



**APPLIED HYBRID PULTRUDED PROFILES REINFORCED WITH KENAF
AND GLASS FIBRES FOR LADDER**

By

THINESH SHARMA A/L BALAKRISHNAN

**Thesis Submitted to the School of Graduate Studies, Universiti Putra
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Philosophy**

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fulfilment of the requirement for the degree of Doctor of Philosophy

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This thesis explores the development and evaluation of hybrid pultruded profiles for structural ladder applications, incorporating plant and glass fibres. Existing ladder materials, such as fibreglass and aluminum, present challenges related to sustainability, cost-effectiveness, health risks, heavyweight, and electrical conductivity. Moreover, there exists a gap in research regarding the utilization of plant fibres for structural applications. Therefore, there is a pressing need to explore the development of plant/glass hybrid pultruded profiles to address these issues. Incorporating plant fibres into hybrid pultruded profiles will yield mechanical properties comparable to conventional fibreglass profiles, while reducing material costs and weight, and meeting industry standards for structural integrity and sustainability. Beginning with an Analytic Hierarchy Process (AHP) analