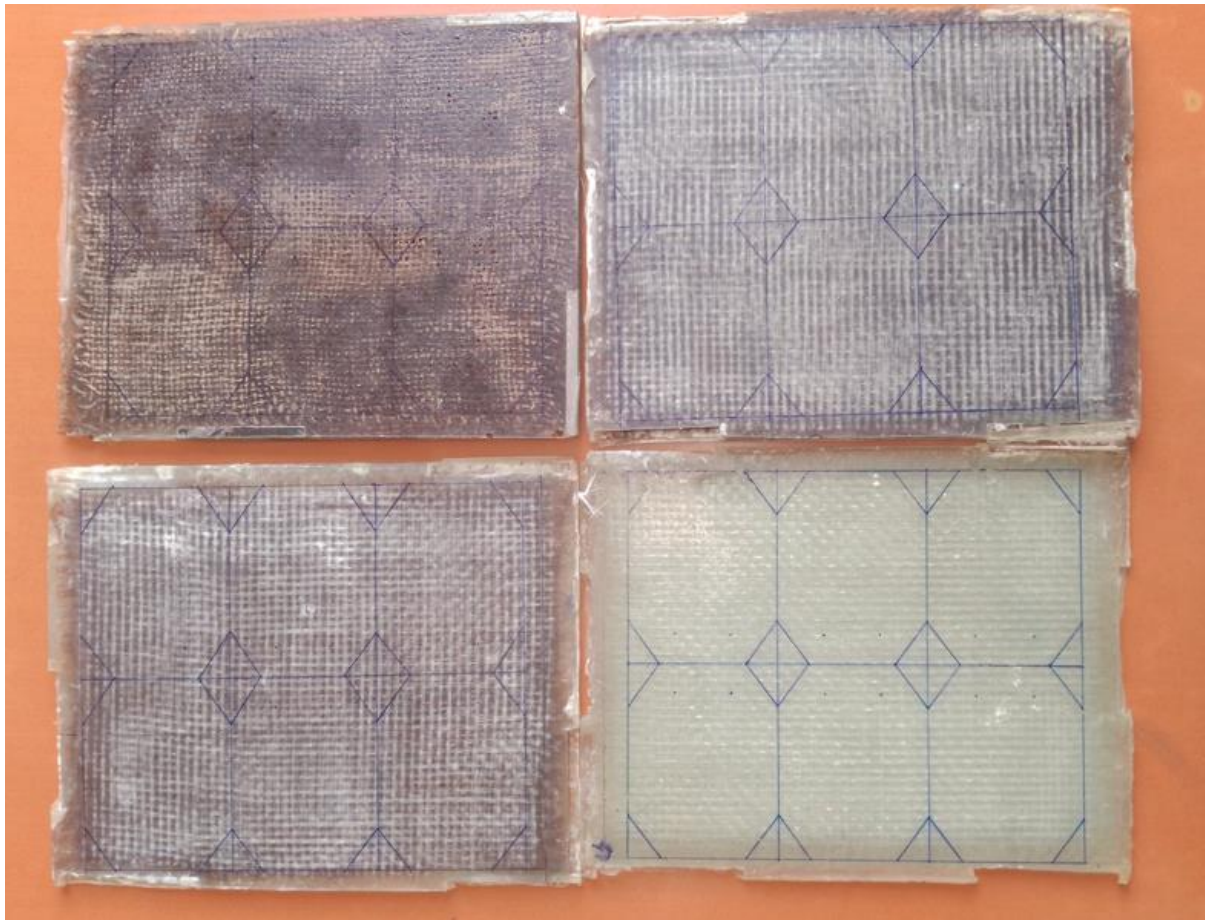
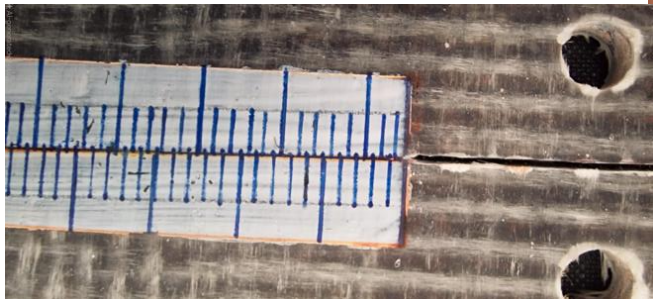
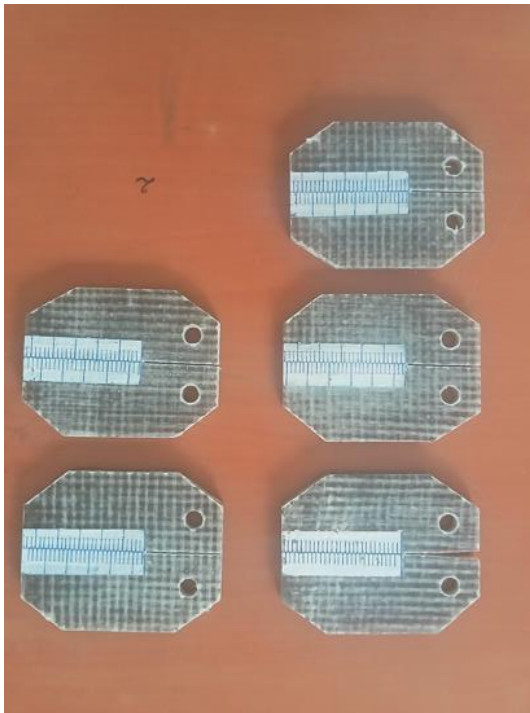


Figure 20 modeling the 2TCT on the laminates

3.5.2 Specimen Cutting and Precracking

Laminate panels were cut into individual specimens with a wet hack saw to reduce thermal damage and delamination of the edges during cutting, and following the experimental procedure validated by Blanco et al. for 2TCT specimens [38]. A sharp, reproducible precrack was introduced ahead of the machined notch using a three-stage sharpening procedure: the first 33 mm crack was introduced using a 0.6 mm hack saw then followed by 0.4 thick surgical baled for half of the final 1 mm notch and at the end with 0.1 thick razor blade [38]. The staged precracking procedure was chosen so that a sharp, reproducible tip can be used to measure the fracture toughness; blunt and poorly sharpened notches have been found to overestimate the toughness when compared with those precracked in the same manner [26], [27].





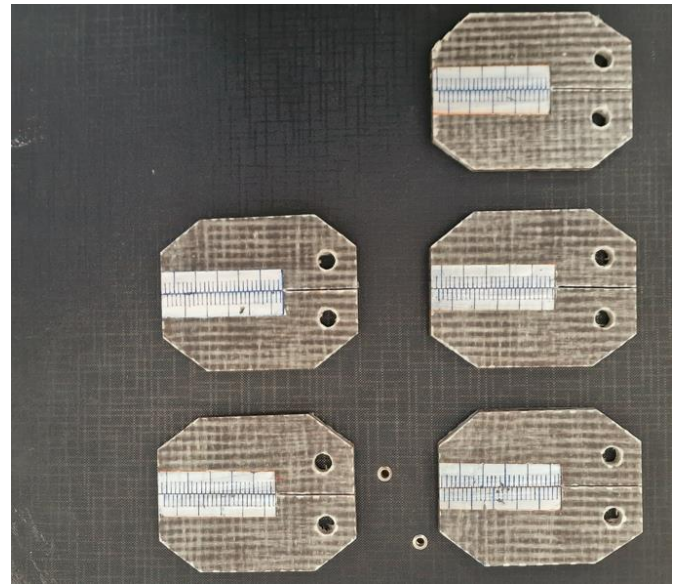
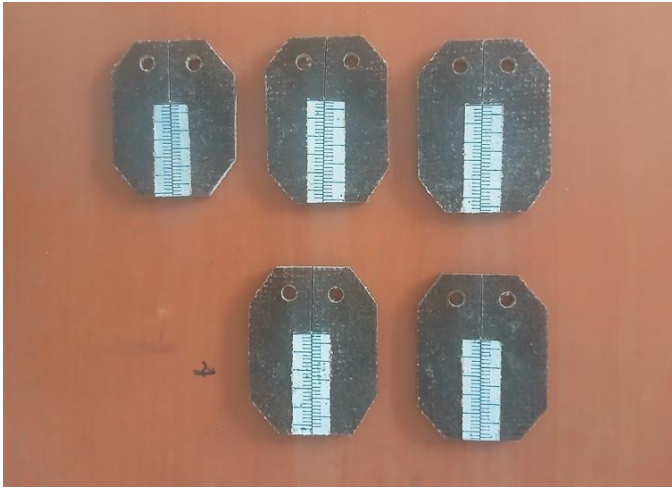


Figure 21 specimen cutting and pre-crack initiation

3.6 Experimental Testing Procedure

3.6.1 Universal Testing Machine Setup

Fracture toughness tests were carried out on [Model: WDW-100s having 100KN capacity universal testing machine equipped with clevis-pin grips that clamped the two loading holes of 2TCT specimen and under the same loading condition as illustrated in Figure 3, with the load cell capacity of 100 KN. Specimens were oriented so that the load line was across the notch plane, and load and crosshead displacement were measured continuously during each test at a sampling rate of 0.5 mm/min.



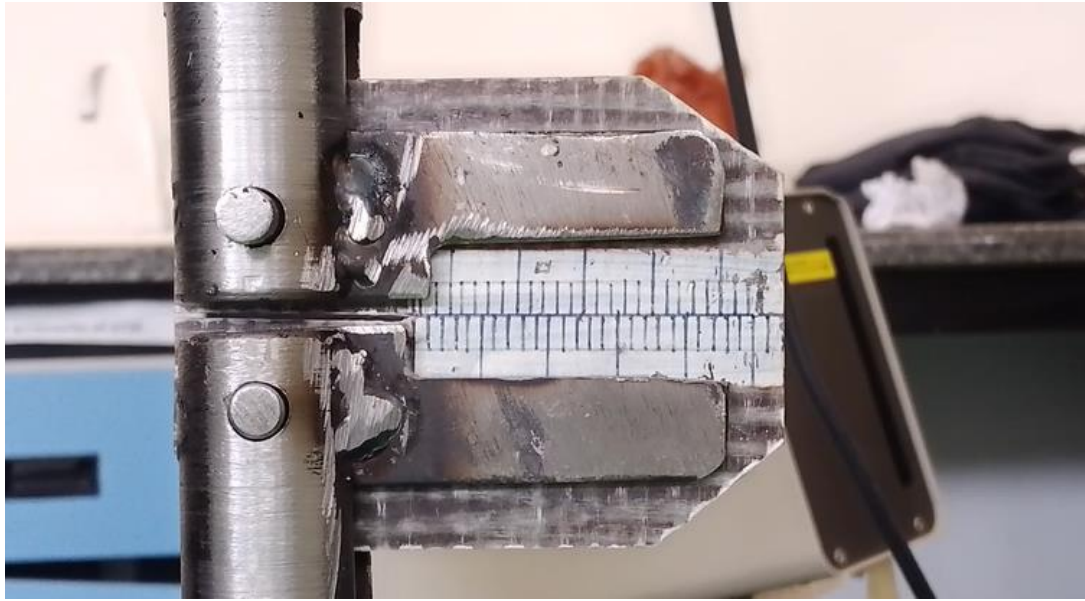


Figure 22 experimental setup

3.6.2 Mode I Intralaminar Fracture Test Procedure

Precracked 2TCT specimens were tested under displacement control with a constant crosshead rate of 0.5 mm/min, which corresponds to 2TCT testing rates used for quasi-static Mode I intralaminar fracture testing [40]. Loading was continued until stable crack propagation was observed across the full ligament, with the resulting load-displacement curve recorded for each of the fifteen specimens (five per configuration) and used as the primary experimental data set for the data-reduction procedure described in Section 3.7.

Table 6 Summary of the intralaminar fracture toughness test matrix used in this study.

Configuration	Specimens Tested	Test Speed	Environment
A (Control, 0% jute)	5	0.5 mm/min	Ambient laboratory conditions
B (Low jute)	5	0.5 mm/min	Ambient laboratory conditions
C (High jute)	5	0.5 mm/min	Ambient laboratory conditions

3.7 Modeling and Numerical Analysis

3.7.1 Data Reduction

The Mode I fracture toughness is calculated from the fracture load measured and the specimen geometry for an isotropic compact tension specimen, following ASTM E399 [36]. If the material is orthotropic composite laminate, the fracture resistance can be

connected to the critical energy release rate, based on the laminate's anisotropic elastic properties that can be calculated from the properties of the constituent plies according to classical lamination theory [37], [111]. However, Pinho, Robinson, and Iannucci demonstrated for a CT specimen consisting of an orthotropic carbon/epoxy laminate that this approach, based upon an isotropic formula, results in an error of about 11% compared to a full finite element (FE) solution even for a laminate of equal longitudinal and transverse moduli, and they concluded on this basis that the ASTM E399 stress-intensity approach is not recommended for orthotropic composite materials [37]. ,

In this thesis, following this finding and in parallel with the same result obtained by Blanco et al. for the 2TCT woven-composite sample used in the thesis, the intralaminar critical energy release rate of the laminate, G_{IC-lam} , was therefore evaluated directly using the general form of the finite element solution

$$G_{IC-lam} = \left(\frac{P_c}{t}\right)^2 (c_3 a^3 + c_2 a^2 + c_1 a + c_0) \text{----- Equation 3.1}$$

$$f(a) = J \cdot \left(\frac{1 \text{ mm}}{1N}\right)^2 \text{----- Equation 3.2}$$

where P_c is the experimental load associated with crack propagation at a given crack length a , t is the specimen thickness, $f(a)$ is a normalized energy release rate obtained from FE analysis, and $C_0 - C_3$ are polynomial data-reduction coefficients fitted to $f(a)$ over a series of discrete crack-length sub-ranges, rather than obtained from an experimentally measured compliance-crack-length calibration [37], [39]. This is the same data-reduction philosophy originally developed by Pinho et al. for unidirectional and cross-ply CT/CC specimens and subsequently adapted by Blanco et al. specifically for the 2TCT geometry used with woven composite laminates; both formulations are algebraically equivalent, differing only in whether $f(a)$ is expressed as a normalized energy release rate (Pinho et al.) or folded directly into the $C_0 - C_3$ coefficients (Blanco et al.) [37–39].

3.7.2 Finite Element/VCCT Procedure for Determining Data-Reduction Coefficients

The FE/VCCT procedure for generating data-reduction coefficients in Section 3.7.1 is a two-stage mesh-validation procedure as originally developed by Pinho et al. and later by Blanco et al. for the 2TCT geometry [37], [38].

I. Mesh-Convergence Check

First, a mesh-convergence check was performed: a half crack FE models of the 2TCT geometry (Figure 23, Table 7) were built in Abaqus/CAE 2020 using 8-node doubly curved shell elements with reduced integration (S8R5), with uniform square element sizes of course, intermediate and refined, each assigned a unit thickness and subjected to a unit load, following the exact mesh-density comparison used by Pinho et al. to validate their own FE model [37].

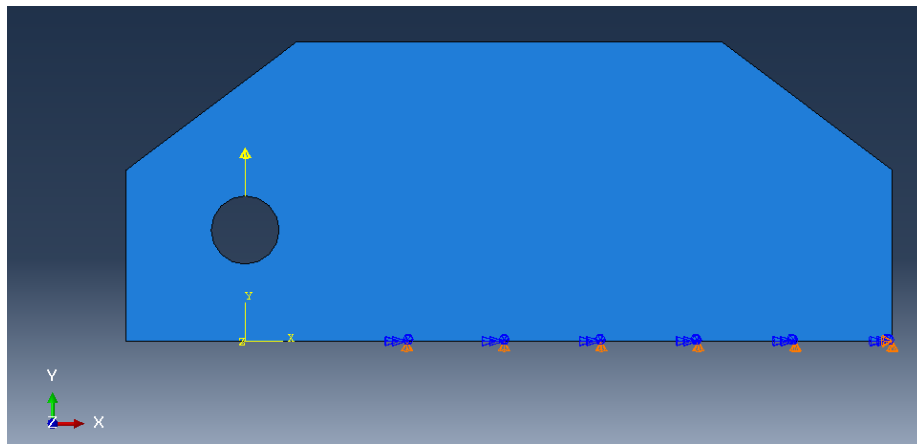


Figure 23 Half crack model of 2TCT

Convergence analysis was performed for jute-glass 2TCT model for various mesh size, and before moving on to parametric analysis, this convergence analysis was performed. The model was tested at different mesh levels to check the convergence of the mesh. The size of the elements was controlled in two ways: a minimum size setting ensured that the mesh was fine around critical areas such as the crack tip and load points; a maximum size setting ensured that the mesh was bigger at places further away from the critical areas. The 2TCT finite element models at coarse, medium and fine meshes are illustrated in figure 24.

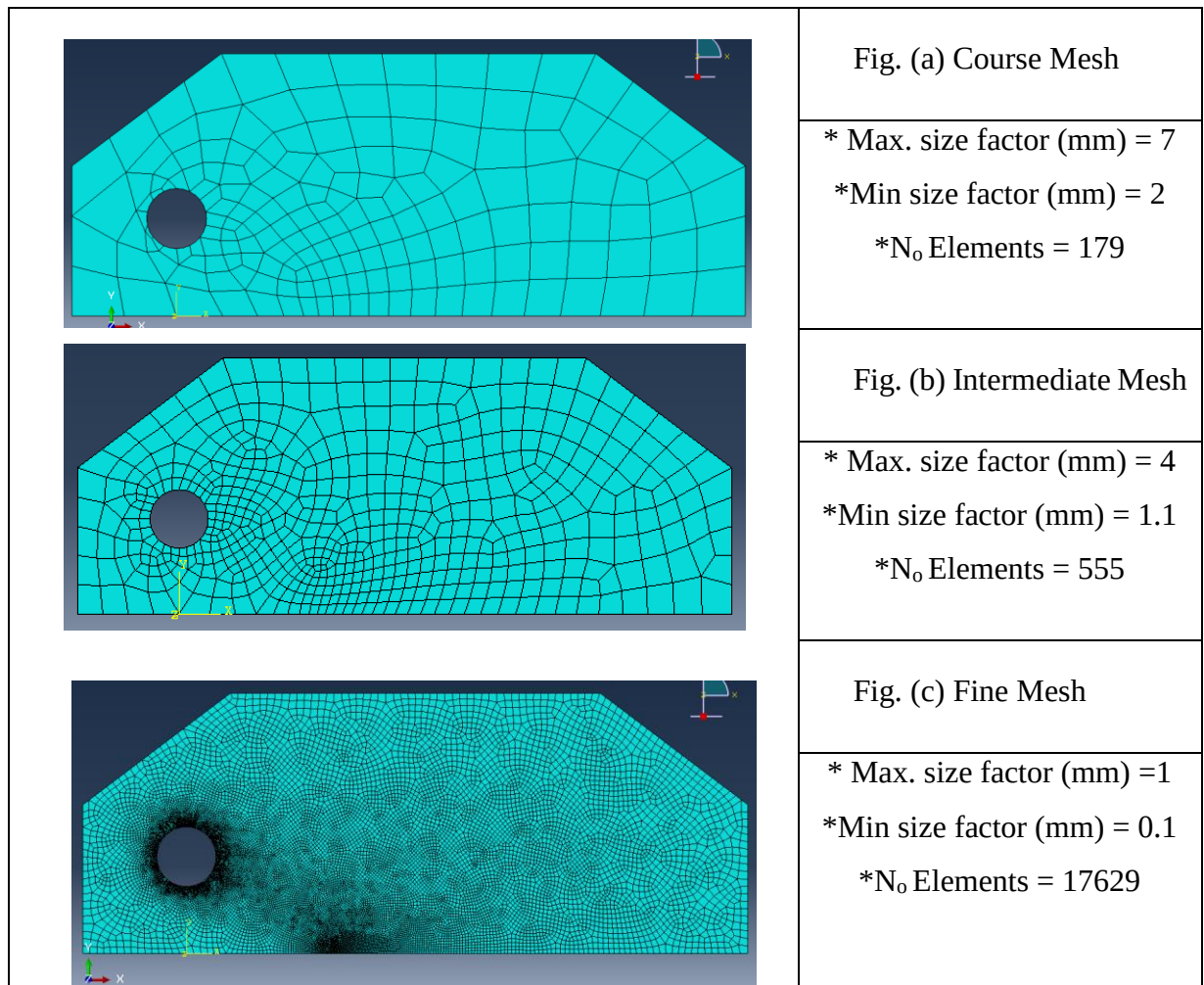


Figure 24 the different level of mesh (a-Course mesh, b-Intermediate mesh and c-Fine mesh)

Table 7 mesh refinement data for convergence check

Refinement level	Size Factor		N _o of Elements	CPU Time (Sec)	Normalized Energy release rate	Percentage Error (%)
	Maximum (mm)	Minimum (mm)				
1	7	2	179	0.3	1.4909E-04	0.5205
2	6	1.7	230	0.3	1.4956E-04	0.2068
3	5	1.4	336	0.3	1.4960E-04	0.1802
4	4	1.1	555	0.4	1.4969E-04	0.1201
5	3	0.8	973	0.5	1.4978E-04	0.0601
6	2	0.5	2216	0.8	1.4983E-04	0.0267
7	1	0.2	10298	2.8	1.4985E-04	0.0133
8	1	0.1	17629	4	1.4987E-04	Reference

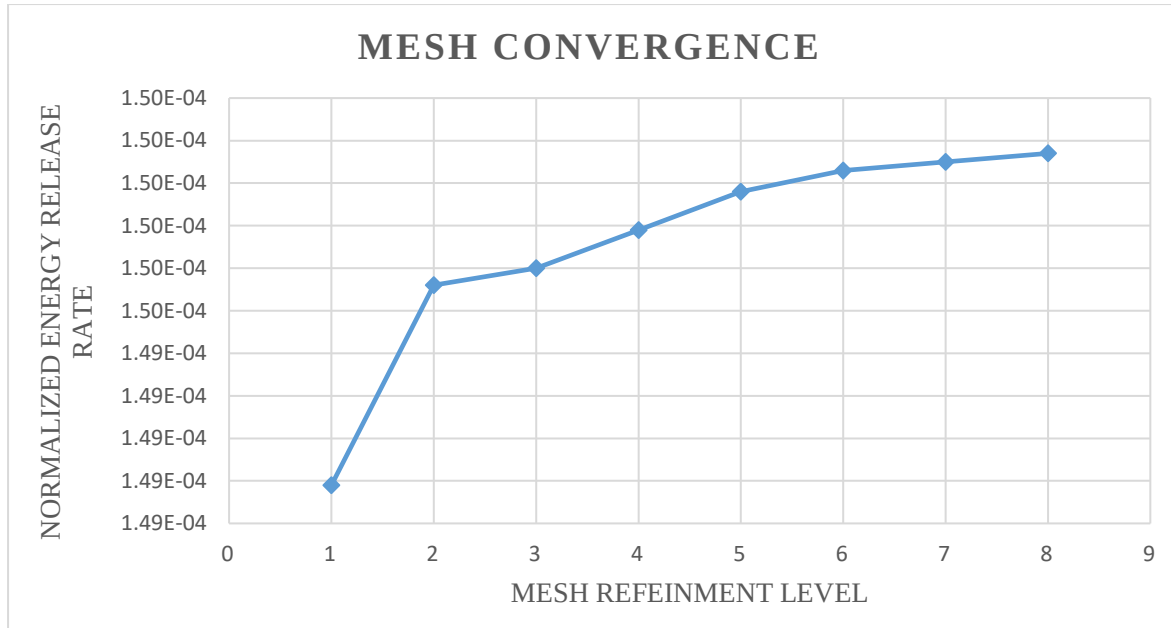


Figure 25 Mesh convergence graph

Without any changes, it can be seen from the simulation results shown in Figure 29 that the results tend to stabilize and flatten out as the mesh density increases. The energy release rate for the medium mesh (Level 4) differs by only 0.1201% and the coarse mesh (Level 1) by only 0.5205% when compared to the finest mesh (Level 7) used as a reference. Then, a level of mesh refinement 6 was chosen as a compromise between the high accuracy and the computational efficiency, and the final analysis was set up using this level of refinement as shown in figure 26.

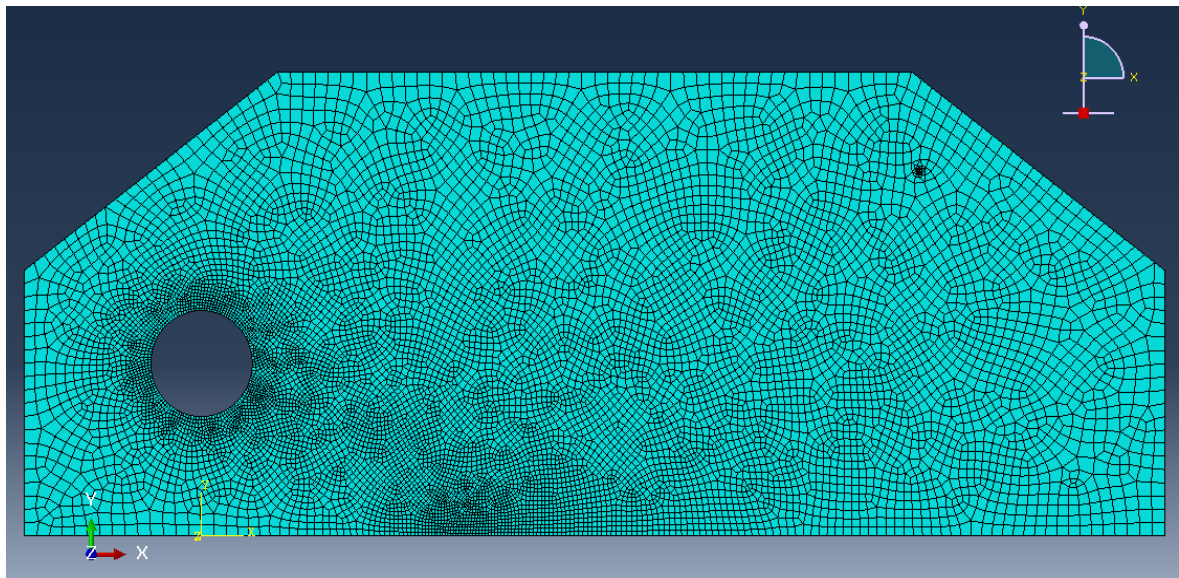


Figure 26 Mesh of the selected refinement level

The FEA Work flow

Second, the model was then lumped with the validated mesh to obtain orthotropic in-plane elastic properties for each of the three laminate configurations listed in Table 2, using a lamination-theory approach similar to that used by Pinho et al. and Blanco et al. for obtaining laminate properties from ply properties [37], [38]. The laminate elastic properties (Table 4) were calculated directly from the properties of the plies (Table 3) using classical lamination theory. The fundamental elastic properties of Jute/Polyester composite were taken from [112], and the inplane shear modulus and major Poisson's ratio were taken from [113] and [114]. The elastic constants, in-plane shear modulus, and major Poisson's ratio for the glass/polyester lamina were adopted from [115] and [116].

Table 8 Elastic properties of composite laminae of Jute/Glass-Polyester [112-116]

Lamina	Elastic Modulus (Gpa)			Major Poisson's ratio, ν_{12}
	E_1	E_2	G_{12}	
Jute/Polyester	3.26	3.26	1.455	0.322
Glass/Polyester	11.3	11.3	4.2	0.27

Table 9 Elastic properties of composite laminates used

Laminate	Elastic Modulus (Gpa)			Major Poisson's ratio, ν_{12}
	E_1	E_2	G_{12}	
J	3.26	3.26	1.46	0.32
H1	7.858	7.8577	3.0236(3.024)	0.2795 (0.28)
H2	9.0054	9.0054	3.4157	0.2755
G	11.3	11.3	4.2	0.27

Different orthotropic properties of the laminates were added, that is, a unit load was applied at the central node of one loading hole, which was transferred through stiff beam elements, and the x-displacement of the bottom-right node was restricted, as shown in Figure 27. The fracture behavior was evaluated by imposing the crack front at the crack tip and propagating the crack in the direction expected to be the crack plane, thus enabling the finite element analysis to determine J-integrals along five concentric contours.

For the repeated analyses of crack lengths ranging from 20 mm to 64 mm, increasing the crack length by 1 mm at each step, a Python script (Appendix A) was developed to automate the setup in Abaqus. This enabled rapid changes of the crack tip location, material parameters and mesh controls, and it was easy to obtain J-integral values for each composite laminate

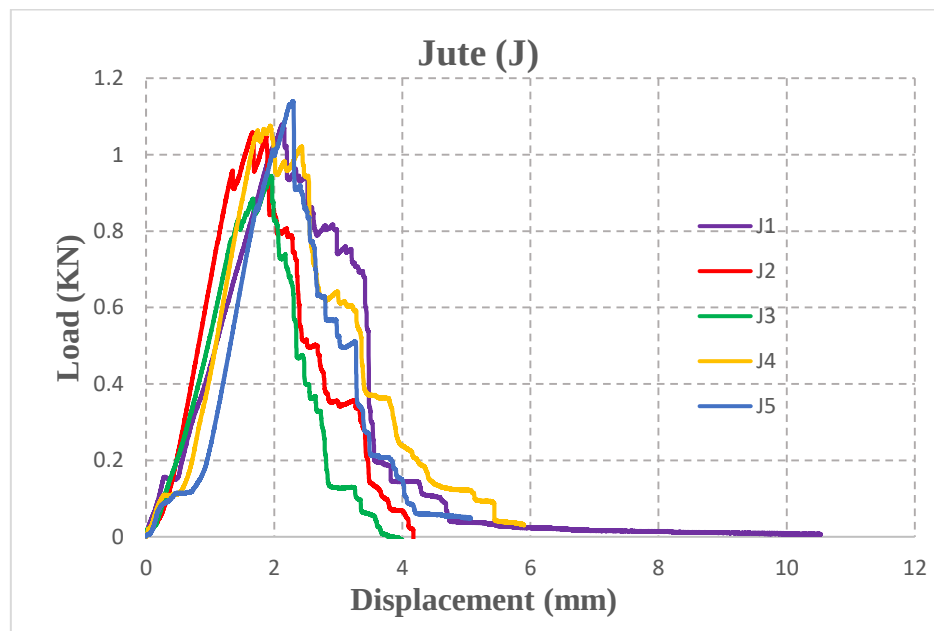
CHAPTER FOUR

RESULT AND DISCUSSION

The results from the intralaminar fracture toughness testing of the three laminate configurations studied (jute-only control, two jute-glass hybrid configurations (H1 and H2), see Table 5 in Chapter Three) are presented and discussed in this chapter. In both hybrid configurations, the total fiber volume fraction was kept constant at 30%, with different proportions and stacking order of jute and glass (H1: 13% jute / 17% glass, and H2: 8.5% jute / 21.5% glass). This will allow the effect of jute content and stacking position to be isolated from the effect of overall fiber loading.

4.1 Experimental Load-Displacement Curve

To perform the tests, the load-displacement curves for each 2TCT specimen were recorded continuously throughout the tests following the procedure outlined in Section 3.6. The curve of the specimen at each laminates has a similar trend with the behavior the same as that reported for compact-tension and 2TCT testing of unidirectional and woven composite laminates.



(a)

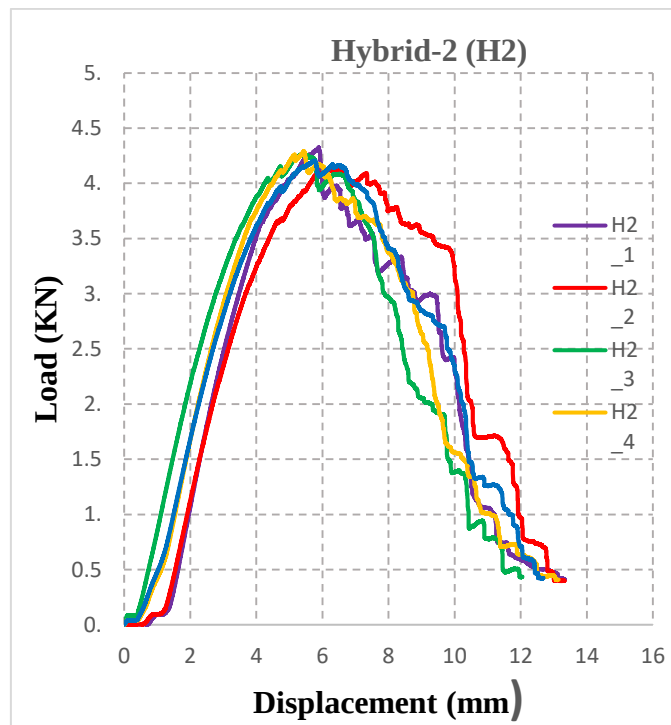
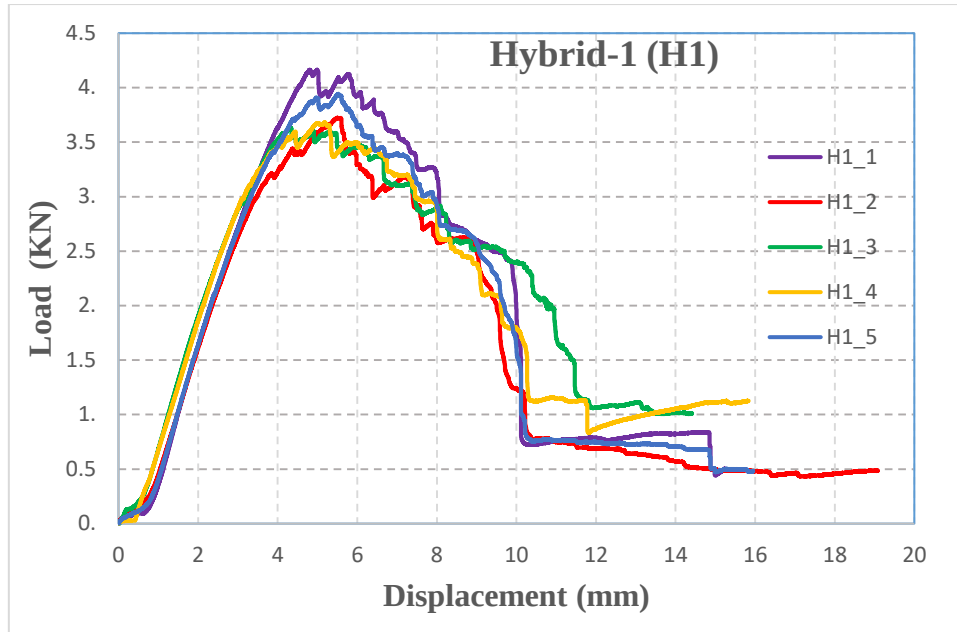


Figure 27 Load-Displacement Curve (a-pure jute, b-Hybrid 1 and c-Hybrid 2)

The load-displacement curve in Figure 27 can be considered a series of deformation and fracture events taking place during testing. The starting-seating of the loading fixtures, and the correct contact between the loading pins and the specimen holes, results in a small nonlinear region at the beginning of loading. This preliminary adjustment is helping the system to become compliant with the requirement prior to large deformation of the specimen.

During loading, the load is linearly related to the displacement with the specimen showing predominantly elastic behavior. The deformations here are substantially recoverable and there will be no serious damage to the composite structure. The curves start to gradually curve off from being linear before reaching the maximum load with further increase in displacement. This change in slope is the beginning of internal damage processes. Local failure phenomena like fiber breakage and debonding of fibers and matrix are initiated at the crack tip at this point. Despite the absence of visible extension of cracks during the test, the occurrence of these types of micro-damage events can be recorded as audible cracking sounds.

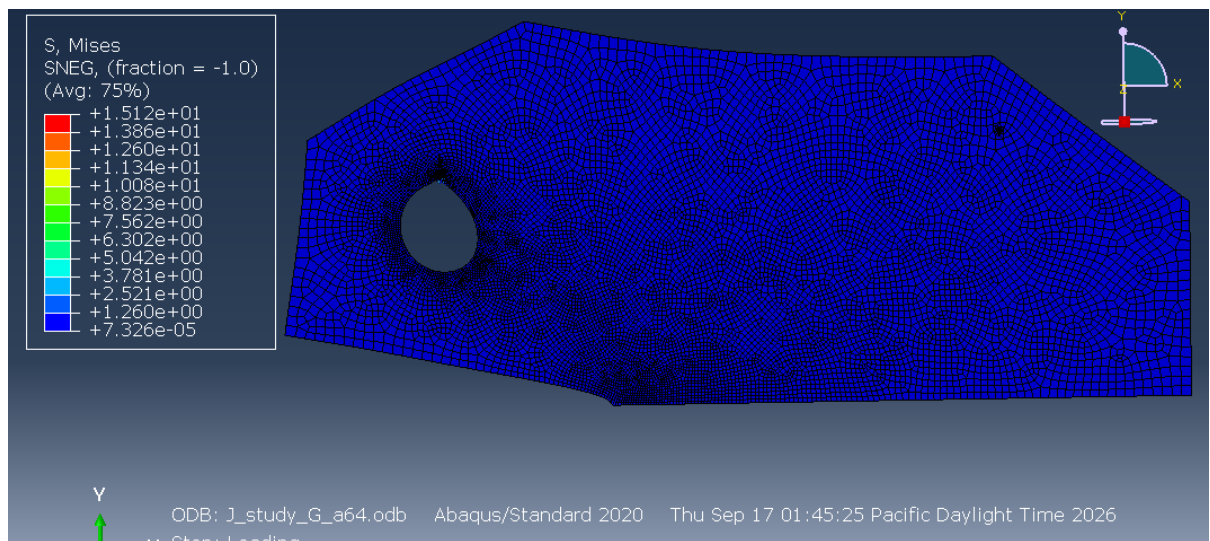
In addition to the peak load, the specimens show progressive crack propagation with load decreases and temporary load stabilization. The sharp load drops are explained by a lack of crack stability in parts of the test pieces containing a matrix-rich region, while the relatively steady parts of the curves can be explained by crack arrest due to the presence of reinforcing fibers bridging the crack surfaces. As the crack front propagates, it continually encounters the fiber bundles, which causes the crack front to be retarded intermittently. When these bridging fibers break, the crack grows quickly until another mechanism of resistance to crack growth is met. The progressive damage development is advantageous as it enables the material to absorb more energy during fracture.

As the crack length increases, other failure mechanisms are important. In regions near the crack path, besides the crack extension in the opening mode, compressive damage phenomena such as fiber kinking, matrix crushing and local delamination are also possible. The effect of these mechanisms increases with increasing displacement and eventually leads to failure of the specimens.

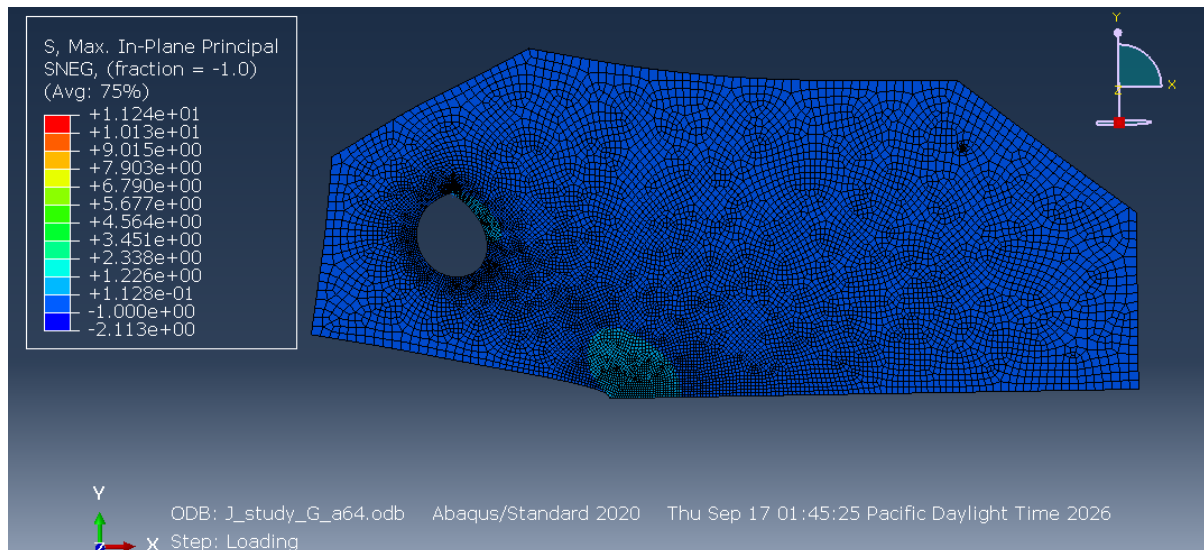
The experimental results also show that there are differences in stiffness and load carrying capacity between the laminates. For laminates (a) to (c), the average stiffness values were calculated as 0.78, 1.24, and 1.41, kN/mm respectively and the average peak loads were 0.7774, 3.13 and 3.67 kN respectively. The results obtained have revealed that the addition of reinforcing fibres can improve the structural stiffness and crack propagation resistance.

4.2 Polynomial Data-Reduction Coefficients

Following the finite element procedure described in Section 3.7.2, a mesh-convergence study was carried out across eight refinement levels (Table 7), and refinement level 6 (maximum element size 2 mm, minimum element size 0.5 mm; 2216 elements) was selected for the parametric analysis as the level that balanced solution accuracy (0.0267% deviation from the finest-mesh reference solution) against computational cost. By using Abaqus/CAE 2020 with a unit load the finite element analysis was performed.

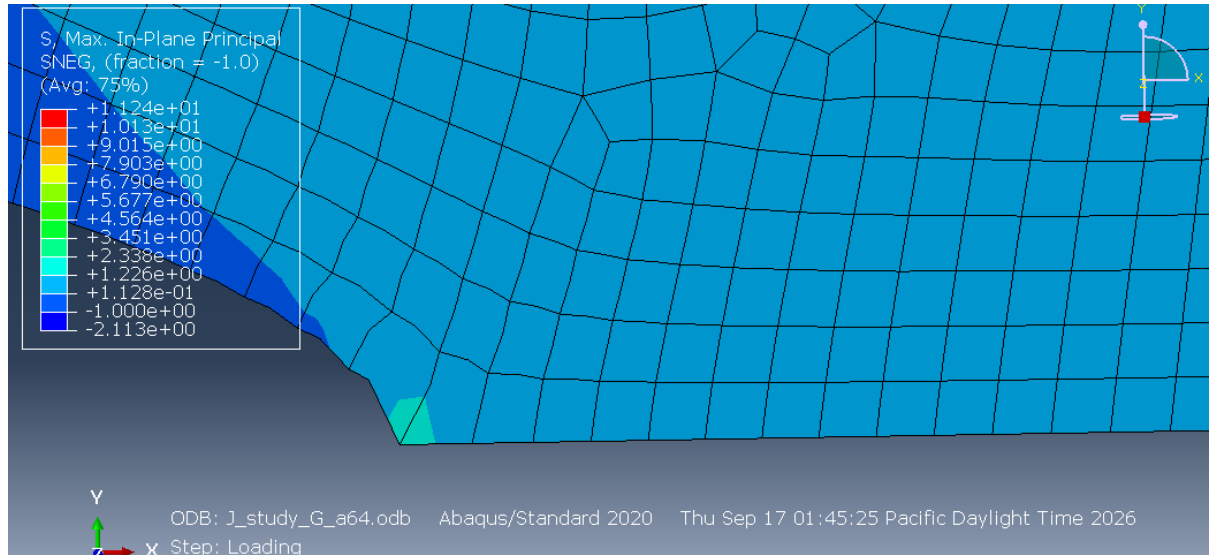


(a)

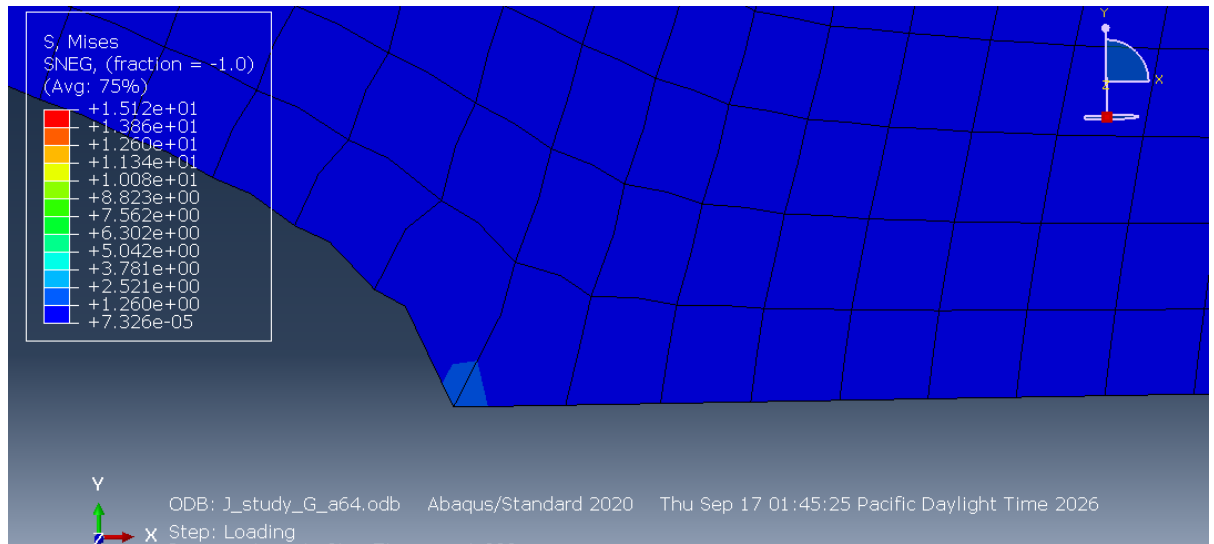


(b)

Figure 28 stress distribution of 2TCT (a-Von Miss and b-In-plane principal stresses)



(a)



(b)

Figure 29 close-up view of the crack tip

As shown in Figures 28 and 29, the region around the crack tip is the region with the most critical stresses obtained from the numerical analysis, both in terms of von Mises stress and in-phase principal stress. A stress concentration zone is observed at this location, thus suggesting that the applied loading is being transferred to the crack-tip zone effectively. Therefore, the specimen is expected to start and propagate the crack along the intended crack path as is expected of the 2TCT specimen.

The three composite laminates were then analyzed in Abaqus/CAE 2020 using the Python code provided in Appendix A by varying the crack length from 19 mm to 64 mm to obtain the normalized energy release rate, $f(a)$ as shown in Appendix B. The result values were

then plotted to determine the relationship between the energy release rate and the crack length. Math modelling of this relationship was performed by polynomial fitting in MATLAB R2018b. The polynomial coefficients and the maximum errors obtained for the various length intervals of crack are summarized in Table 10.

Table 10 Values of polynomial coefficients for the four composite laminates

For Laminate ‘J’					
Crack Length Range	C₃	C₂	C₁	C₀	Error (%)
19 ≤ a < 30mm	1.1719e-08	-5.8166e-07	1.8341e-05	-6.9054e-05	0.016002
30 ≤ a < 40mm	4.5383e-08	-3.6774e-06	0.00011366	-0.0010512	0.02507
40 ≤ a < 50mm	2.4818e-07	-2.8619e-05	0.0011383	-0.01511	0.10166
50 ≤ a < 60mm	2.8064e-06	-0.00042394	0.02152	-0.36569	0.61203
60 ≤ a < 64mm	3.5217e-05	-0.0062544	0.37132	-7.3647	0.083884
Laminate H1 (G/G/J/J/G/G)					
19 ≤ a < 30mm	5.0962e-09	-2.5084e-07	7.8514e-06	-2.7364e-05	0.01817
30 ≤ a < 40mm	1.9773e-08	-1.6006e-06	4.9405e-05	-0.00045543	0.025686
40 ≤ a < 50mm	1.0778e-07	-1.2421e-05	0.00049379	-0.0065506	0.10133
50 ≤ a < 60mm	1.2124e-06	-0.00018312	0.0092955	-0.15795	0.60918
60 ≤ a < 64mm	1.5317e-05	-0.0027208	0.16156	-3.205	0.086711
Laminate H2 (G/G/J/G/J/G/G)					
19 ≤ a < 30mm	4.4528e-09	-2.187e-07	6.8496e-06	-2.3587e-05	0.018072
30 ≤ a < 40mm	1.7956e-08	-1.4679e-06	4.5545e-05	-0.00042475	0.035353
40 ≤ a < 50mm	9.4522e-08	-1.0893e-05	0.00043305	-0.0057448	0.099213
50 ≤ a < 60mm	1.0616e-06	-0.00016034	0.0081387	-0.13829	0.60795
60 ≤ a < 64mm	1.3425e-05	-0.0023848	0.14161	-2.8093	0.087553

4.3 Critical Energy Release Rate Values (G_{IC})

For each specimen, the critical energy release rate was estimated from the peak load recorded during the experiment, and the crack length measured, using the polynomial expression of the data reduction technique (Section 3.7.1) to which the appropriate crack-length sub-range in Table 10 was applied. The mean G_{IC} and standard deviations for each configuration are presented in table 11 and in the figure.

Table 11 Critical Energy Release rate value and standard deviation

Parameters	Laminate J	Laminate H1	Laminate H2
G_{IC} (kJ/m ²)	2.887	20.74	25.03
SD (kJ/m ²)	0.92	2.55	1.19

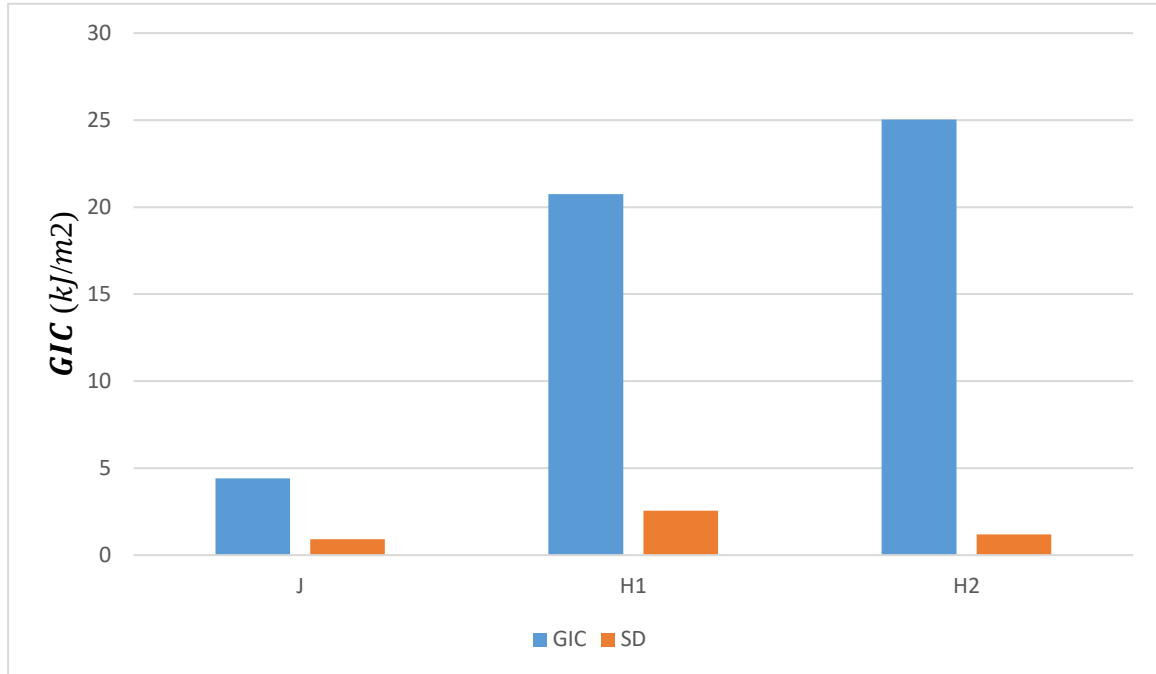


Figure 30 critical energy release rate (G_{IC}) and SD

Another measure of the effect of introducing glass fiber to the pure jute laminate is the change in critical energy release rate. For the H1 laminate, the glass fiber content of the composite was about 56.7% with the jute reinforcement kept within the middle section (G-G-J-J-J-G-G). This modification raised the measured value of G_{IC} from 2.887 kJ/m² (pure jute laminate) to 20.74 kJ/m² (H1), which is an increase of about 86.08% compared to the pure jute laminate.

The stacking sequence for the H2 laminate was G-G-J-G-J-G-G with an increased amount of glass fiber content to about 71.7%. The G_{IC} value increased to 25.03 kJ/m² which is about 88.46% higher than the pure jute laminate. This increased fracture toughness for H2 versus H1 may be attributed not only to the increased amount of glass-fiber, but also to the different orientation of the reinforcing layers. The presence of the glass layers is more distributed in the thickness of the laminate in H2, thus engaging more reinforcing interfaces during fracture.

Increased G_{IC} after hybridization suggests that the incorporation of the glass fibers significantly enhanced the Mode I crack growth resistance of the laminate. The order of the reinforcing layers can affect crack deflection, fiber bridging, fiber-matrix debonding, and fiber pull-out during crack propagation, thus influencing the energy to be consumed for further crack propagation.

The overall results show the significant alteration that the glass fiber replacement of the part of jute reinforcement brought into the Mode I fracture behavior of the laminates. The values of G_{IC} of all the three configurations differ, with H2 having the highest value followed by H1 and the lowest value is for pure jute laminate.

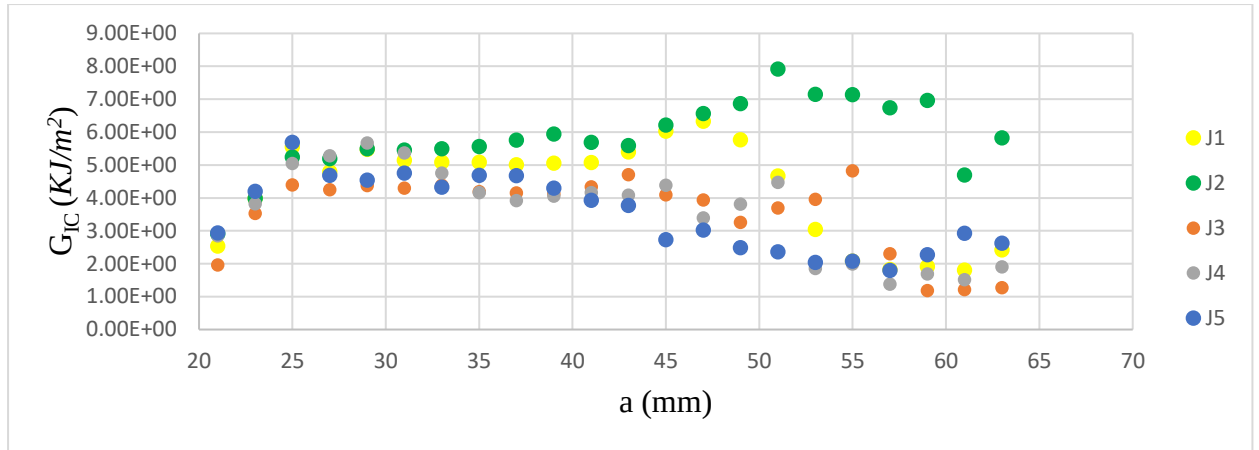
Table 12 stating the difference in critical energy release rate obtained in data reduction formula and ASTM D5045 standard

Laminates	Critical Energy Release Rate value (Fracture Toughness)			Relative difference (%)
	From Eq-3.1 G _{IC} (KJ/m ²)	ASTM D5045		
		G _{IC} (KJ/m ²)	K _{IC} (MP√m)	
Pure Jute (J)	2.887	1.792	2.551	37.93
Hybrid 1	20.74	12.48	10.316	39.83
Hybrid 2	25.03	14.582	11.921	41.74

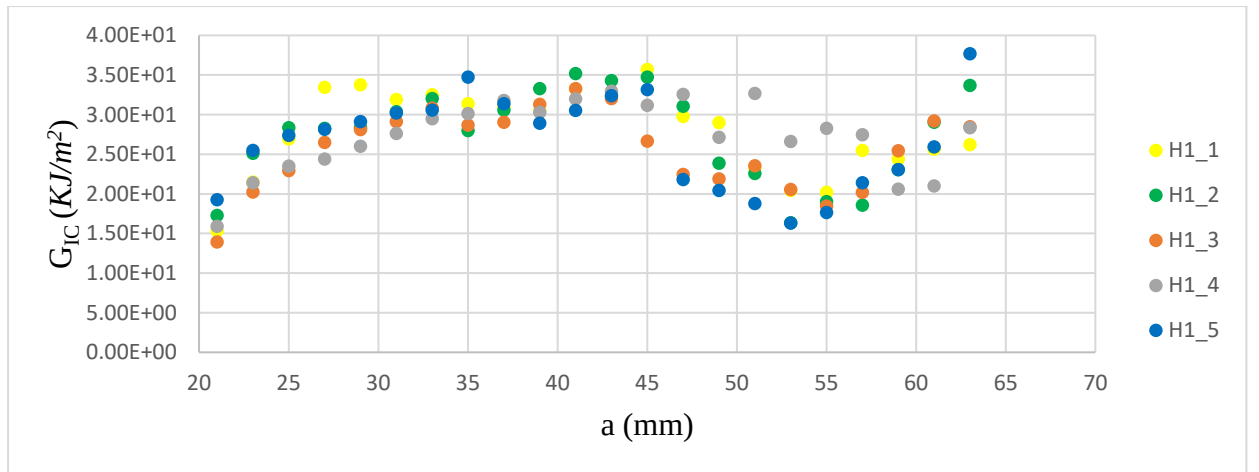
The results of this critical energy release rate G_{IC} , are compared with results calculated from ASTM D5045 in table 12. The values calculated from Equation 3-1 are always greater than the values calculated from the ASTM for all three laminates. The relative differences were 37.93%, 39.83% and 41.74% for pure jute laminate, H1 and H2 respectively. The fracture toughness of each of these materials, although measured over different scales, shows a similar general trend, with the highest fracture toughness being that of H2, followed by H1 and the pure jute laminate. This comparison shows that the adopted data-reduction method causes a noticeable effect on the calculated G_{IC} values, which is significant when interpreting the Mode I fracture behavior of the investigated composite laminates.

4.4 Resistance Curves (R-Curves)

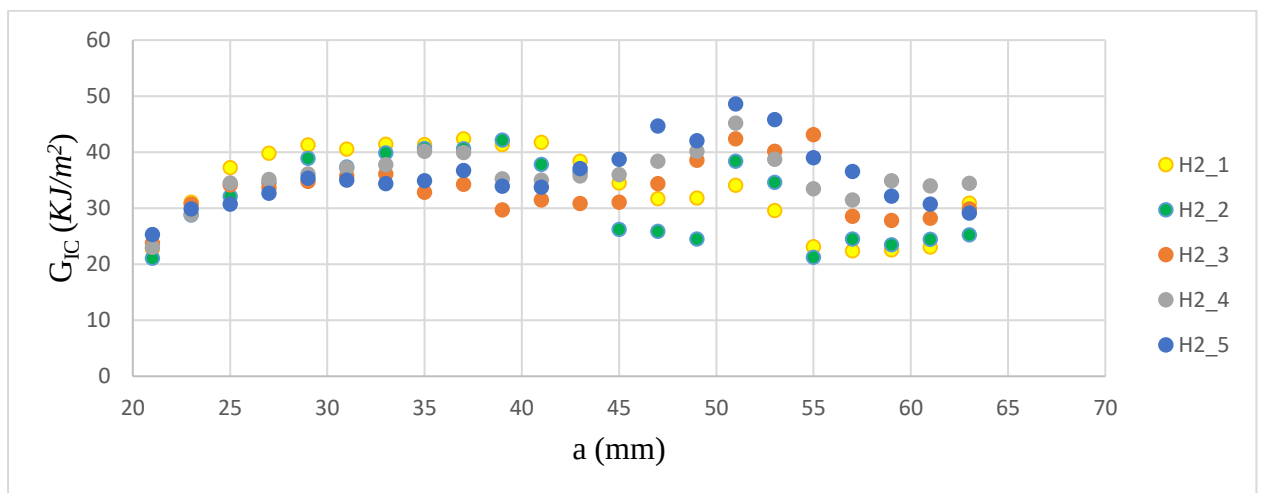
During the test, the crack length, a , was recorded by video, and the load-displacement data were used with the data-reduction procedure described in Section 3.3.1 to determine the fracture resistance. Figure X shows the resulting R-curves (G_{IC} versus a) for the pure jute, H1 and H2 laminates.



(a) Pure jute laminates



(b) Hybrid 1 laminates



(c) Hybrid 2 laminates

Figure 31 31 R-curve (G_{IC} vs a)

The R-curves derived from the pure jute and H1 and H2 laminates are shown in the figure 31. The curves illustrate the variation of fracture resistance with the crack propagation through the specimens. There is some variation from specimen to specimen, but a general trend can be seen in the three laminate configurations. The effect of the shorter crack lengths is relatively gradual, and larger differences in fracture resistance can be observed as the crack goes further through the specimen.

The R-curves for the pure jute laminate are generally increasing from around 21 mm to 27 mm crack length as shown in Figure 31(a). For the range of 27 -40 mm, most of the specimens show a relatively linear relationship with little variation in fracture resistance. This behavior suggests that there is not a significant increase in resistance during this stage of crack-growth and is typical of a relatively brittle fracture response behavior. The curves start to diverge at about 40 mm. Some specimens still show a fracture resistance change from 40 to 55 mm while others show a fracture resistance reduction. When cracks are about 55 to 63 mm long, the scatter is more noticeable; and the majority of specimens exhibit a decreasing tendency. This widening of scatter at these longer cracks suggests that the magnitude of crack growth is less uniform when the crack grows through the pure jute laminate.

The R-curves for H1 are not similar to that of the pure jute laminate, as shown in Figure 31(b). There is a gradual rise in fracture resistance as crack extension is initiated (around 21-30 mm). The curves between approximately 30 mm and 40 mm are relatively stable, showing a more continuous pattern in crack propagation, suggesting that the resistance to cracking changes relatively little. In this area, it is also inferred that a relatively brittle-type response occurs in the early and intermediate phases of crack propagation. The behavior is less regular after about 40 mm. The resistance of several specimens remains relatively high from 40-48 mm, and then drops significantly from 48-57 mm, and then rises again for some specimens and remains relatively flat for others from 57 mm onward. The difference between the specimens increases as the range of crack growth is approached towards the end.

The H2 laminate (Figure 31(c)) also shows an early rise in fracture resistance from around 21 to 30 mm. between 30 and 40 mm. most specimens have an approximately parallel R-curves in this range. As with H1, the relatively smooth behavior in this range suggests that there is no significant rise in crack-growth resistance in the early crack propagation stage.

This may be connected to a more brittle-type response prior to the formation of more severe damage mechanisms. The curves start to exhibit more variation from 40-48 mm. Some specimens become resistant or resistant; others start to become less resistant. There are several curves that have higher resistance between about 48 and 55 mm while the rest of the curve generally decreases from about 55 mm to 63 mm.

The R-curves are plotted for the three laminates, and it is seen that the curves are relatively smooth and very close to linear up to approximately 40 mm in each case, reflecting limited development of crack-growth resistance and more brittle behaviour for the early stage of crack growth on each laminate. When the crack length exceeds 40 mm, there is a greater difference in crack length between specimens due to the interaction of the crack with the various reinforcement layers. A better resistance to crack propagation has been found for the hybrid laminates, especially for H2, which could be explained by the fiber debonding, fiber-matrix debonding, and fiber bridging mechanisms. As crack length increases, above about 55 mm, the scatter in the results observed, which is attributed to variations in the distribution, bonding and crack-path development of the fibers.

Table 13 the average critical energy release rate for crack propagation (G_{IC_PRO})

Parameters	Laminate J	Laminate H1	Laminate H2
G_{IC} (kJ/m ²)	4.133	25.809	33.645
SD (kJ/m ²)	1.065	0.889	1.441

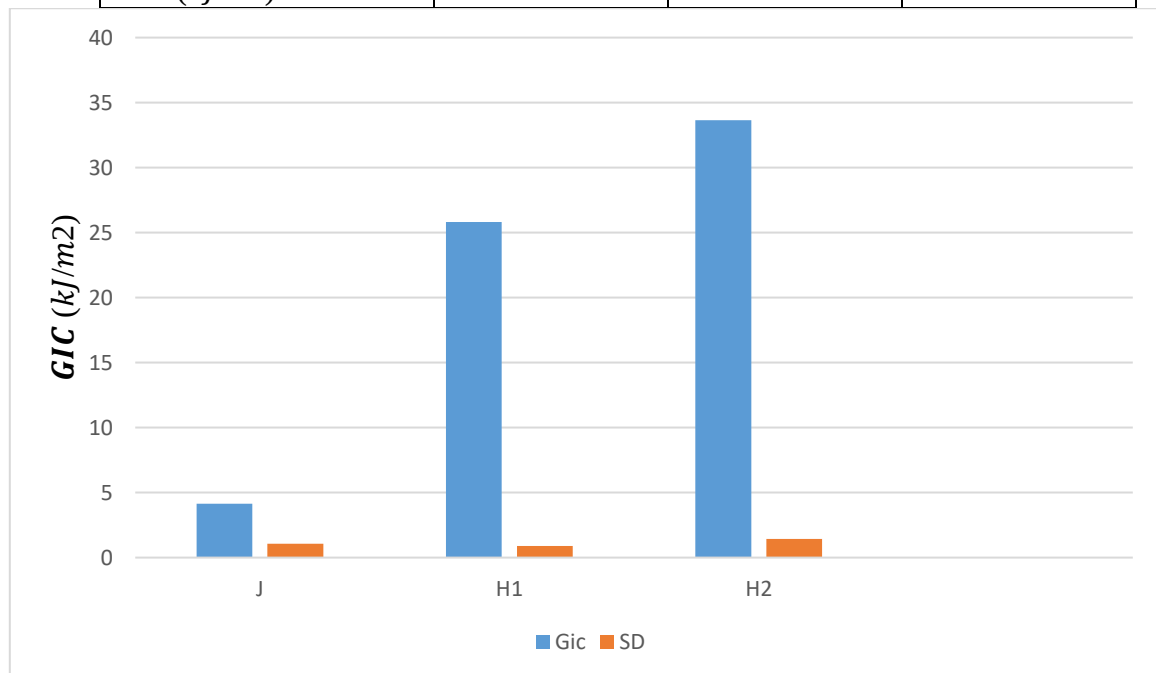


Figure 32 graph of G_{IC_PRO}

The R-curve response results from the present study are in line with the overall fracture behavior of other fiber-reinforced polymer composites. The same behavior has been found for different specimen configurations, as well as different FE-based data reduction methods, when studying crack-growth in both woven and unidirectional CFRP composites [37], [39]. The material systems and laminate architectures are different from those studied in this work, but the similar trends in the R curve suggest that the fracture behavior exhibited by the jute-glass reinforced polyester laminates studied in this work is typical of fiber-reinforced composite materials.

4.5 Fractographic and Damage Mechanism Analysis

4.5.1 Fractographic Analysis of Pure Jute Composite Laminate

Under Conditions of Mode I (opening) loads, optical macro-graphs and radiographic tests of the tested compact tension (CT) specimen's show the characteristic fracture behaviors of unreinforced natural fiber composites. As seen in the surface profiles and sub-surface X-ray images, crack initiation is clean at the apex of the pre-crack notch and then progresses through the ligament length along the expected center plane.

High resolution optical images show evidence of localized fiber bridging across the crack flanks in the primary propagation zone. As the crack progresses, the natural jute fibers separate from the matrix material and, prior to total splitting failure, the fibers absorb energy by frictional sliding.

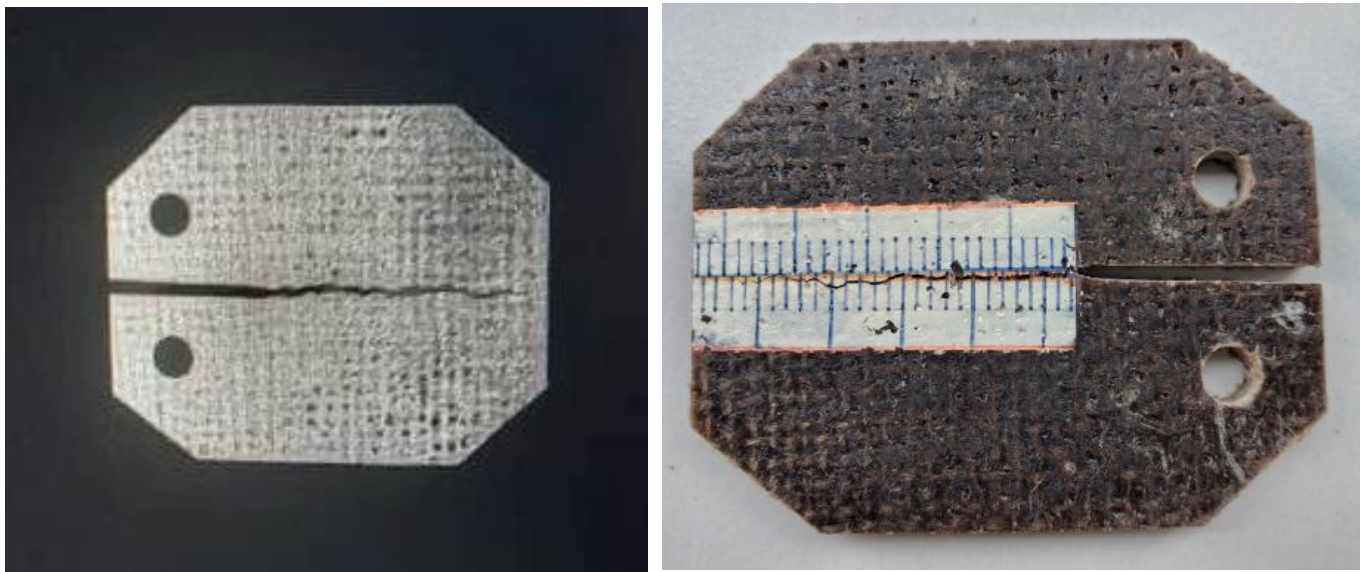
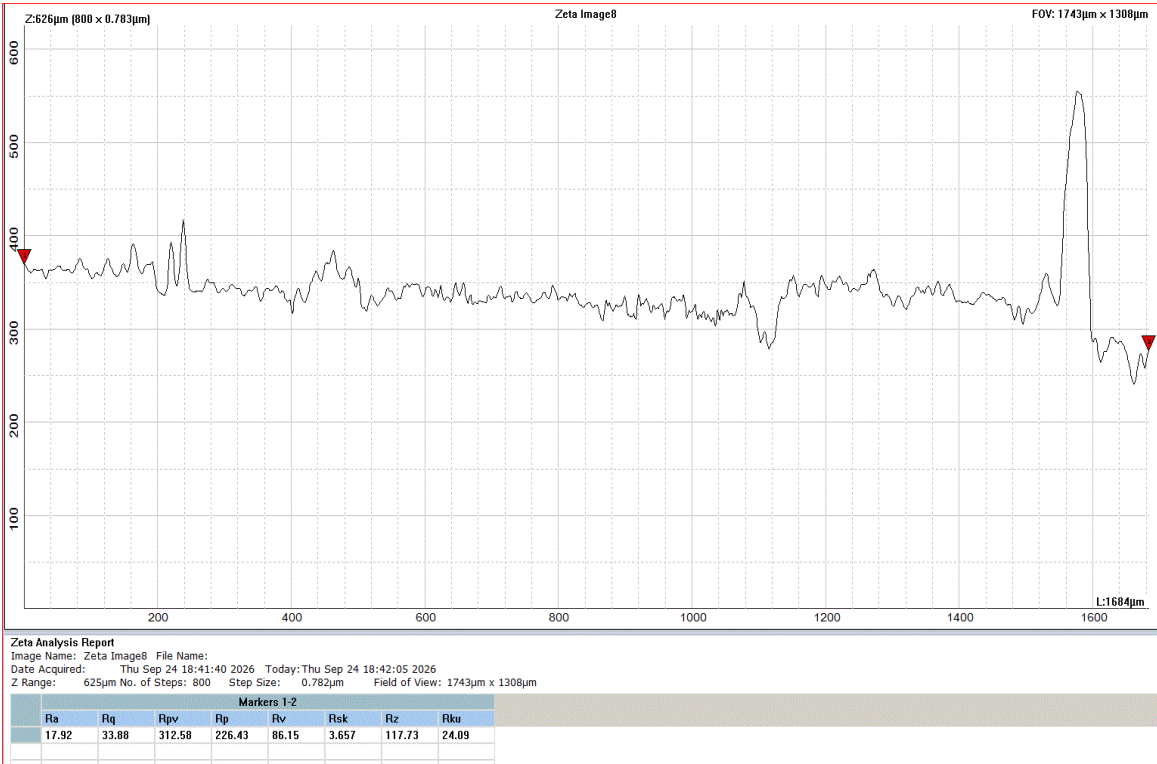


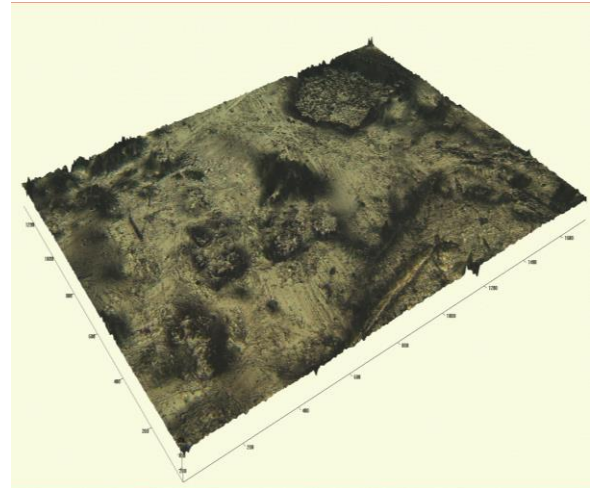
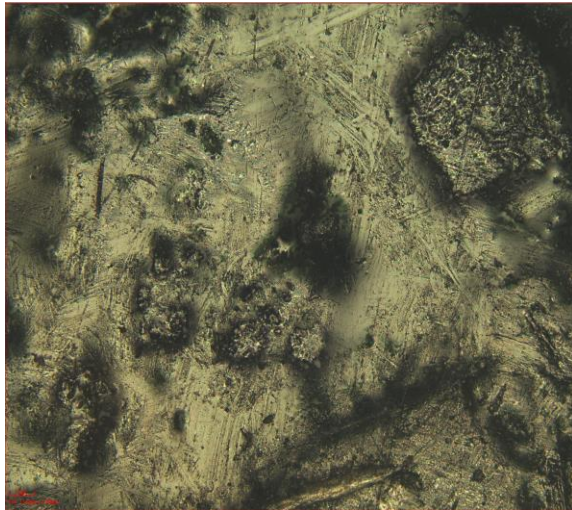
Figure 33 X-ray Imaging and Fractography of pure Jute laminate

Damage assessment by X-ray imaging shows a very localized degradation along the flanks of the crack. The pure jute laminate exhibits very little far field delamination or significant micro-cracking regions off the main fracture path. The primary modes of energy dissipation in this uniform system are fiber-matrix debonding, matrix micro-cracking, and extensive bridging by trailing natural fibers resisting crack opening due to interfacial friction before final failure at the tensile end of the fiber.

The comparative surface profilometry of pure jute composite as shown in figure 34 is found to be consistent with a change from a uniform baseline surface to highly complex fracture surfaces that absorb energy. The variation of height is as expected in the unfractured reference surface, showing an average height (Ra) of 17.92 μm , root mean square height (Rq) of 33.88 μm and the maximum peak to valley height (Rpv) of 312.58 μm . The uniformity of this near-planar topography indicates that unsaturated polyester resin matrix is uniformly distributed and consolidated throughout the laminate manufactured by the hand layup fabrication process resulting in a defect-free initial composite structure.



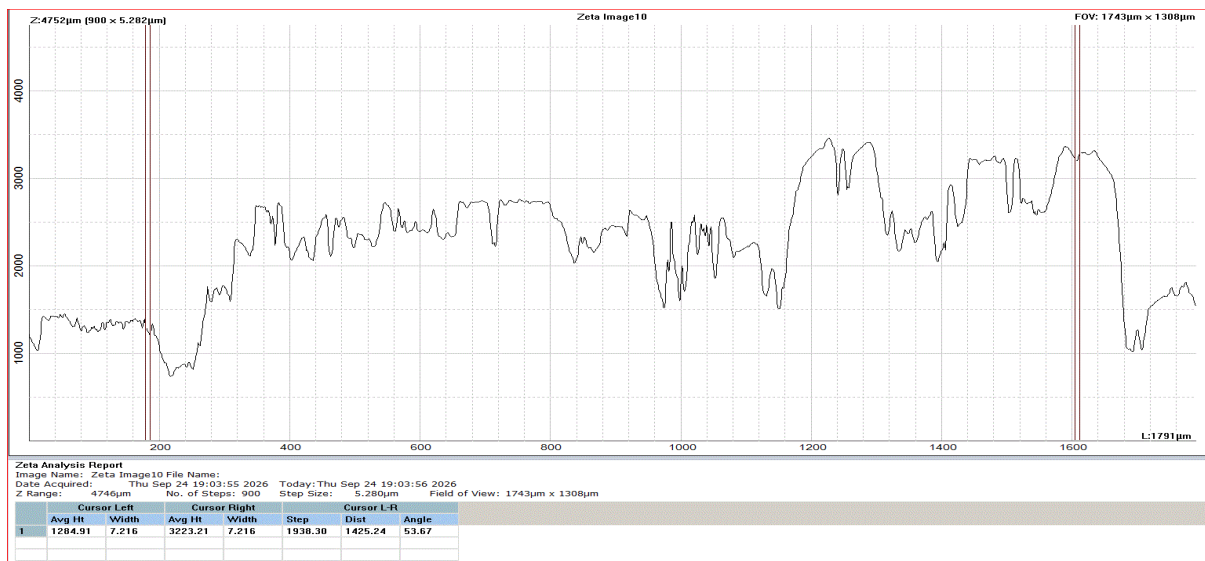
(a)



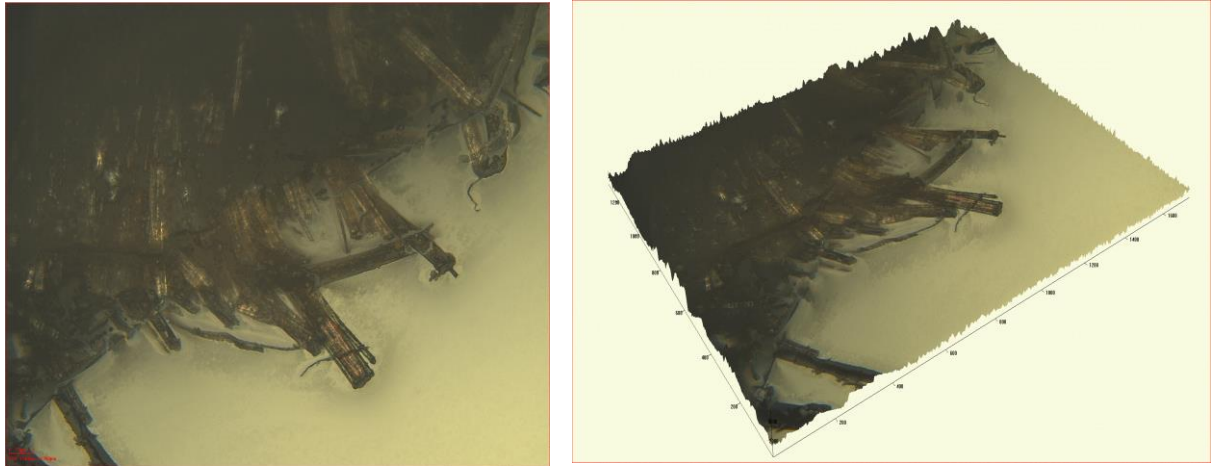
(b)

Figure 34 (a) surface profilometry of jute surface, (b) 2-D and 3-D Morphology of the surface

The opposite sides of the top and bottom surfaces, however, show considerable topographical variation with signs of large amounts of Mode I intralaminar damage propagation. Over a distance of 1425.24 μm , the top fracture zone has a dramatic vertical step increase of 1938.30 μm (from the average height of 1284.91 μm to 3223.21 μm), and sharp micro-peaks can be seen, which reflect the matrix tearing and failure of axial fiber bundles. The fracture surface at the bottom has a steep drop step of 1200.86 μm (4026.24 μm to 2825.38 μm) measured over a distance of 1342.00 μm and features numerous deep narrow troughs that represent areas of localized fibre pull out and interfacial debonding.



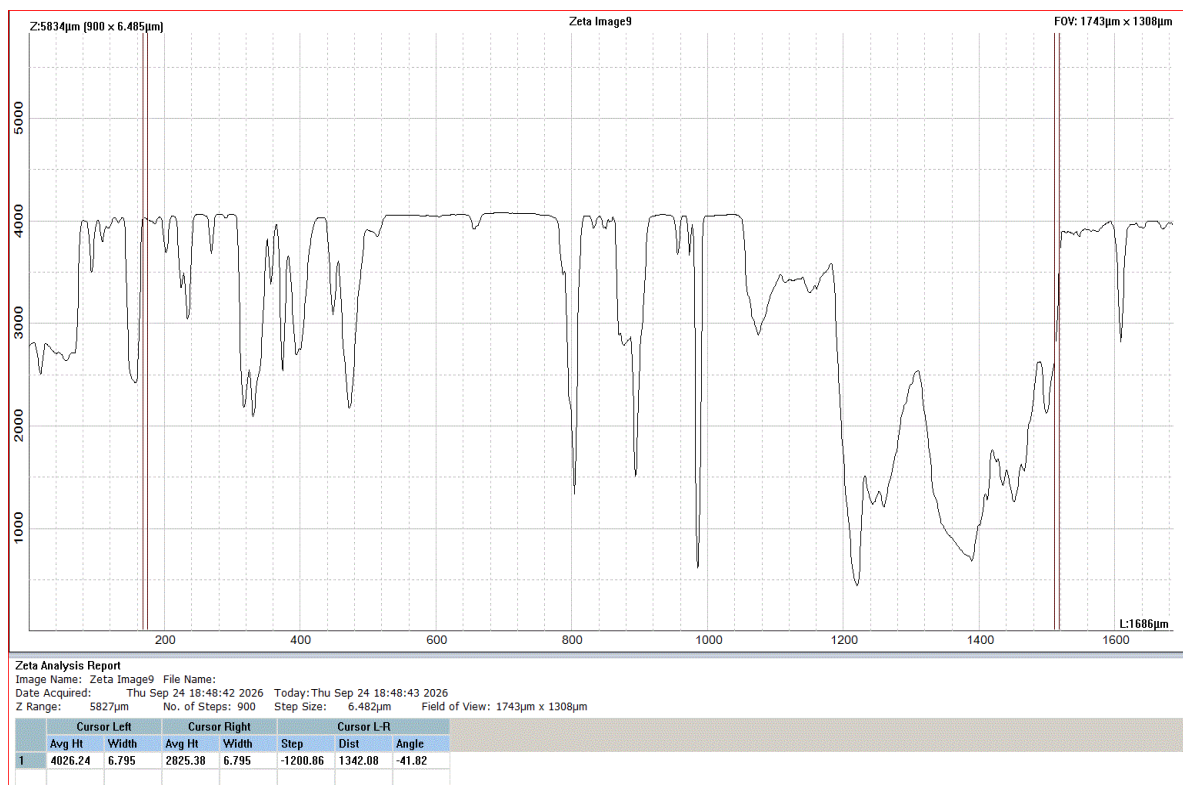
(a)



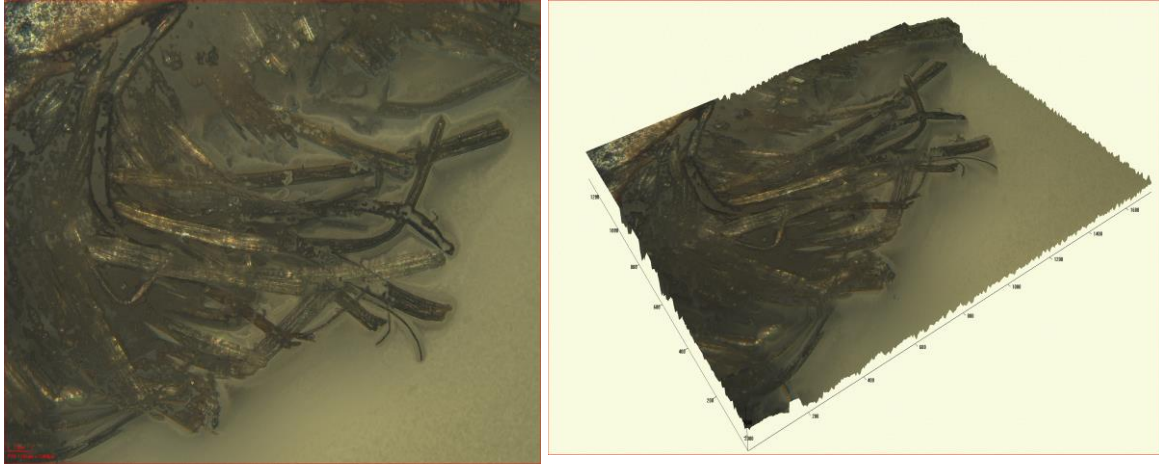
(b)

Figure 35 (a) top crack surface profilometry of jute , (b) 2-D and 3-D Morphology of the surface

These extreme surface deviations (Z-ranges up to 5827 μm) reflect substantial crack deflection and multi-planar fracture mechanisms and directly contribute to the strain energy dissipation of the jute composite.



(a)



(b)

Figure 36 (a) bottom crack surface profilometry of jute, (b) 2-D and 3-D Morphology of the surface

4.5.2 Fractographic Analysis of Hybrid 1 (H_1) Composite Laminate

The use of high strength woven glass fiber plies as outer skins in the Hybrid 1 (H_1) laminate has a considerable effect on the Mode I fracture progression, which is different from the unreinforced jute system. Surface macro-graphs and cross-sectional views reveal that significant glass fiber pull-out and tow splitting occur along the outer plies in the entire crack propagation region. The energy input needed to cause debonding between the fibers and fiber tensile rupture in the fracture tip is greater because a large amount of energy is necessary to cause the main crack to grow as the high tensile strength glass filaments span the crack tip.

One distinct characteristic seen on the front surfaces of the H_1 specimens is the development of a generally broad stress-whitening band in the path of the crack. This optical opacity indicates areas of internal matrix micro-cracking and areas of sub-surface interlaminar delamination between adjacent glass and jute layers. For Mode I opening, the interlaminar shear stresses are generated between the outer glass plies and the inner jute core plies due to mismatch in stiffness. This leads to interlayer debonding ahead of the crack tip in these zones.

From the cross sectional view, significant differences between the outer glasses skinned material and the jute core in the center can be seen: The glass layers have high density fiber

pulls out and frayed edges; the middle jute core has more of a rough surface with unevenness and jute pulls out as well as shearing the jute matrix.

The results of the radiographic X-ray analysis also confirm the dominant failure modes in H_1, which are outer glass tow splitting, glass fiber pull-out, localized matrix crushing and interlayer delamination at the glass-jute interface. All these failure modes contribute to the superior fracture toughness of the hybrid structure.

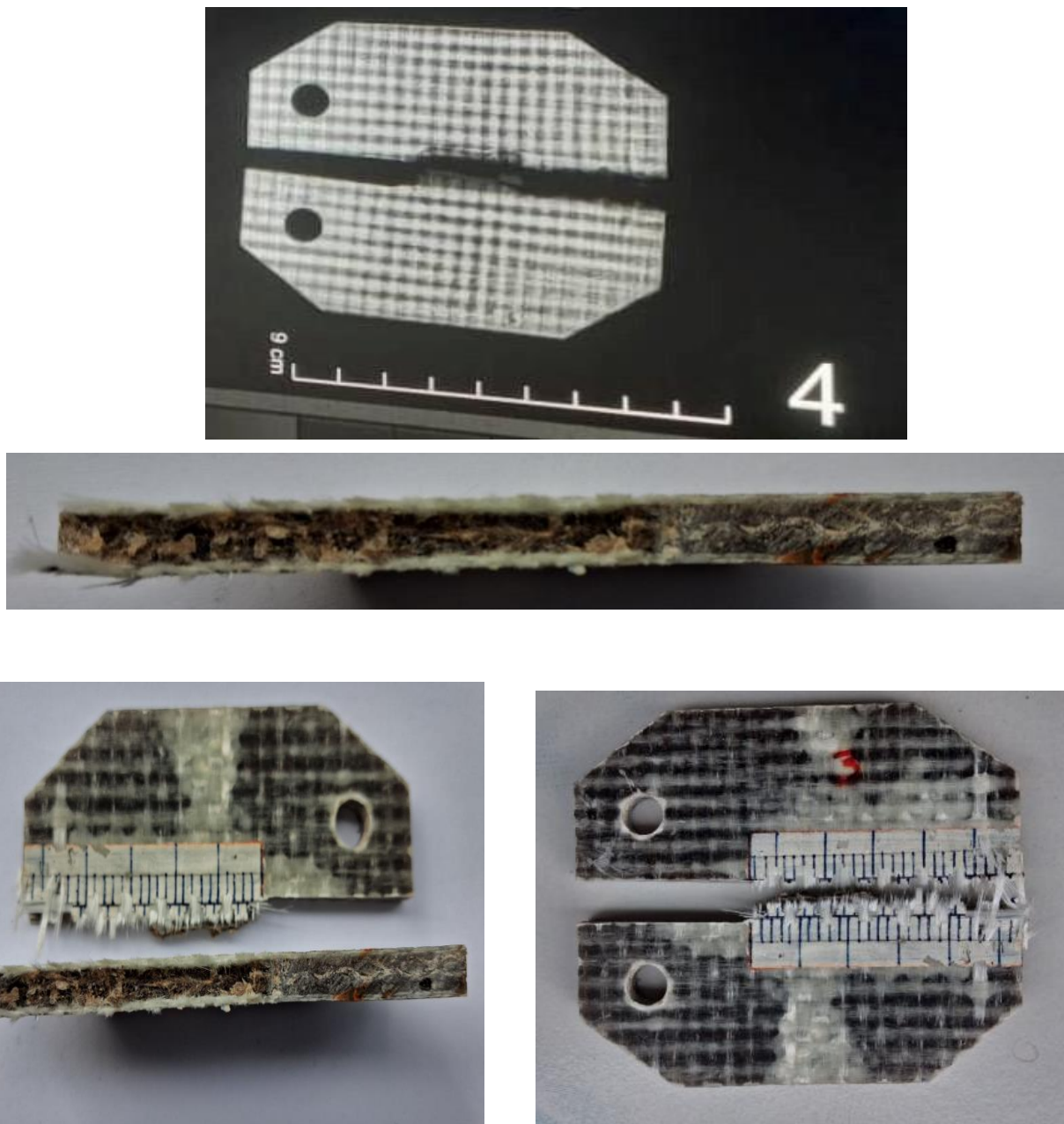
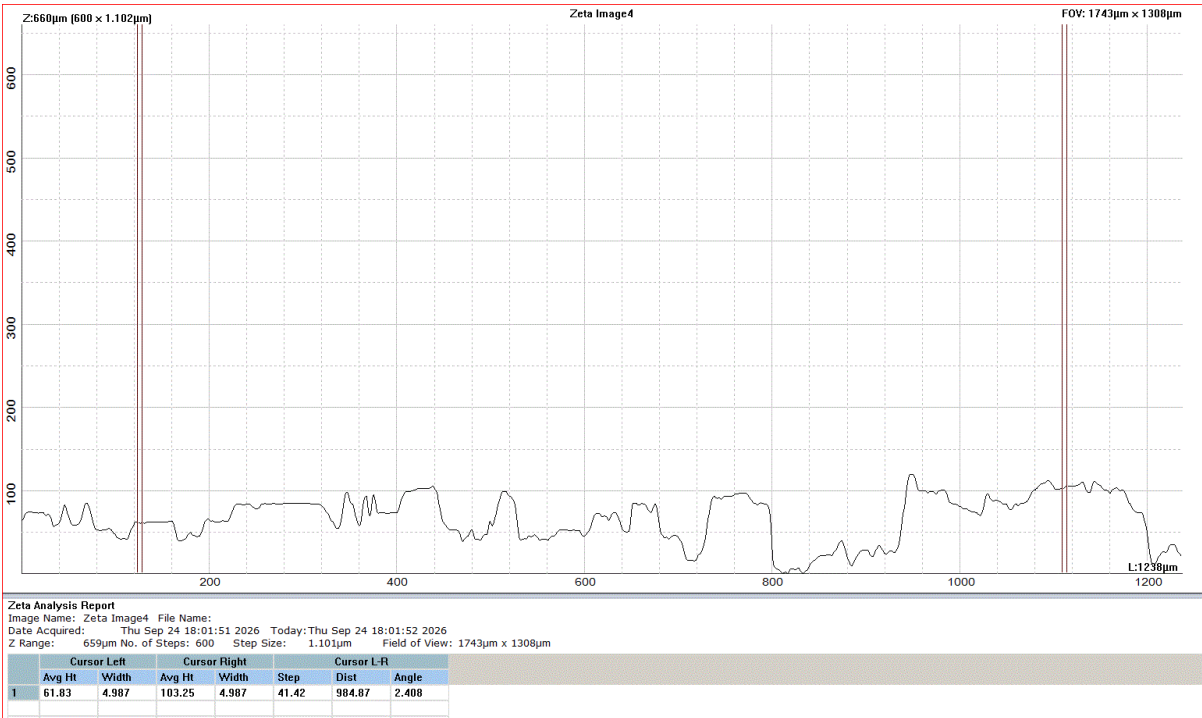


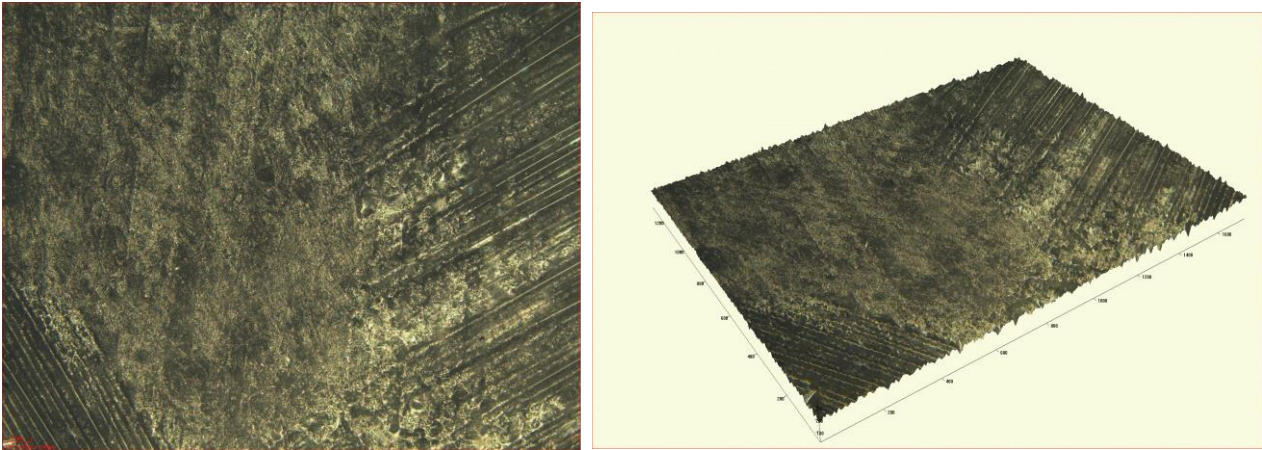
Figure 37 X-ray Imaging and Fractography of pure Hybrid 1 laminate

The surface profilometry of H_1 shows a gradient from relatively flat uncracked laminate surface to moderately tortuous, feature rich fracture topographies as shown in figure 38. The unfractured reference surface has very little topographic variation with a Z-range of

659 μm and an average change of height of 41.42 μm (from 61.83 μm to 103.25 μm) over 984.87 μm evaluated. The uniform resin distribution and correct wet-out of the composite consolidation phase are emphasized by this consistent low profile baseline.



(a)



(b)

Figure 38(a) surface profilometry of H-1 surface, (b) 2-D and 3-D Morphology of the surface

The bottom fracture surface, however, shows more signs of Mode I failure, along with localized energy absorption characteristics that are apparent in the top surface. The top fracture zone shows continuous peak and valley oscillations through a Z-range of 777 μm with a net step height of 124.57 μm (from 312.88 μm to 437.44 μm), and micro-peaks are seen at regular intervals, indicating localized matrix tearing and tow splitting.

The lower fracture surface on the other hand has a total Z-range of 1232 μm with a locally pronounced peak at $X = 980 \mu\text{m}$, where the value is $900 \mu\text{m}$, and a net step change of $-18.87 \mu\text{m}$ over $1345.90 \mu\text{m}$. These are 'isolated' vertical extensions with valleys extending around them, indicating fiber bundle pull-outs and local interfacial debonding, and hence deflection of the crack trajectory along the composite laminate plane.

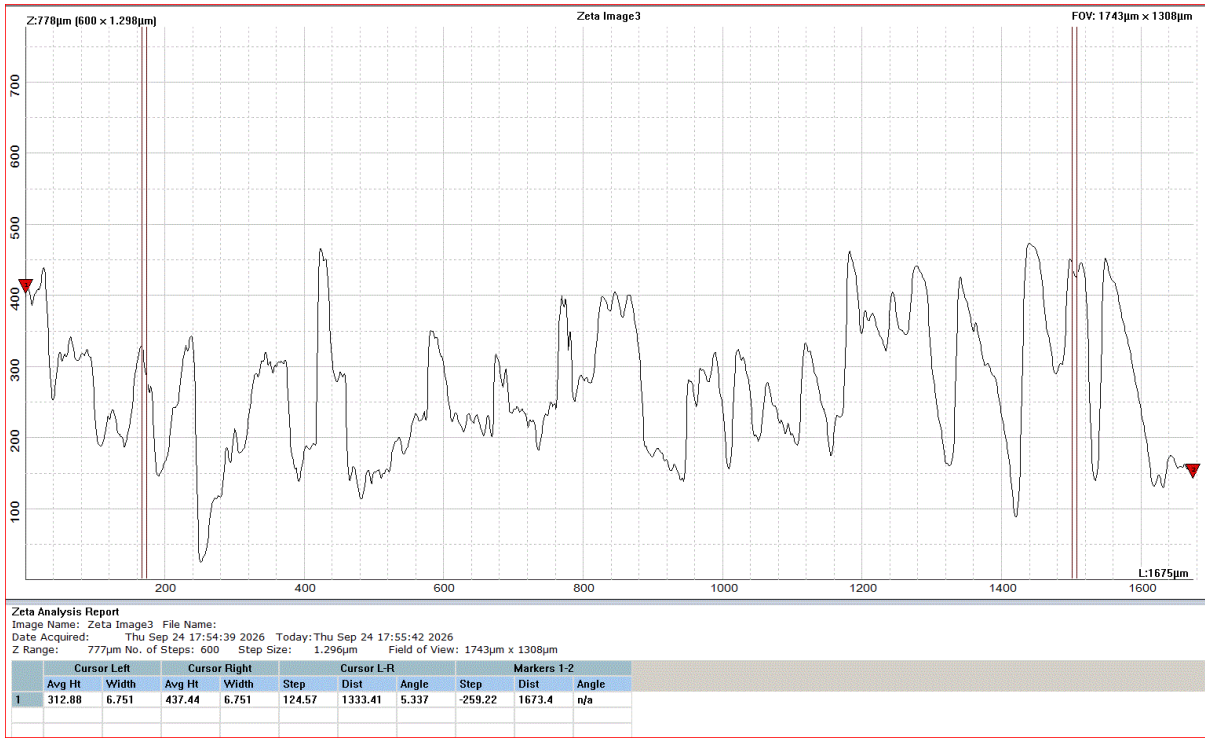
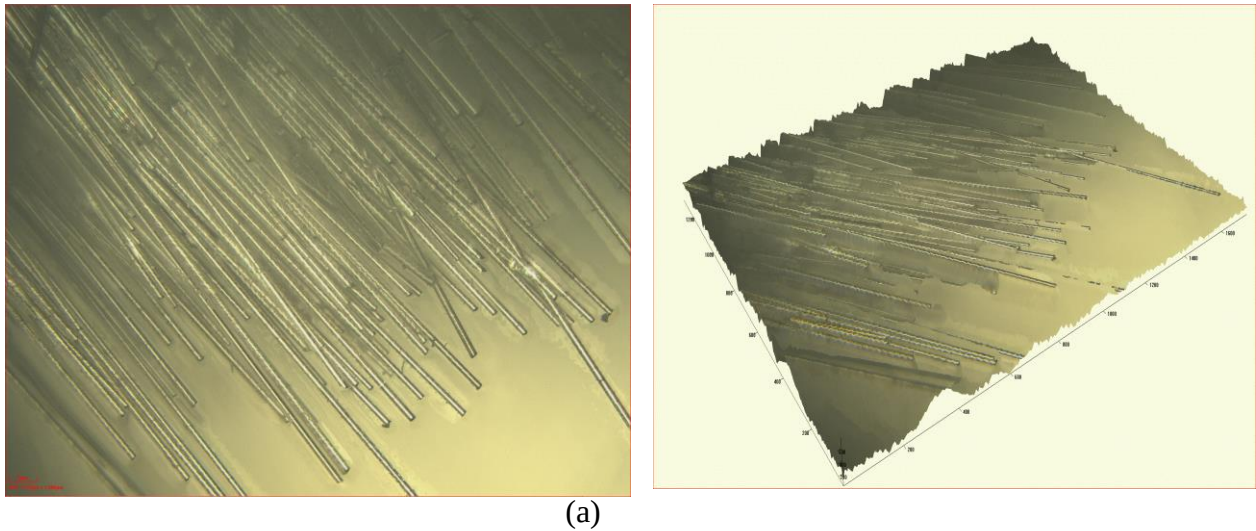
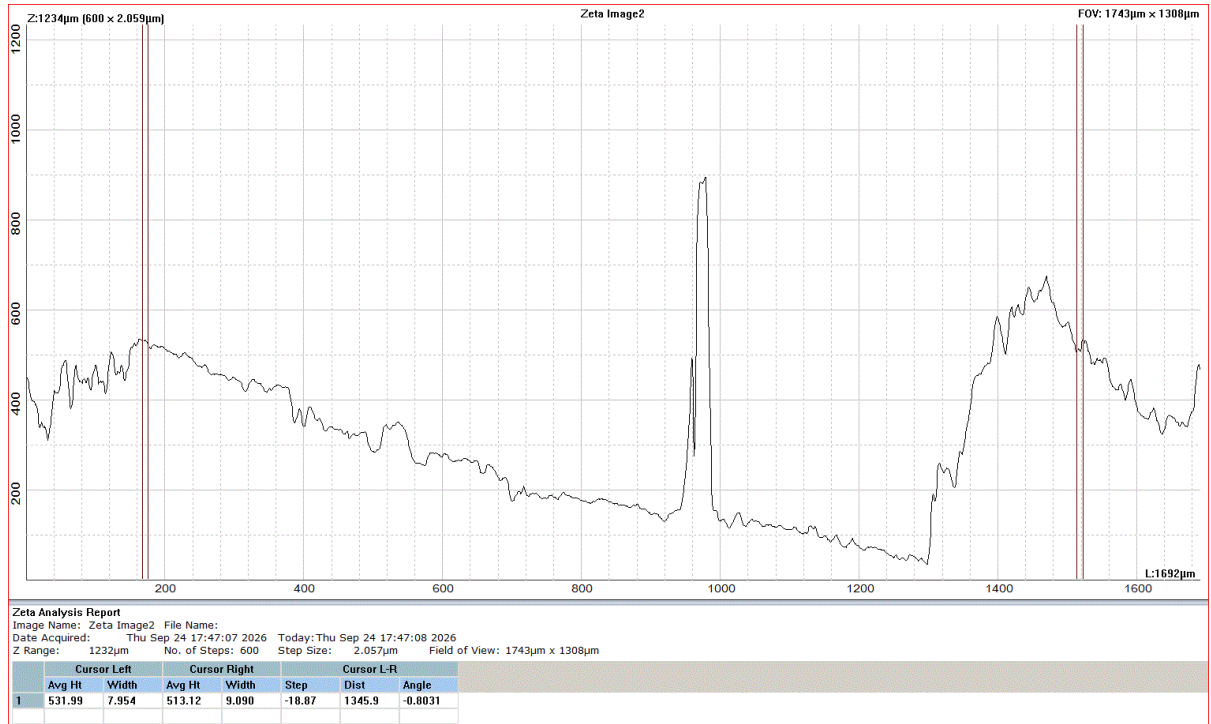
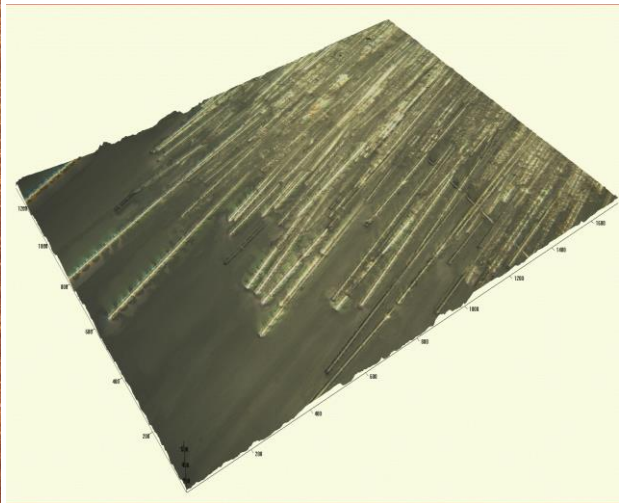
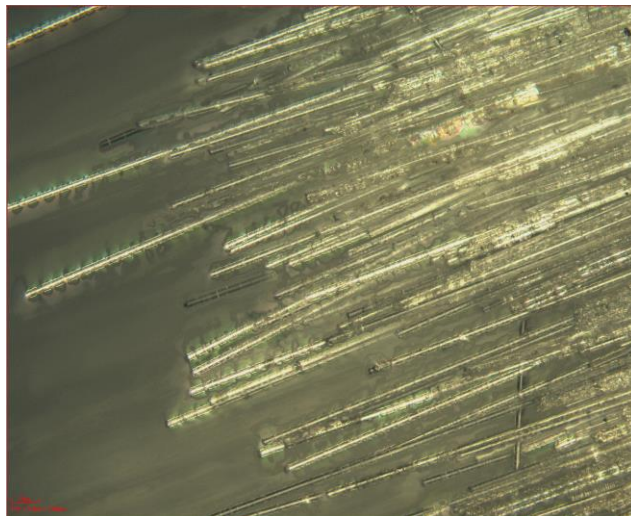


Figure 39 (a) 2-D and 3-D Morphology of the Top crack surface of H1, (b) profilometry graph



(a)



(b)

Figure 40 (a) bottom crack surface profilometry of H₁, (b) 2-D and 3-D Morphology of the surface

4.5.3 Fractographic Analysis of Hybrid 2 (H₂) Composite Laminate

The internal damage development and fracture surface features of the Hybrid 2 (H₂) laminate shows the effect of interleaving the glass fiber layers within the laminate structure. Optical macro-graphs and cross sectional inspection shows a very well-organized failure mode with widespread simultaneous pull-out of glass fibers throughout a ply depth along the failure plane.

The H2 configuration has an almost consistent linear crack path throughout the ligament length. The embedded glass layers limit the development of crack branching and direct the crack plane to expend its energy by means of parallel failure mechanisms throughout the thickness. The high magnification cross-sectional images verify that failure under H_2 is controlled by multi-interface delamination, extensive fiber pull out and fiber bridging throughout the interior. The main crack grows in Mode I opening and embeds significant elastic strain energy into the interior glass layers that are subsequently debonded from the adjacent layers and stretched in tension.

The sub-surface damage band is evenly distributed throughout the crack flank and is seen as a diffused band in the X-ray radiographic analysis. The distribution of density gradients shows that interlaminar shear stresses are spread out over several interior glass-jute interfaces, causing no catastrophic early onset of delamination and distributing the total strain energy release rate (G_{IC}) by multiple layers of fiber bridging and micro-cracking.

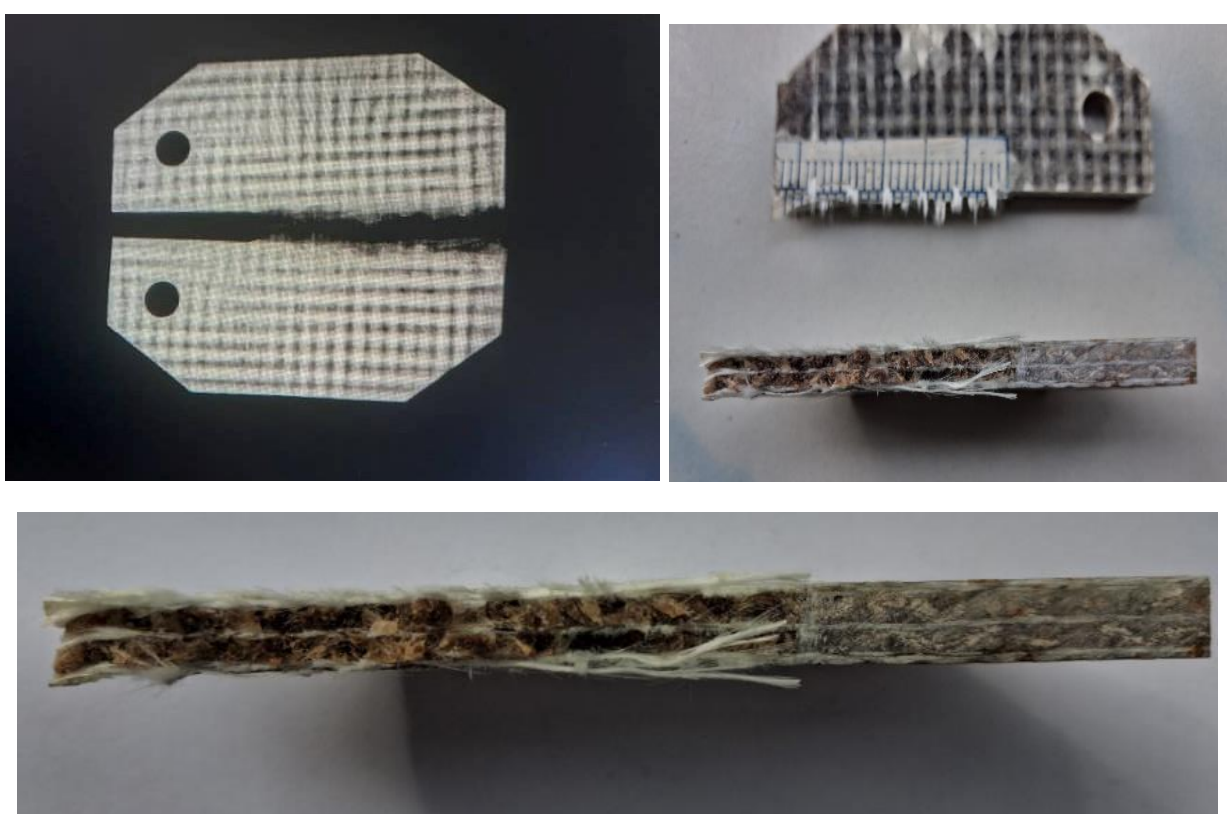
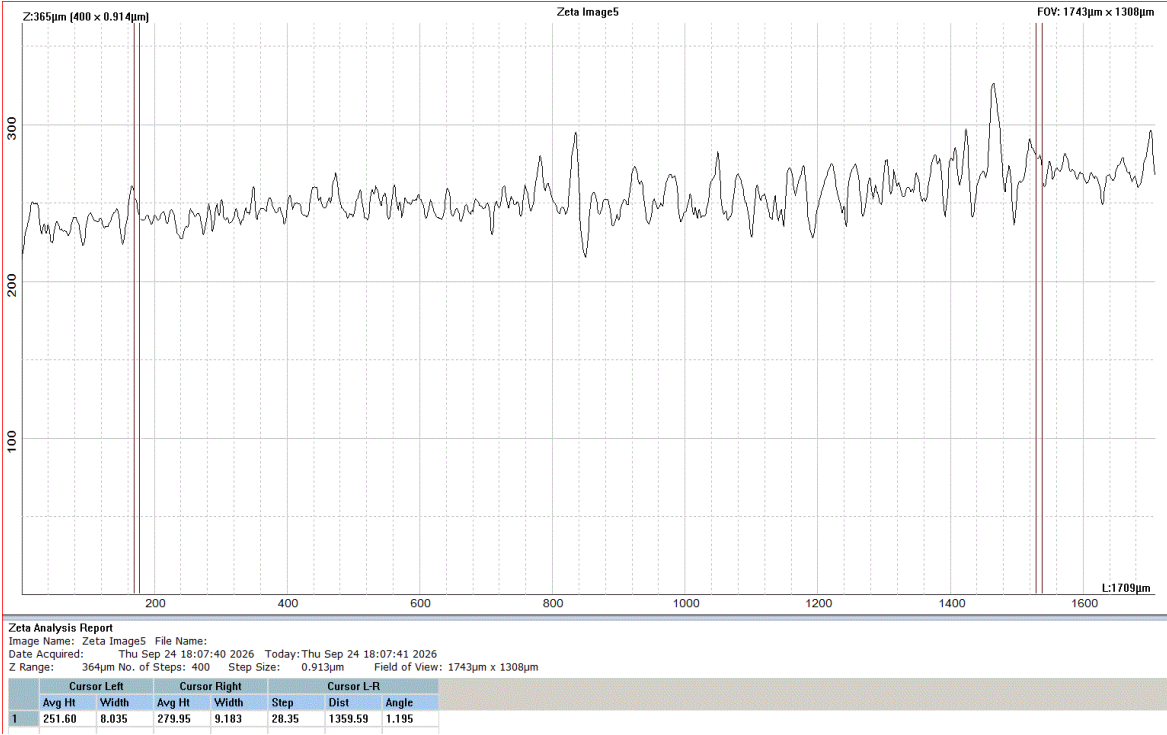


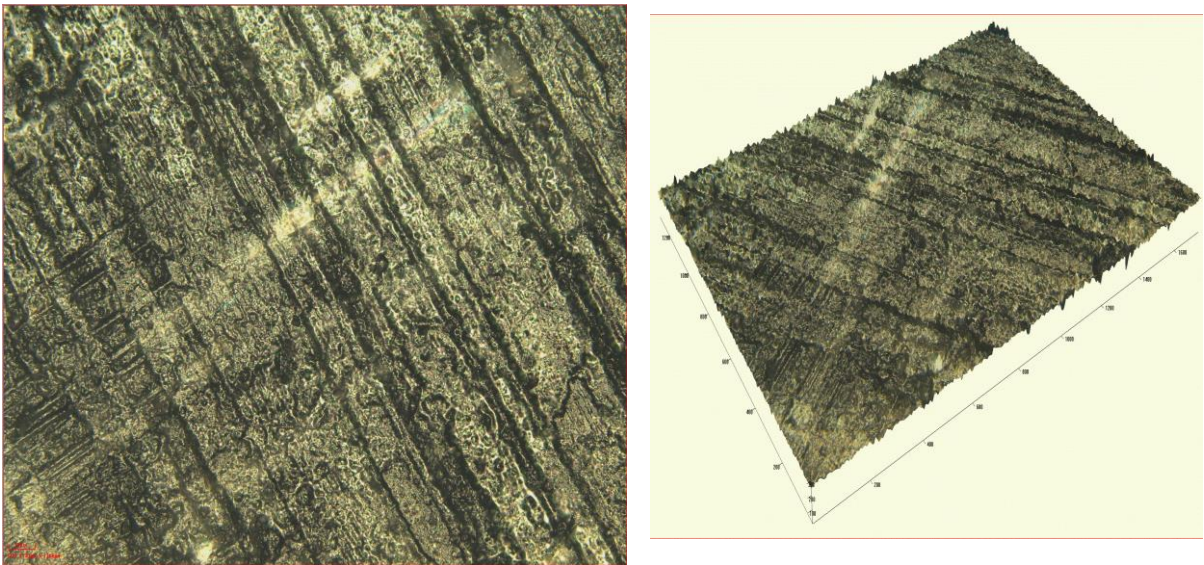
Figure 41 X-ray Imaging and Fractography of pure Hybrid 2 laminate

The surface profilometry of H_2 indicates an excellent range of transition from a very smooth uncracked surface to very rough, multiplanar fracture surfaces as shown in figure 42. On the unfractured reference surface a tightly bounded Z-range of 364 μm is seen with

a minimal step difference of 28.35 μm (251.60 μm to 279.95 μm) over a span of 1359.59 μm . This is a near level profile that indicates that the matrix distribution and the compaction of the laminate during fabrication has been optimal and that it will provide a consistent reference plane before mechanical loading.



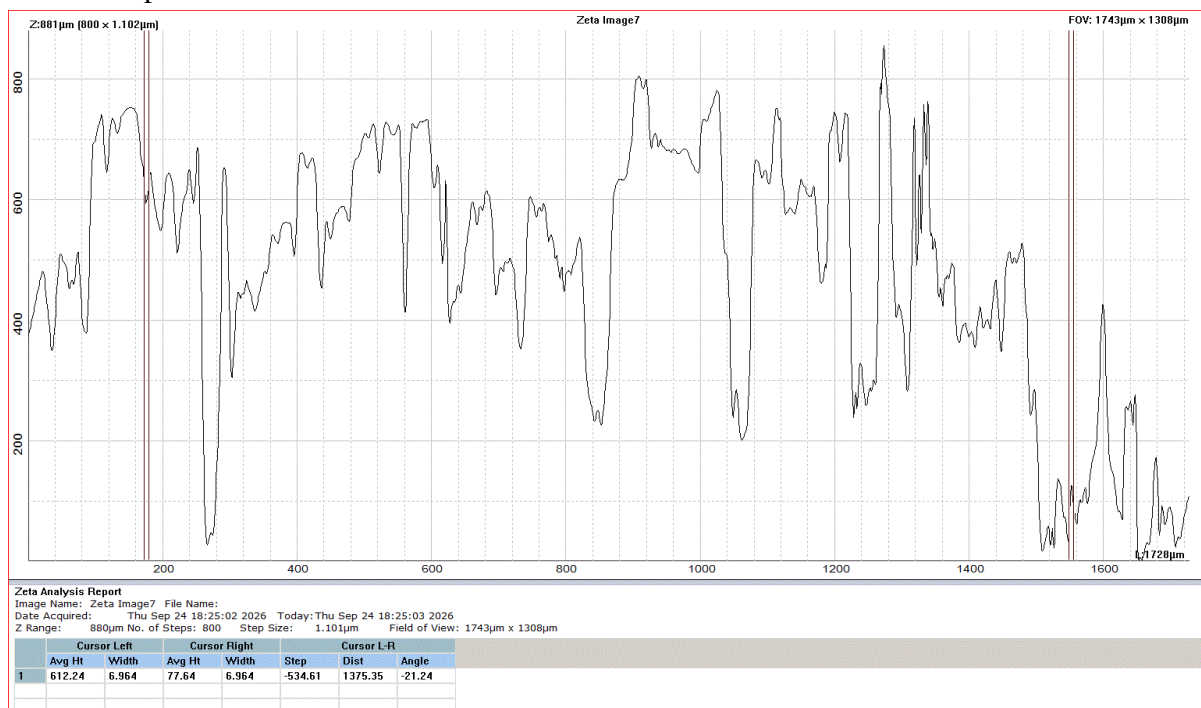
(a)



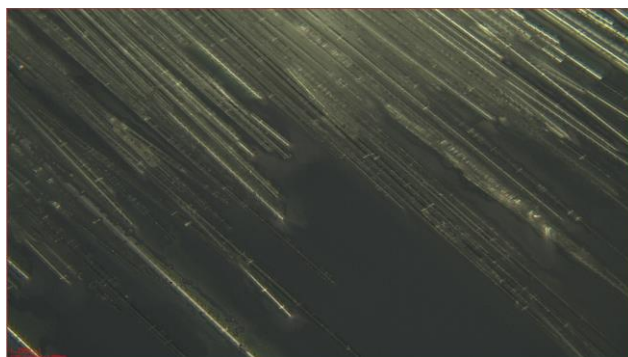
(b)

Figure 42 (a) surface profilometry of H-2 surface, (b) 2-D and 3-D Morphology of the surface

The top and bottom fracture surfaces, on the other hand, show large vertical changes and a large amount of energy is dissipated during Mode I intralaminar crack propagation. The upper fracture zone has a Z-range of 880 μm and net change of -534.61 μm (from 612.24 μm to 77.64 μm) for a distance of 1375.35 μm and has dense micro peaks and sharp valleys that indicate local tow failure and matrix tearing. The bottom fracture surface, on the other hand, shows the highest surface tortuosity all over a wide Z-range of 2263 μm , with a step rise of 653.80 μm (from 1260.1 μm to 1913.9 μm) spanning 1280.62 μm . The high height gradient changes across the 2000 μm boundary are common, indicating a high amount of fiber pull-out, debonding, and severe crack deflection along the composite failure path.



(a)



(b)

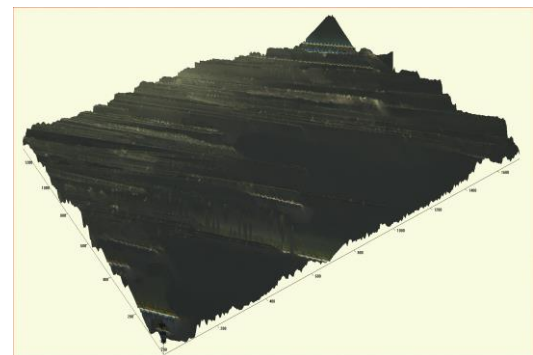
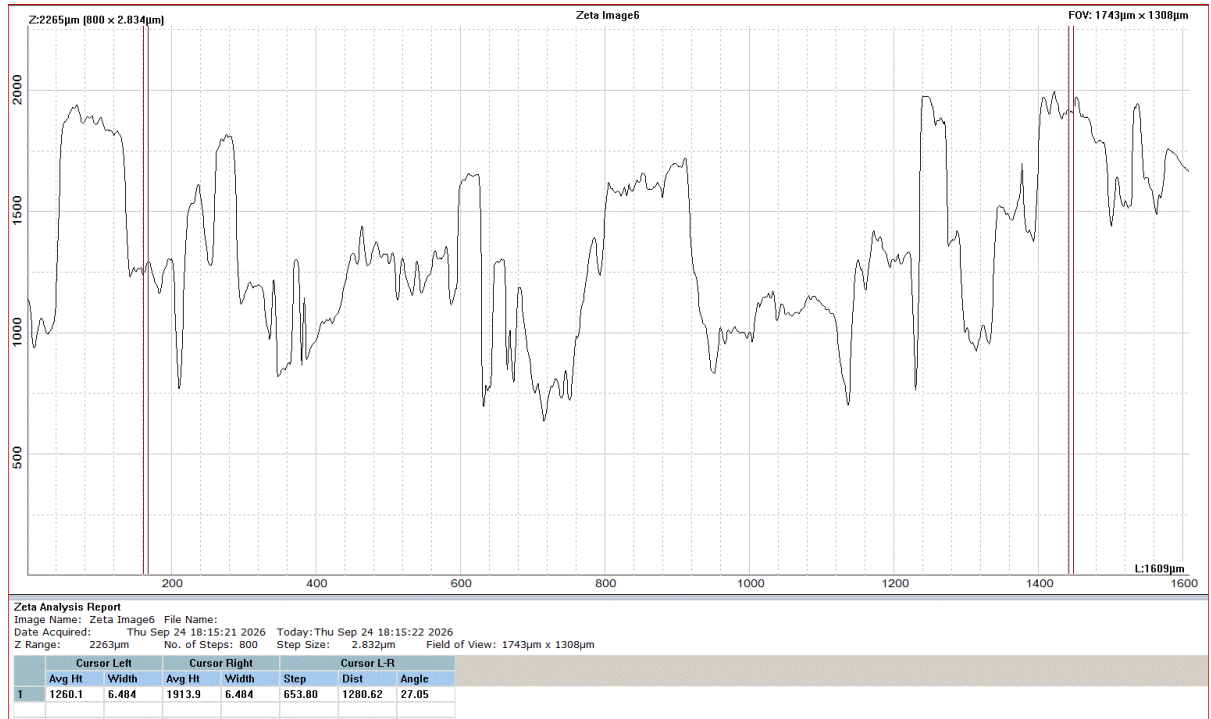
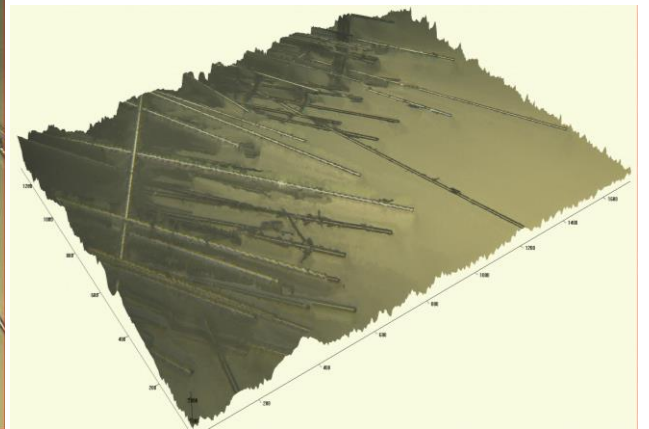
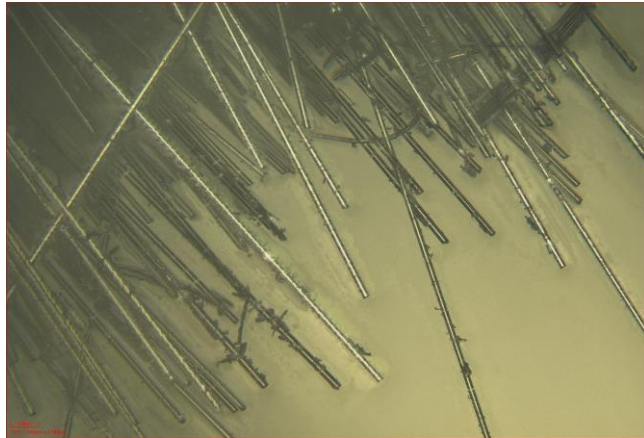


Figure 43 (a) top crack surface profilometry of H₂, (b) 2-D and 3-D Morphology of the surface



(a)



(b)

Figure 44 (a) bottom crack surface profilometry of H_2, (b) 2-D and 3-D Morphology of the surface

over all the crack propagation was smooth and progressive for all the three laminates and they showed brittle fracture behavior showed three stages, where the crack initially started with precracking then followed by the crack propagation zone in which the material started failing (cracking) exhibiting fiber pullout, micro-cracking, fiber bridging and tow splitting. And the last region was compressive zone where the specimen was pulled apart and the force was applied in a compressed way on the end part of the composite which showed no fiber pullout

Chapter Five

Conclusion and recommendation

5.1 Conclusion

The Mode I fracture toughness, crack-growth resistance (R-curve) and underlying damage progression mechanisms of hybrid jute glass fiber-reinforced polyester composites were considered in this study. The research, which integrates experimental testing of doubly-tapered compact tension (2TCT) specimens, finite element numerical data reduction and non-destructive X-ray fractography, gives an overall picture of the influence of natural and synthetic fiber hybridization on fracture behavior.

The durability to crack initiation or propagation is significantly increased after a combination of alkali treated natural jute plies and synthetic E-glass plies are hybridized together. The critical initiation energy release rate (G_{IC}) was improved to 20.74 kJ/m² for the skin-core hybrid configuration (H_1) and 25.03 kJ/m² for the interleaved hybrid configuration (H_2) with the replacement of part of the jute fibers with the same volume fraction of E-glass composite. The improvements in these numbers represent 86.08% and 88.46% performance enhancements, respectively. The stacking architecture can greatly influence the direction and energy of the crack propagation. The interleaved (H_2: G-G-J-G-J-G-G) structure proved to be superior to the skin-core (H_1: G-G-J-J-J-G-G) structure because of the distribution of the shear stresses over the multiple internal interfaces. This configuration has caused the occurrence of parallel damage mechanisms and resulted in a higher average crack propagation resistance ($G_{IC-PROG}$ = 33.645 kJ/m² as compared to H_1 (25.809 kJ/m²) and pure jute (4.133 kJ/m²) materials.

The investigation also verified that the energy release rates of orthotropic composite laminates are greatly underpredicted by a standard isotropic fracture formulation (e.g., ASTM D5045). Two-stage finite element compliance calibration procedure, developed in Abaqus and MATLAB, was successfully applied to consider the orthotropic elastic interactions and it was found that the fracture energy under the standard isotropic assumption is underestimated by 37% to 41%. Fractographic and R-curve analyses revealed that pure jute laminates show localized failure with matrix cracking and little fiber bridging, whereas hybrid laminates exhibit extensive stress whitening as well as large areas of glass tow splitting, multi-interface delamination and strong trailing fiber bridging resulting in more effective reduction of crack-tip stress concentrations. Overall, the partial use of

chemically treated jute fiber through an interleaved stacking in place of synthetic glass fiber leads to a damage-tolerant composite which can potentially be a viable route for lightweight and sustainable structural engineering applications.

5.2 Recommendations Future Work

From this experimental and numerical study some practical suggestions are proposed for the design of structural composite and industrial applications. Design engineers should always prefer interleaved hybridization designs to isolated skin-core designs when considering damage tolerance and preventing catastrophic failure in high impact and crack growth areas, such as automotive underbody panels, marine hatch covers and building panels. For manufacturing purposes, the chemical treatment of raw jute fibers has to be carefully monitored, and the concentration has to be 5 wt% of NaOH for 24 hours and then the fibers have to be neutralized properly; otherwise, if the concentration is higher or exposure period is longer, the removal of surface wax would not be complete, and if it is lower or shorter, cellulose degradation would be severe. Moreover, design engineers who are considering damage tolerance for natural and synthetic orthotropic hybrids should not use traditional linear elastic fracture mechanics equations, but should instead use finite element-aided numerical compliance data reduction techniques to assure safe structural margins.

5.3 Future Work

Several future research directions are suggested to build on the results of this thesis and further increase the engineering maturity of hybrid natural composites. Since this study was limited to mode I intralaminar opening failure, future studies should address mode II in-plane shear and mixed-mode fracture toughness for complete failure envelopes. The moisture, temperature and UV durability of natural fibers will require long-term environmental durability testing to determine the degradation of toughness over time. The finite element models should also be extended from linear elastic models to include Cohesive Zone Modeling (CZM) or Extended Finite Element Methods (XFEM) in Abaqus for accurate prediction of progressive fiber pull-out and bridging traction laws. Last, but not least, cyclic fatigue crack growth rates and high strain rate impact behavior will be evaluated, giving information to be used in safety critical applications in the transportation and structural fields.

Reference

- [1] S. H. Kamarudin *et al.*, “A Review on Natural Fiber Reinforced Polymer Composites (NFRPC) for Sustainable Industrial Applications,” *Polymers*, vol. 14, no. 17, p. 3698, Sep. 2022, doi: 10.3390/polym14173698.
- [2] V. Prasad, A. Alliyankal Vijayakumar, T. Jose, and S. C. George, “A Comprehensive Review of Sustainability in Natural-Fiber-Reinforced Polymers,” *Sustainability*, vol. 16, no. 3, p. 1223, Jan. 2024, doi: 10.3390/su16031223.
- [3] A. Lopez-Arraiza, L. Essamari, M. Iturrondobeitia, D. Boullosa-Falces, and D. Justel, “Life cycle assessment of glass fibre versus flax fibre reinforced composite ship hulls,” *Sci. Rep.*, vol. 15, no. 1, p. 16283, May 2025, doi: 10.1038/s41598-025-00811-y.
- [4] J. Korol, A. Hejna, D. Burchart-Korol, and J. Wachowicz, “Comparative Analysis of Carbon, Ecological, and Water Footprints of Polypropylene-Based Composites Filled with Cotton, Jute and Kenaf Fibers,” *Materials*, vol. 13, no. 16, p. 3541, Aug. 2020, doi: 10.3390/ma13163541.
- [5] S. J. Skosana, C. Khoathane, and T. Malwela, “Driving towards sustainability: A review of natural fiber reinforced polymer composites for eco-friendly automotive light-weighting,” *J. Thermoplast. Compos. Mater.*, vol. 38, no. 2, pp. 754–780, Feb. 2025, doi: 10.1177/08927057241254324.
- [6] N. E. Ajayi, S. Rusnakova, A. E. Ajayi, R. O. Ogunleye, S. O. Agu, and A. N. Amenaghawon, “A comprehensive review of natural fiber reinforced Polymer composites as emerging materials for sustainable applications,” *Appl. Mater. Today*, vol. 43, p. 102666, Apr. 2025, doi: 10.1016/j.apmt.2025.102666.
- [7] A. S. M. Sayem, J. Haider, and M. A. Sayeed, “Development and characterisation of multi-layered jute fabric-reinforced HDPE composites,” *J. Compos. Mater.*, vol. 54, no. 14, pp. 1831–1845, Jun. 2020, doi: 10.1177/0021998319885440.
- [8] H. Chandekar, V. Chaudhari, and S. Waigaonkar, “A review of jute fiber reinforced polymer composites,” *Mater. Today Proc.*, vol. 26, pp. 2079–2082, 2020, doi: 10.1016/j.matpr.2020.02.449.
- [9] X. Wang, L. Chang, X. Shi, and L. Wang, “Effect of Hot-Alkali Treatment on the Structure Composition of Jute Fabrics and Mechanical Properties of Laminated Composites,” *Materials*, vol. 12, no. 9, p. 1386, Apr. 2019, doi: 10.3390/ma12091386.
- [10] H. Wang, H. Memon, E. A. M. Hassan, Md. S. Miah, and Md. A. Ali, “Effect of Jute Fiber Modification on Mechanical Properties of Jute Fiber Composite,” *Materials*, vol. 12, no. 8, p. 1226, Apr. 2019, doi: 10.3390/ma12081226.
- [11] K. Roy, S. C. Debnath, L. Tzounis, A. Pongwisuthiruchte, and P. Potiyaraj, “Effect of Various Surface Treatments on the Performance of Jute Fibers Filled Natural Rubber (NR) Composites,” *Polymers*, vol. 12, no. 2, p. 369, Feb. 2020, doi: 10.3390/polym12020369.
- [12] J. I. P. Singh, S. Singh, and V. Dhawan, “Effect of alkali treatment on mechanical properties of jute fiber-reinforced partially biodegradable green composites using epoxy resin matrix,” *Polym. Polym. Compos.*, vol. 28, no. 6, pp. 388–397, Jul. 2020, doi: 10.1177/0967391119880046.
- [13] E. Haq *et al.*, “Improved mechanical properties of environmentally friendly jute fibre reinforced metal laminate sandwich composite through enhanced interface,” *Heliyon*, vol. 10, no. 2, p. e24345, Jan. 2024, doi: 10.1016/j.heliyon.2024.e24345.
- [14] C. R. Ferreira, A. M. Araújo, J. D. C. M. Fonseca, and Í. A. D. P. E. Silva, “Analysis of mechanical properties of hybrid composites reinforced with jute / fiberglass in

- epoxy matrix,” *Int. J. Adv. Eng. Res. Sci.*, vol. 7, no. 5, pp. 503–508, 2020, doi: 10.22161/ijaers.75.62.
- [15] H. Ikbāl, “Mechanical properties of jute/glass fiber reinforced hybrid composites in epoxy resin matrix,” *Smart Textiles*, 2018. [Online]. Available: <https://textilefocus.com/mechanical-properties-juteglass-fiber-reinforced-hybrid-composites-epoxy-resin-matrix/>
- [16] M. Zannat, R. Roy, and M. N. Sultana, “Jute-Glass Fiber Based Composite for Engineering Application,” 2017.
- [17] U. S. Pawar, S. S. Chavan, and D. D. Mohite, “Synthesis of glass FRP-natural fiber hybrid composites (NFHC) and its mechanical characterization,” *Discov. Sustain.*, vol. 5, no. 1, p. 44, Mar. 2024, doi: 10.1007/s43621-024-00231-4.
- [18] M. Y. Khalid, Z. U. Arif, M. F. Sheikh, and M. A. Nasir, “Mechanical characterization of glass and jute fiber-based hybrid composites fabricated through compression molding technique,” *Int. J. Mater. Form.*, vol. 14, no. 5, pp. 1085–1095, Sep. 2021, doi: 10.1007/s12289-021-01624-w.
- [19] M. U. Ghani *et al.*, “Performance Evaluation of Jute/Glass-Fiber-Reinforced Polybutylene Succinate (PBS) Hybrid Composites with Different Layering Configurations,” *Materials*, vol. 15, no. 3, p. 1055, Jan. 2022, doi: 10.3390/ma15031055.
- [20] M. Islam, M. T. Islam, M. U. Apu, A. Islam, S. Khandaker, and F. Sarker, “Development of graphene-modified jute/glass hybrid composites *via* fiber wrapping for enhanced structural applications,” *RSC Adv.*, vol. 15, no. 34, pp. 27594–27605, 2025, doi: 10.1039/D5RA02968F.
- [21] M. Y. Khalid, M. A. Nasir, A. Ali, A. Al Rashid, and M. R. Khan, “Experimental and numerical characterization of tensile property of jute/carbon fabric reinforced epoxy hybrid composites,” *SN Appl. Sci.*, vol. 2, no. 4, p. 577, Apr. 2020, doi: 10.1007/s42452-020-2403-2.
- [22] S. C. Das *et al.*, “Effect of stacking sequence on the performance of hybrid natural/synthetic fiber reinforced polymer composite laminates,” *Compos. Struct.*, vol. 276, p. 114525, Nov. 2021, doi: 10.1016/j.compstruct.2021.114525.
- [23] M. Kamruzzaman and S. Alam, “Influence of stacking sequence on the mechanical properties of banana-glass fiber hybrid laminates for automotive shells,” *Heliyon*, vol. 10, no. 21, p. e40130, Nov. 2024, doi: 10.1016/j.heliyon.2024.e40130.
- [24] V. Ramesh, K. Karthik, R. Cep, and M. Elangovan, “Influence of Stacking Sequence on Mechanical Properties of Basalt/Ramie Biodegradable Hybrid Polymer Composites,” *Polymers*, vol. 15, no. 4, p. 985, Feb. 2023, doi: 10.3390/polym15040985.
- [25] P. Kumaravelu, J. Kandasamy, S. Kailasamani, and U. T. G. Pillai, “Effect of stacking sequence on the mechanical and tribological properties of hybrid natural fibers composites reinforced with nano-hBN and steel mesh,” *Emergent Mater.*, vol. 8, no. 1, pp. 913–931, Jan. 2025, doi: 10.1007/s42247-024-00894-9.
- [26] M. May, S. Kilchert, and T. Gerster, “A Modified Compact Tension Test for Characterization of the Intralaminar Fracture Toughness of Tri-Axial Braided Composites,” *Materials*, vol. 14, no. 17, p. 4890, Aug. 2021, doi: 10.3390/ma14174890.
- [27] 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.

- [28] G. Pappas and J. Botsis, "Intralaminar fracture of unidirectional carbon/epoxy composite: experimental results and numerical analysis," *Int. J. Solids Struct.*, vol. 85–86, pp. 114–124, May 2016, doi: 10.1016/j.ijsolstr.2016.02.007.
- [29] D. Dalli, G. Catalanotti, L. F. Varandas, B. G. Falzon, and S. Foster, "Mode I intralaminar fracture toughness of 2D woven carbon fibre reinforced composites: A comparison of stable and unstable crack propagation techniques," *Eng. Fract. Mech.*, vol. 214, pp. 427–448, Jun. 2019, doi: 10.1016/j.engfracmech.2019.04.003.
- [30] S. Gouda *et al.*, "Crack suppression by natural fiber integration for improved interlaminar fracture toughness in fiber hybrid composites," *Frat. Ed Integrità Strutt.*, vol. 16, no. 60, pp. 158–173, Mar. 2022, doi: 10.3221/IGF-ESIS.60.12.
- [31] R. Neto, B. Mendes, B. Borges, C. Moreira, E. Sampaio, and M. Banea, "Assessment of Shear Fracture Energy in Hybrid Composites with Natural and Synthetic Fibers," *Materials*, vol. 17, no. 15, p. 3794, Aug. 2024, doi: 10.3390/ma17153794.
- [32] J. O. Olusanya, T. P. Mohan, and K. Kanny, "Fracture toughness of hybrid natural fiber/nanoclay reinforced starch biocomposite material," *Compos. Adv. Mater.*, vol. 32, p. 26349833231188980, Jan. 2023, doi: 10.1177/26349833231188980.
- [33] Z. Zhang *et al.*, "Numerical and experimental investigation of silk/carbon hybrid composites: Mechanical properties and progressive damage," *Compos. Sci. Technol.*, vol. 277, p. 111523, Apr. 2026, doi: 10.1016/j.compscitech.2026.111523.
- [34] P. Madhavi *et al.*, "Experimental investigation of flexural strength and plane strain fracture toughness of carbon/silk fabric epoxy hybrid composites," *J. Mech. Behav. Mater.*, vol. 33, no. 1, p. 20240016, Nov. 2024, doi: 10.1515/jmbm-2024-0016.
- [35] G. T. Truong, H. V. Tran, and K.-K. Choi, "Investigation on Mode I Fracture Toughness of Woven Carbon Fiber-Reinforced Polymer Composites Incorporating Nanomaterials," *Polymers*, vol. 12, no. 11, p. 2512, Oct. 2020, doi: 10.3390/polym12112512.
- [36] W. G. Tilson, "ASTM E399 Standard Development – Analysis Method".
- [37] S. T. Pinho, P. Robinson, and L. Iannucci, "Fracture toughness of the tensile and compressive fibre failure modes in laminated composites," *Compos. Sci. Technol.*, vol. 66, no. 13, pp. 2069–2079, Oct. 2006, doi: 10.1016/j.compscitech.2005.12.023.
- [38] N. Blanco, D. Trias, S. T. Pinho, and P. Robinson, "Intralaminar fracture toughness characterisation of woven composite laminates. Part I: Design and analysis of a compact tension (CT) specimen," *Eng. Fract. Mech.*, vol. 131, pp. 349–360, Nov. 2014, doi: 10.1016/j.engfracmech.2014.08.012.
- [39] N. Blanco, D. Trias, S. T. Pinho, and P. Robinson, "Intralaminar fracture toughness characterisation of woven composite laminates. Part II: Experimental characterisation," *Eng. Fract. Mech.*, vol. 131, pp. 361–370, Nov. 2014, doi: 10.1016/j.engfracmech.2014.08.011.
- [40] D20 Committee, *Test Methods for Plane-Strain Fracture Toughness and Strain Energy Release Rate of Plastic Materials*. doi: 10.1520/D5045-99R07E01.
- [41] T. Sathishkumar, S. Satheeshkumar, and J. Naveen, "Glass fiber-reinforced polymer composites – a review," *J. Reinf. Plast. Compos.*, vol. 33, no. 13, pp. 1258–1275, Jul. 2014, doi: 10.1177/0731684414530790.
- [42] D. K. Rajak, P. H. Wagh, and E. Linul, "Manufacturing Technologies of Carbon/Glass Fiber-Reinforced Polymer Composites and Their Properties: A Review," *Polymers*, vol. 13, no. 21, p. 3721, Oct. 2021, doi: 10.3390/polym13213721.
- [43] S. Z. Hussain *et al.*, "Glass fibers for advanced composites: Manufacturing, surface engineering, performance-driven selection and future direction," *Mater. Today Commun.*, vol. 54, p. 115479, Jun. 2026, doi: 10.1016/j.mtcomm.2026.115479.

- [44] P. Morampudi, K. K. Namala, Y. K. Gajjela, M. Barath, and G. Prudhvi, "Review on glass fiber reinforced polymer composites," *Mater. Today Proc.*, vol. 43, pp. 314–319, 2021, doi: 10.1016/j.matpr.2020.11.669.
- [45] R. M. Iqbal, R. Ahammad, M. Arifuzzaman, M. S. Islam, and M. M. Islam, "Manufacturing and Properties of Jute Fiber-Reinforced Polymer Composites—A Comprehensive Review," *Materials*, vol. 18, no. 5, p. 1016, Feb. 2025, doi: 10.3390/ma18051016.
- [46] P. Madhu, J. Praveenkumara, M. R. Sanjay, S. Siengchin, and S. Gorbatyuk, "Introduction to bio-based fibers and their composites," in *Advances in Bio-Based Fiber*, Elsevier, 2022, pp. 1–20. doi: 10.1016/B978-0-12-824543-9.00014-1.
- [47] Z. Ahmed, . Md. S. H., . F. A., and . M. B., "Study of the Chemical Composition of Different Pipeline Varieties of Jute Fibres," *Pak. J. Biol. Sci.*, vol. 6, no. 16, pp. 1463–1467, Aug. 2003, doi: 10.3923/pjbs.2003.1463.1467.
- [48] PatSnap Eureka, "Jute Fiber Natural Fiber: Comprehensive Analysis of Properties, Processing, and Advanced Applications in Sustainable Composites," PatSnap Eureka. [Online]. Available: https://eureka.patsnap.com/materials/jute-fiber-composites?utm_source=chatgpt.com
- [49] PatSnap Eureka, "Jute Fiber Woven Material: Comprehensive Analysis of Properties, Manufacturing Processes, and Advanced Engineering Applications," PatSnap Eureka. [Online]. Available: <https://eureka.patsnap.com/materials/jute-fiber-woven-material>
- [50] M. E. Alves Fidelis, T. V. C. Pereira, O. D. F. M. Gomes, F. De Andrade Silva, and R. D. Toledo Filho, "The effect of fiber morphology on the tensile strength of natural fibers," *J. Mater. Res. Technol.*, vol. 2, no. 2, pp. 149–157, Apr. 2013, doi: 10.1016/j.jmrt.2013.02.003.
- [51] A. Majumder, F. Stochino, I. Farina, M. Valdes, F. Fraternali, and E. Martinelli, "Physical and mechanical characteristics of raw jute fibers, threads and diatons," *Constr. Build. Mater.*, vol. 326, p. 126903, Apr. 2022, doi: 10.1016/j.conbuildmat.2022.126903.
- [52] S. Shahinur, M. M. A. Sayeed, M. Hasan, A. S. M. Sayem, J. Haider, and S. Ura, "Current Development and Future Perspective on Natural Jute Fibers and Their Biocomposites," *Polymers*, vol. 14, no. 7, p. 1445, Apr. 2022, doi: 10.3390/polym14071445.
- [53] B. S. Keerthi Gowda, B. E. Megha, G. L. E. Prasad, R. Abhishek, and R. Velmurugan, "A Study on Tensile Strength Attributes of Jute Fiber-Reinforced Polyester Composite," in *Dynamic Behavior of Soft and Hard Materials, Volume 3*, vol. 36, R. Velmurugan, G. Balaganesan, N. Kakur, and K. Kanny, Eds., in Springer Proceedings in Materials, vol. 36. , Singapore: Springer Nature Singapore, 2024, pp. 75–97. doi: 10.1007/978-981-99-6259-4_8.
- [54] A. S. Virk, W. Hall, and J. Summerscales, "Modelling tensile properties of jute fibres," *Mater. Sci. Technol.*, vol. 27, no. 1, pp. 458–460, Jan. 2011, doi: 10.1179/026708309X12578491814636.
- [55] Md. S. Rana *et al.*, "Morphological, Spectroscopic and Thermal Analysis of Cellulose Nanocrystals Extracted from Waste Jute Fiber by Acid Hydrolysis," *Polymers*, vol. 15, no. 6, p. 1530, Mar. 2023, doi: 10.3390/polym15061530.
- [56] Most. S. Begum, M. Hummel, S. Mandal, S. Mahmood, Md. R. Repon, and R. Milašius, "Thermal Degradation and Chemical Analysis of Flame-Retardant-Treated Jute Fabrics," *Polymers*, vol. 16, no. 14, p. 2049, Jul. 2024, doi: 10.3390/polym16142049.
- [57] V. Lakshmi Narayana and L. Bhaskara Rao, "A brief review on the effect of alkali treatment on mechanical properties of various natural fiber reinforced polymer

- composites,” *Mater. Today Proc.*, vol. 44, pp. 1988–1994, 2021, doi: 10.1016/j.matpr.2020.12.117.
- [58] S. A. Rafiqah, N. Abdullah, K. Abdan, M. H. M. Roslim, and M. N. Radzuan, “Influence of Alkali Treatment on Mechanical, Physical, Thermal and Morphological Properties of Kenaf Fiber/Polyamide 6 Composites,” *J. Nat. Fibers*, vol. 22, no. 1, p. 2515468, Dec. 2025, doi: 10.1080/15440478.2025.2515468.
- [59] M. Z. Hassan *et al.*, “Mercerization Optimization of Bamboo (*Bambusa vulgaris*) Fiber-Reinforced Epoxy Composite Structures Using a Box–Behnken Design,” *Polymers*, vol. 12, no. 6, p. 1367, Jun. 2020, doi: 10.3390/polym12061367.
- [60] J. Hindi, K. Muralishwara, and B. M. Gurumurthy, “Comparative analysis of physical, morphological, tensile and thermal stability characteristics of raw and alkali treated novel *Tinospora cordifolia* natural fiber,” *Sci. Rep.*, vol. 15, no. 1, p. 18596, May 2025, doi: 10.1038/s41598-025-03627-y.
- [61] T. Kadire and S. N. Joshi, “Effects of alkaline treatment and manufacturing process on mechanical and absorption properties of Wild Abyssinia Banana fiber reinforced epoxy composite,” *Mater. Today Proc.*, vol. 98, pp. 212–218, 2024, doi: 10.1016/j.matpr.2023.11.045.
- [62] A. Gopinath, M. S. Kumar, and A. Elayaperumal, “Experimental Investigations on Mechanical Properties Of Jute Fiber Reinforced Composites with Polyester and Epoxy Resin Matrices,” *Procedia Eng.*, vol. 97, pp. 2052–2063, 2014, doi: 10.1016/j.proeng.2014.12.448.
- [63] T. N. Babu, S. Singh, D. R. Prabha, S. Mishra, and V. Pandey, “Mechanical, machinability and water absorption properties of novel kenaf fiber, glass fiber and graphene composites reinforced with epoxy,” *Sci. Rep.*, vol. 14, no. 1, p. 29955, Dec. 2024, doi: 10.1038/s41598-024-81314-0.
- [64] H. Sreenivas, N. Krishnamurthy, M. Murali, and G. Arpitha, “Influence of stacking sequence and orientation of the fabric on mechanical properties of twill Kenaf/Kevlar reinforced unsaturated polyester hybrid composites,” *J. Ind. Text.*, vol. 51, no. 8, pp. 1330–1351, Mar. 2022, doi: 10.1177/15280837211019901.
- [65] G. Marom, S. Fischer, F. R. Tuler, and H. D. Wagner, “Hybrid effects in composites: conditions for positive or negative effects versus rule-of-mixtures behaviour,” *J. Mater. Sci.*, vol. 13, no. 7, pp. 1419–1426, Jul. 1978, doi: 10.1007/BF00553194.
- [66] M. G. Phillips, “Composition parameters for hybrid composite materials,” *Composites*, vol. 12, no. 2, pp. 113–116, Apr. 1981, doi: 10.1016/0010-4361(81)90417-1.
- [67] S. F. Zhafer, A. R. Rozyanty, S. B. S. Shahnaz, L. Musa, and A. Zuliahani, “Kenaf-glass fiber reinforced unsaturated polyester hybrid composites: Tensile properties,” presented at the THE 2ND INTERNATIONAL CONFERENCE ON FUNCTIONAL MATERIALS AND METALLURGY (ICoFM 2016), Penang, Malaysia, 2016, p. 040009. doi: 10.1063/1.4958770.
- [68] A. B. M. Supian *et al.*, “Kenaf/glass fiber-reinforced polymer composites: Pioneering sustainable materials with enhanced mechanical and tribological properties,” *Polym. Compos.*, vol. 45, no. 16, pp. 14421–14447, Nov. 2024, doi: 10.1002/pc.28785.
- [69] V. Dinesh, H. K. Shivanand, H. N. Vidyasagar, and V. S. Chari, “Investigation of mechanical properties of kenaf, hemp and E-glass fiber reinforced composites,” presented at the ADVANCES IN MECHANICAL DESIGN, MATERIALS AND MANUFACTURE: Proceedings of the First International Conference on Design, Materials and Manufacture (ICDEM 2018), Karnataka, India, 2018, p. 020117. doi: 10.1063/1.5029693.

- [70] M. A. Jaafar, S. A. Abdullah, A. Jumahat, M. A. Muslim, N. Sapiai, and R. S. Teng Loy, "Effect of stacking sequence on tensile properties of glass, hemp and kenaf hybrid composites," *Phys. Sci. Rev.*, vol. 9, no. 1, pp. 95–105, Jan. 2024, doi: 10.1515/psr-2022-0052.
- [71] J. K. Fink, "Unsaturated Polyester Resins," in *Reactive Polymers Fundamentals and Applications*, Elsevier, 2013, pp. 1–48. doi: 10.1016/B978-1-4557-3149-7.00001-2.
- [72] M. R. Karthika, A. Deb, and G. S. Venkatesh, "An investigation into mechanical properties of jute–polyester laminates for numerical prediction of strength and failure," *Polym. Compos.*, vol. 42, no. 11, pp. 5975–5999, Nov. 2021, doi: 10.1002/pc.26278.
- [73] L. Krishnan, B. K. Kandola, D. Deli, and J. R. Ebdon, "Thermal Stability, Flammability and Mechanical Performances of Unsaturated Polyester–Melamine Resin Blends and of Glass Fibre-Reinforced Composites Based on Them," *Polymers*, vol. 14, no. 22, p. 4885, Nov. 2022, doi: 10.3390/polym14224885.
- [74] A. Deb, S. Das, A. Mache, and R. Laishram, "A Study on the Mechanical Behaviors of Jute-polyester Composites," *Procedia Eng.*, vol. 173, pp. 631–638, 2017, doi: 10.1016/j.proeng.2016.12.120.
- [75] X. Fu, X. Wang, J. Zhu, and M. Chen, "Long Chopped Glass Fiber Reinforced Low-Density Unsaturated Polyester Resin under Different Initiation," *Materials*, vol. 14, no. 23, p. 7307, Nov. 2021, doi: 10.3390/ma14237307.
- [76] A. Barakat *et al.*, "Development of a Cure Model for Unsaturated Polyester Resin Systems Based on Processing Conditions," *Polymers*, vol. 16, no. 17, p. 2391, Aug. 2024, doi: 10.3390/polym16172391.
- [77] R. Baghloul, L. Babouri, H. Hebhouh, F. Boukhelf, and Y. El Mendili, "Assessment of Mechanical Behavior and Microstructure of Unsaturated Polyester Resin Composites Reinforced with Recycled Marble Waste," *Buildings*, vol. 14, no. 12, p. 3877, Dec. 2024, doi: 10.3390/buildings14123877.
- [78] G. Rizzo *et al.*, "Enhancing Sustainability in Unsaturated Polyester Resin: A Way to Use Biobased Curing Agents for Reduced Styrene Content and Improved Recyclability Properties," *ACS Appl. Polym. Mater.*, vol. 6, no. 10, pp. 5714–5725, May 2024, doi: 10.1021/acsapm.4c00388.
- [79] Y. Dobah, M. Bouchak, A. Bezazi, A. Belaadi, and F. Scarpa, "Multi-axial mechanical characterization of jute fiber/polyester composite materials," *Compos. Part B Eng.*, vol. 90, pp. 450–456, Apr. 2016, doi: 10.1016/j.compositesb.2015.10.030.
- [80] T. Prabhuram, S. Prathap Singh, D. Elil Raja, J. Immanuel Durairaj, M. Chrispin Das, and P. Ravichandran, "Development and mechanical characterization of jute fibre and multi-walled carbon nanotube-reinforced unsaturated polyester resin composite," *Mater. Today Proc.*, p. S2214785323045832, Aug. 2023, doi: 10.1016/j.matpr.2023.08.302.
- [81] I. El-Sagheer, A. A. Abd-Elhady, H. E.-D. M. Sallam, and S. A. R. Naga, "An Assessment of ASTM E1922 for Measuring the Translaminar Fracture Toughness of Laminated Polymer Matrix Composite Materials," *Polymers*, vol. 13, no. 18, p. 3129, Sep. 2021, doi: 10.3390/polym13183129.
- [82] D30 Committee, *Test Method for Translaminar Fracture Toughness of Laminated and Pultruded Polymer Matrix Composite Materials*. doi: 10.1520/E1922-04R15.
- [83] A. Ghadirdokht and M. Heidari-Rarani, "Delamination R-curve behavior of curved composite laminates," *Compos. Part B Eng.*, vol. 175, p. 107139, Oct. 2019, doi: 10.1016/j.compositesb.2019.107139.

- [84] 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.
- [85] A. Szekrényes and J. Uj, "Advanced beam model for fiber-bridging in unidirectional composite double-cantilever beam specimens," *Eng. Fract. Mech.*, vol. 72, no. 17, pp. 2686–2702, Nov. 2005, doi: 10.1016/j.engfracmech.2005.05.001.
- [86] G. B. Murri, "Effect of data reduction and fiber-bridging on Mode I delamination characterization of unidirectional composites," *J. Compos. Mater.*, vol. 48, no. 19, pp. 2413–2424, Aug. 2014, doi: 10.1177/0021998313498791.
- [87] A. Pirondi, G. Giuliese, F. Moroni, A. Bernasconi, and A. Jamil, "Comparative Study of Cohesive Zone and Virtual Crack Closure Techniques for Three-Dimensional Fatigue Debonding," *J. Adhes.*, vol. 90, no. 5–6, pp. 457–481, Jun. 2014, doi: 10.1080/00218464.2013.859616.
- [88] A. Raimondo, "Numerical Investigation of the R-Curve Effect in Delamination of Composite Materials Using Cohesive Elements," *Appl. Sci.*, vol. 14, no. 6, p. 2535, Mar. 2024, doi: 10.3390/app14062535.
- [89] H. Ben Gur and L. Banks-Sills, "Evaluation of the effect of fiber bridging on mode I quasi-static testing," *Fatigue Fract. Eng. Mater. Struct.*, vol. 46, no. 4, pp. 1357–1374, Apr. 2023, doi: 10.1111/ffe.13930.
- [90] M. Heidari-Rarani and M. Sayedain, "Finite element modeling strategies for 2D and 3D delamination propagation in composite DCB specimens using VCCT, CZM and XFEM approaches," *Theor. Appl. Fract. Mech.*, vol. 103, p. 102246, Oct. 2019, doi: 10.1016/j.tafmec.2019.102246.
- [91] M. Zhao, S. Wang, Z. Liu, Z. Chang, Z. Wang, and Y. Kang, "A semi-analytical method for determining the mode-I delamination R-curve and fiber bridging traction-separation law of Double-double laminates," *Thin-Walled Struct.*, vol. 205, p. 112383, Dec. 2024, doi: 10.1016/j.tws.2024.112383.
- [92] Z. Chen, Y. Dai, and Y. Liu, "Structural fatigue crack propagation simulation and life prediction based on improved XFEM-VCCT," *Eng. Fract. Mech.*, vol. 310, p. 110519, Nov. 2024, doi: 10.1016/j.engfracmech.2024.110519.
- [93] H.-G. Kim, R. Howe, R. Wiebe, S. M. Spottswood, P. J. O'Hara, and M. Salviato, "Experimental characterization of cohesive laws for mode-II interlaminar fracture in geometrically scaled composites using through-thickness deformation analysis," *Eng. Fract. Mech.*, vol. 326, p. 111361, Sep. 2025, doi: 10.1016/j.engfracmech.2025.111361.
- [94] A. K. Salve and S. N. Jalwadi, "Implementation of Cohesive Zone in ABAQUS to Investigate Fracture Problems".
- [95] Y. Navidtehrani, C. Betegón, and E. Martínez-Pañeda, "A simple and robust Abaqus implementation of the phase field fracture method," Apr. 16, 2021, *arXiv*: arXiv:2104.08132. doi: 10.48550/arXiv.2104.08132.
- [96] E. S. Greenhalgh, Ed., *Failure analysis and fractography of polymer composites*. in Woodhead Publishing in materials. Cambridge: Woodhead Pub, 2009.
- [97] M. M. Azad, A. U. R. Shah, M. N. Prabhakar, and H. S. Kim, "Deep Learning-Based Microscopic Damage Assessment of Fiber-Reinforced Polymer Composites," *Materials*, vol. 17, no. 21, p. 5265, Oct. 2024, doi: 10.3390/ma17215265.
- [98] K. Giridharan, B. Elumalai, M. Vinothkumar, G. Chakravarthi, D. Manikandan, and K. Ramaswamy, "Investigation of dry sliding wear and mechanical properties of hybrid epoxy composites reinforced with pineapple leaf and roselle fibers," *Sci. Rep.*, vol. 15, no. 1, p. 27991, Jul. 2025, doi: 10.1038/s41598-025-10431-1.

- [99] S. S. Salins, S. Shetty, and H. K. Sachidananda, "Investigating energy absorption and crack propagation in natural rubber–epoxy composites: design, fabrication, and fracture analysis," *Polym. Bull.*, vol. 82, no. 11, pp. 5463–5491, Jul. 2025, doi: 10.1007/s00289-025-05738-y.
- [100] S. N. A. B. Safri, M. T. H. Sultan, and M. Jawaid, "Damage analysis of glass fiber reinforced composites," in *Durability and Life Prediction in Biocomposites, Fibre-Reinforced Composites and Hybrid Composites*, Elsevier, 2019, pp. 133–147. doi: 10.1016/B978-0-08-102290-0.00007-6.
- [101] "60-IJMET_07_03_017.pdf."
- [102] M. Sakai, R. Matsuyama, and T. Miyajima, "The pull-out and failure of a fiber bundle in a carbon fiber reinforced carbon matrix composite," *Carbon*, vol. 38, no. 15, pp. 2123–2131, 2000, doi: 10.1016/S0008-6223(00)00067-1.
- [103] J. K. Morrison, S. P. Shah, and Y. Jenq, "Analysis of Fiber Debonding and Pullout in Composites," *J. Eng. Mech.*, vol. 114, no. 2, pp. 277–294, Feb. 1988, doi: 10.1061/(ASCE)0733-9399(1988)114:2(277).
- [104] K. G. Dassios, "A Review of the Pull-Out Mechanism in the Fracture of Brittle-Matrix Fibre-Reinforced Composites," *Adv. Compos. Lett.*, vol. 16, no. 1, p. 096369350701600102, Jan. 2007, doi: 10.1177/096369350701600102.
- [105] S. Rudraraju, A. Salvi, K. Garikipati, and A. M. Waas, "In-Plane fracture of laminated fiber reinforced composites with varying fracture resistance: experimental observations and numerical crack propagation simulations," *Int. J. Solids Struct.*, vol. 47, no. 7–8, pp. 901–911, Apr. 2010, doi: 10.1016/j.ijsolstr.2009.12.006.
- [106] F. E. Silva, L. L. Goncalves, D. B. B. Fereira, and J. M. A. Rebello, "Characterization of Failure Mechanism in Composite Materials Through Fractal Analysis of Acoustic Emission Signals," *Chaos Solitons Fractals*, vol. 26, no. 2, pp. 481–494, Oct. 2005, doi: 10.1016/j.chaos.2004.12.042.
- [107] T. J. Pramanik, Md. Rafiquzzaman, A. Karmakar, M. H. Nayeem, S. M. K. S. Turjo, and Md. R. Abid, "Evaluation of mechanical properties of natural fiber based polymer composite," *BenchCouncil Trans. Benchmarks Stand. Eval.*, vol. 4, no. 3, p. 100183, Sep. 2024, doi: 10.1016/j.tbench.2024.100183.
- [108] S. C. Das *et al.*, "Effect of stacking sequence on the performance of hybrid natural/synthetic fiber reinforced polymer composite laminates," *Compos. Struct.*, vol. 276, p. 114525, Nov. 2021, doi: 10.1016/j.compstruct.2021.114525.
- [109] A. Gupta, S. M. Shohel, M. Singh, and J. Singh, "Study on mechanical properties of natural fiber (Jute)/synthetic fiber (Glass) reinforced polymer hybrid composite by representative volume element using finite element analysis: A numerical approach and validated by experiment," *Hybrid Adv.*, vol. 6, p. 100239, Aug. 2024, doi: 10.1016/j.hybadv.2024.100239.
- [110] A. M. Sadoun *et al.*, "Effect of functionalization of graphene nanoplatelets on the mechanical response of hybrid graphene-fiber reinforced epoxy laminates," *J. Mater. Res. Technol.*, vol. 42, pp. 6271–6290, May 2026, doi: 10.1016/j.jmrt.2026.04.221.
- [111] "P. C. Paris and G. C. Sih.pdf."
- [112] S. C. Das *et al.*, "Effect of stacking sequence on the performance of hybrid natural/synthetic fiber reinforced polymer composite laminates," *Compos. Struct.*, vol. 276, p. 114525, Nov. 2021, doi: 10.1016/j.compstruct.2021.114525.
- [113] M. A. Altaee and N. H. Mostafa, "Mechanical properties of interply and intraply hybrid laminates based on jute-glass/epoxy composites," *J. Eng. Appl. Sci.*, vol. 70, no. 1, p. 121, Dec. 2023, doi: 10.1186/s44147-023-00293-7.
- [114] A. Gupta, S. M. Shohel, M. Singh, and J. Singh, "Study on mechanical properties of natural fiber (Jute)/synthetic fiber (Glass) reinforced polymer hybrid composite by

- representative volume element using finite element analysis: A numerical approach and validated by experiment,” *Hybrid Adv.*, vol. 6, p. 100239, Aug. 2024, doi: 10.1016/j.hybadv.2024.100239.
- [115] H. Herranen *et al.*, “Design and Testing of Sandwich Structures with Different Core Materials,” *Mater. Sci.*, vol. 18, no. 1, pp. 45–50, Mar. 2012, doi: 10.5755/j01.ms.18.1.1340.
- [116] T. Sathishkumar, S. Satheeshkumar, and J. Naveen, “Glass fiber-reinforced polymer composites – a review,” *J. Reinf. Plast. Compos.*, vol. 33, no. 13, pp. 1258–1275, Jul. 2014, doi: 10.1177/0731684414530790.

APPENDIXES

A Python code for determining the Normalised energy release rate

```
#####
######
#Normalized Energy Release Rate Analysis of 2TCT Specimen#
#####
######
#=====
#=====#
#Preparation
#=====
#=====#
from abaqus import *
from abaqusConstants import *
session.viewports['Viewport: 1'].makeCurrent()
session.viewports['Viewport: 1'].maximize()
from caeModules import *
from driverUtils import executeOnCaeStartup
executeOnCaeStartup()
Mdb ()
import os
os.chdir(r"C:\Temporary")
s = mdb.models['Model-1'].ConstrainedSketch(name='__profile__',
    sheetSize=200.0)
g, v, d, c = s.geometry, s.vertices, s.dimensions, s.constraints
s.setPrimaryObject(option=STANDALONE)
#=====
#=====#
#Parameters#
#=====
#=====#
#Crack Length
Csize = 19.0
#Material Properties
E1 = 3260.0
E2 = 3260.0
Nu = 0.32
G12 = 1460.0
G13 = 1460.0
G23 = 1460.0
#Mesh Size Factors
MAXsize = 1.0
MINsize = 0.2
#=====
#=====#
#Part Module#
#=====
#=====#
```

```

#Sketch the Geometry
s.Line(point1=(0.0, 0.0), point2=(Csize, 0.0))
s.HorizontalConstraint(entity=g[2], addUndoState=False)
s.Line(point1=(Csize, 0.0), point2=(76.0, 0.0))
s.HorizontalConstraint(entity=g[3], addUndoState=False)
s.ParallelConstraint(entity1=g[2], entity2=g[3], addUndoState=False)
s.Line(point1=(76.0, 0.0), point2=(76.0, 20.0))
s.VerticalConstraint(entity=g[4], addUndoState=False)
s.PerpendicularConstraint(entity1=g[3], entity2=g[4], addUndoState=False)
s.Line(point1=(76.0, 20.0), point2=(56.0, 35.0))
s.Line(point1=(56.0, 35.0), point2=(6.0, 35.0))
s.HorizontalConstraint(entity=g[6], addUndoState=False)
s.Line(point1=(6.0, 35.0), point2=(-14.0, 20.0))
s.Line(point1=(-14.0, 20.0), point2=(-14.0, 0.0))
s.VerticalConstraint(entity=g[8], addUndoState=False)
s.Line(point1=(-14.0, 0.0), point2=(0.0, 0.0))
s.HorizontalConstraint(entity=g[9], addUndoState=False)
s.PerpendicularConstraint(entity1=g[8], entity2=g[9], addUndoState=False)
s.CircleByCenterPerimeter(center=(0.0, 13.0), point1=(0.0, 17.0))
#Create 3D, Deformable, Shell Planar Part
p = mdb.models['Model-1'].Part(name='Part-1', dimensionality=THREE_D,
    type=DEFORMABLE_BODY)
p = mdb.models['Model-1'].parts['Part-1']
p.BaseShell(sketch=s)
s.unsetPrimaryObject()
p = mdb.models['Model-1'].parts['Part-1']
session.viewports['Viewport: 1'].setValues(displayedObject=p)
del mdb.models['Model-1'].sketches['__profile__']
#Create Set 'CrackTip', 'SymmetricLine', and 'EndConstraintPoint'
session.viewports['Viewport: 1'].setValues(displayedObject=None)
p = mdb.models['Model-1'].parts['Part-1']
v = p.vertices
verts = v.getSequenceFromMask(mask=(['#8 '], ), )
p.Set(vertices=verts, name='CrackTip')
p = mdb.models['Model-1'].parts['Part-1']
e = p.edges
edges = e.getSequenceFromMask(mask=(['#8 '], ), )
p.Set(edges=edges, name='SymmetricLine')
p = mdb.models['Model-1'].parts['Part-1']
v = p.vertices
verts = v.getSequenceFromMask(mask=(['#10 '], ), )
p.Set(vertices=verts, name='EndConstraintPoint')
#Create the Set 'LoadingPoint'
p = mdb.models['Model-1'].parts['Part-1']
session.viewports['Viewport: 1'].setValues(displayedObject=p)
p = mdb.models['Model-1'].parts['Part-1']
v = p.vertices
verts = v.getSequenceFromMask(mask=(['#1 '], ), )
p.Set(vertices=verts, name='LoadingPoint')

```

```

=====
#####
#Property Module                                     #
=====
#####
#Set Material Property
mdb.models['Model-1'].Material(name='Material-1')
mdb.models['Model-1'].materials['Material-1'].Elastic(type=LAMINA, table=((
    E1, E2, Nu, G12, G13, G23), ))
#Section Creation and Assignment
mdb.models['Model-1'].HomogeneousShellSection(name='Section-1',
    preIntegrate=OFF, material='Material-1', thicknessType=UNIFORM,
    thickness=1.0, thicknessField="", nodalThicknessField="",
    idealization=NO_IDEALIZATION, poissonDefinition=DEFAULT,
    thicknessModulus=None, temperature=GRADIENT, useDensity=OFF,
    integrationRule=SIMPSON, numIntPts=3)
p = mdb.models['Model-1'].parts['Part-1']
f = p.faces
faces = f.getSequenceFromMask(mask=('[#1 ]', ), )
region = regionToolset.Region(faces=faces)
p = mdb.models['Model-1'].parts['Part-1']
p.SectionAssignment(region=region, sectionName='Section-1', offset=0.0,
    offsetType=MIDDLE_SURFACE, offsetField="",
    thicknessAssignment=FROM_SECTION)
=====
#####
#Assembly Module                                     #
=====
#####
a = mdb.models['Model-1'].rootAssembly
a.DatumCsysByDefault(CARTESIAN)
p = mdb.models['Model-1'].parts['Part-1']
a.Instance(name='Part-1-1', part=p, dependent=OFF)
=====
#####
#Interaction Module                                   #
=====
#####
a = mdb.models['Model-1'].rootAssembly
session.viewports['Viewport: 1'].setValues(displayedObject=a)
session.viewports['Viewport: 1'].assemblyDisplay.setValues(interactions=ON,
    constraints=ON, connectors=ON, engineeringFeatures=ON)
a = mdb.models['Model-1'].rootAssembly
crackFront = a.instances['Part-1-1'].sets['CrackTip']
a = mdb.models['Model-1'].rootAssembly
crackTip = a.instances['Part-1-1'].sets['CrackTip']
v11 = a.instances['Part-1-1'].vertices
v21 = a.instances['Part-1-1'].vertices
a.engineeringFeatures.ContourIntegral(name='Crack-1', symmetric=ON,
    crackFront=crackFront, crackTip=crackTip,

```

```

        extensionDirectionMethod=Q_VECTORS, qVectors=((v11[3], v21[4]), ),
        midNodePosition=0.5, collapsedElementAtTip=NONE)
=====
=====#
#Step Module                                                    #
=====
=====#
#Create 'LoadingStep'
mdb.models['Model-1'].StaticStep(name='Loading', previous='Initial')
session.viewports['Viewport: 1'].assemblyDisplay.setValues(step='Loading')
#Create 'History Output-1'
mdb.models['Model-1'].historyOutputRequests['H-Output-1'].setValues(
    frequency=LAST_INCREMENT,                                contourIntegral='Crack-1',
    sectionPoints=DEFAULT,
    rebar=EXCLUDE, numberOfContours=5)
=====
=====#
#Load Module                                                    #
=====
=====#
#Create 'BC-1' and 'BC-2'
a = mdb.models['Model-1'].rootAssembly
session.viewports['Viewport: 1'].setValues(displayedObject=a)
session.viewports['Viewport: 1'].assemblyDisplay.setValues(step='Initial')
a = mdb.models['Model-1'].rootAssembly
region = a.instances['Part-1-1'].sets['SymmetricLine']
mdb.models['Model-1'].YsymmBC(name='BC-1', createStepName='Initial',
    region=region, localCsys=None)
a = mdb.models['Model-1'].rootAssembly
region = a.instances['Part-1-1'].sets['EndConstraintPoint']
mdb.models['Model-1'].DisplacementBC(name='BC-2', createStepName='Initial',
    region=region, u1=SET, u2=UNSET, u3=UNSET, ur1=UNSET, ur2=UNSET,
    ur3=UNSET,
    amplitude=UNSET, distributionType=UNIFORM, fieldName="", localCsys=None)
session.viewports['Viewport: 1'].assemblyDisplay.setValues(step='Loading')
#Create 'Load-1' (concentrated load of 1N)
a = mdb.models['Model-1'].rootAssembly
region = a.instances['Part-1-1'].sets['LoadingPoint']
mdb.models['Model-1'].ConcentratedForce(name='Load-1',
    createStepName='Loading', region=region, cf2=1.0, distributionType=UNIFORM,
    field="", localCsys=None)
=====
=====#
#Mesh Module                                                    #
=====
=====#
a = mdb.models['Model-1'].rootAssembly
session.viewports['Viewport: 1'].setValues(displayedObject=a)
a = mdb.models['Model-1'].rootAssembly
f1 = a.instances['Part-1-1'].faces

```

```

pickedRegions = f1.getSequenceFromMask(mask=('[#1 ]', ), )
a.setMeshControls(regions=pickedRegions, elemShape=QUAD)
elemType1 = mesh.ElemType(elemCode=S8R5, elemLibrary=STANDARD)
elemType2 = mesh.ElemType(elemCode=STRI65, elemLibrary=STANDARD)
a = mdb.models['Model-1'].rootAssembly
f1 = a.instances['Part-1-1'].faces
faces1 = f1.getSequenceFromMask(mask=('[#1 ]', ), )
pickedRegions =(faces1, )
a.setElementType(regions=pickedRegions, elemTypes=(elemType1, elemType2))
a = mdb.models['Model-1'].rootAssembly
e1 = a.instances['Part-1-1'].edges
pickedEdges = e1.getSequenceFromMask(mask=('[#1f2 ]', ), )
a.seedEdgeBySize(edges=pickedEdges, size=MAXsize, deviationFactor=0.1,
    constraint=FINER)
a = mdb.models['Model-1'].rootAssembly
e1 = a.instances['Part-1-1'].edges
pickedEdges = e1.getSequenceFromMask(mask=('[#1 ]', ), )
a.seedEdgeBySize(edges=pickedEdges, size=MINsize, deviationFactor=0.1,
    constraint=FINER)
a = mdb.models['Model-1'].rootAssembly
e1 = a.instances['Part-1-1'].edges
pickedEdges2 = e1.getSequenceFromMask(mask=('[#4 ]', ), )
a.seedEdgeByBias(biasMethod=SINGLE, end2Edges=pickedEdges2, minSize=MINsize,
    maxSize=MAXsize, constraint=FINER)
a = mdb.models['Model-1'].rootAssembly
e1 = a.instances['Part-1-1'].edges
pickedEdges1 = e1.getSequenceFromMask(mask=('[#8 ]', ), )
a.seedEdgeByBias(biasMethod=SINGLE, end1Edges=pickedEdges1, minSize=MINsize,
    maxSize=MAXsize, constraint=FINER)
a = mdb.models['Model-1'].rootAssembly
partInstances =(a.instances['Part-1-1'], )
a.generateMesh(regions=partInstances)
#####
#####
#Job Module                                     #
#####
#Create Job Named 'J_study_G_a20' and Submit for Analysis
mdb.Job(name='J_study_G_a20', model='Model-1', description="", type=ANALYSIS,
    atTime=None, waitMinutes=0, waitHours=0, queue=None, memory=90,
    memoryUnits=PERCENTAGE, getMemoryFromAnalysis=True,
    explicitPrecision=SINGLE, nodalOutputPrecision=SINGLE, echoPrint=OFF,
    modelPrint=OFF, contactPrint=OFF, historyPrint=OFF, userSubroutine="",
    scratch="", resultsFormat=ODB, multiprocessingMode=DEFAULT, numCpus=1,
    numGPUs=0)
mdb.jobs['J_study_G_a20'].submit(consistencyChecking=OFF)
session.viewports['Viewport: 1'].view.fitView()

```

B. Data of the composite constituent

Pure jute

Laminate J(Jute)- J/J/J/J/J/J			
Constants	Values	Parameters	values
Total fiber volume fraction V_f	0..3	Density of composite, ρ (g/cm ³)	1.2780
Required jute fiber V_f	0.3	Mass of composite, m (g)	357.84
Required glass fiber V_f	0	Volume of jute fiber (cm ³)	84
Required relative jute:glass V_f	1	Volume of glass fiber (cm ³)	0
Density of jute fiber, ρ_J (g/cm ³)	1.46	Volume of polyurethane (cm ³)	196
Density of glass fiber, ρ_f (g/cm ³)	2.54	Mass of jute fiber, m_J (g)	122.64
Density of polyester, ρ_m (g/cm ³)	1.2	Mass of glass fiber, m_g (g)	0
Volume of composite, V (cm ³)	280	Mass of polyester, m_p	235.2
		Jute fiber wt%	0.3427
		Glass fiber wt%	0
		Relative jute:glass wt%	1

Hybrid Jute/Glass (H1)

Laminate H1- G/G/J/J/J/G/G			
Constants	Values	Parameters	values
Total fiber volume fraction V_f	0..3	Density of composite, ρ (g/cm ³)	1.4616
Required jute fiber V_f	0.13	Mass of composite, m (g)	409.25
Required glass fiber V_f	0.17	Volume of jute fiber (cm ³)	36.4
Required relative jute:glass V_f	0.433	Volume of glass fiber (cm ³)	47.6
Density of jute fiber, ρ_J (g/cm ³)	1.46	Volume of polyurethane (cm ³)	196
Density of glass fiber, ρ_f (g/cm ³)	2.54	Mass of jute fiber, m_J (g)	53.144
Density of polyester, ρ_m (g/cm ³)	1.2	Mass of glass fiber, m_g (g)	120.904
Volume of composite, V (cm ³)	280	Mass of polyester, m_p	235.2
		Jute fiber wt%	0.1299
		Glass fiber wt%	0.2954
		Relative jute:glass wt%	0.3053

Hybrid Jute/Glass (H2)

Laminate H2- G/G/J/G/J/G/G			
Constants	Values	Parameters	Values
Total fiber volume fraction V_f	0..3	Density of composite, ρ (g/cm ³)	1.5102
Required jute fiber V_f	0.085	Mass of composite, m (g)	422.86
Required glass fiber V_f	0.215	Volume of jute fiber (cm ³)	23.8
Required relative jute:glass V_f	0.2833	Volume of glass fiber (cm ³)	60.2
Density of jute fiber, ρ_J (g/cm ³)	1.46	Volume of polyurethane (cm ³)	196

Density of glass fiber, ρ_f (g/cm ³)	2.54	Mass of jute fiber, m_j (g)	34.748
Density of polyester, ρ_m (g/cm ³)	1.052(1.39)	Mass of glass fiber, m_g (g)	152.91
Volume of composite, V (cm ³)	280	Mass of polyester, m_p	235.2
		Jute fiber wt%	0.0822
		Glass fiber wt%	0.3616
		Relative jute:glass wt%	0.1852

C. Normalized Energy Release Rate Values (α) (m²/kJ) for values of the crack length a ranging from 19 – 64 mm

Laminate J (J/J/J/J/J/J)							
a	19	20	21	22	23	24	25
f(a)	1.4985E-04	1.5884E-04	1.6810E-04	1.7770E-04	1.8769E-04	1.9813E-04	2.0907E-04
a	26	27	28	29	30	31	32
f(a)	2.2059E-04	2.3276E-04	2.4570E-04	2.5951E-04	2.7421E-04	2.9009E-04	3.0717E-04
a	33	34	35	36	37	38	39
f(a)	3.2570E-04	3.4576E-04	3.6781E-04	3.9186E-04	4.1844E-04	4.4768E-04	4.8016E-04
a	40	41	42	43	44	45	46
f(a)	5.1631E-04	5.5670E-04	6.0204E-04	6.5309E-04	7.1094E-04	7.7658E-04	8.5163E-04
a	47	48	49	50	51	52	53
f(a)	9.3761E-04	1.0368E-03	1.1517E-03	1.2858E-03	1.4432E-03	1.6289E-03	1.8497E-03
a	54	55	56	57	58	59	60
f(a)	2.1147E-03	2.4346E-03	2.8255E-03	3.3064E-03	3.9055E-03	4.6601E-03	5.6244E-03
a	61	62	63	64			
f(a)	6.8740E-03	8.5220E-03	1.0738E-02	1.3775E-02			
Laminate H1 (G/G/J/J/J/G/G)							
a	19	20	21	22	23	24	25
f(a)	6.6222E-05	7.0089E-05	7.4075E-05	7.8217E-05	8.2533E-05	8.7045E-05	9.1780E-05
a	26	27	28	29	30	31	32
f(a)	9.6774E-05	1.0205E-04	1.0767E-04	1.1367E-04	1.2006E-04	1.2696E-04	1.3439E-04
a	33	34	35	36	37	38	39
f(a)	1.4246E-04	1.5119E-04	1.6079E-04	1.7128E-04	1.8286E-04	1.9560E-04	2.0977E-04
a	40	41	42	43	44	45	46
f(a)	2.2554E-04	2.4316E-04	2.6295E-04	2.8523E-04	3.1048E-04	3.3913E-04	3.7189E-04
a	47	48	49	50	51	52	53
f(a)	4.0941E-04	4.5268E-04	5.0279E-04	5.6123E-04	6.2976E-04	7.1060E-04	8.0664E-04
a	54	55	56	57	58	59	60
f(a)	9.2179E-04	1.0607E-03	1.2303E-03	1.4388E-03	1.6985E-03	2.0253E-03	2.4428E-03
a	61	62	63	64			
f(a)	2.9837E-03	3.6970E-03	4.6559E-03	5.9710E-03			
Laminate H2 (G/G/J/G/J/G/G)							
a	19	20	21	22	23	24	25
f(a)	5.8154E-05	6.1542E-05	6.5033E-05	6.8662E-05	7.2444E-05	7.6398E-05	8.0547E-05
a	26	27	28	29	30	31	32
f(a)	8.4925E-05	8.9552E-05	9.4475E-05	9.9735E-05	1.0533E-04	1.1139E-04	1.1790E-04
a	33	34	35	36	37	38	39

f(a)	1.2498E-04	1.3264E-04	1.4106E-04	1.5025E-04	1.6040E-04	1.7158E-04	1.8401E-04
a	40	41	42	43	44	45	46
f(a)	1.9784E-04	2.1330E-04	2.3065E-04	2.5019E-04	2.7234E-04	2.9747E-04	3.2620E-04
a	47	48	49	50	51	52	53
f(a)	3.5910E-04	3.9705E-04	4.4100E-04	4.9225E-04	5.5234E-04	6.2322E-04	7.0743E-04
a	54	55	56	57	58	59	60
f(a)	8.0838E-04	9.3014E-04	1.0788E-03	1.2616E-03	1.4891E-03	1.7755E-03	2.1414E-03
a	61	62	63	64			
f(a)	2.6154E-03	3.2405E-03	4.0807E-03	5.2331E-03			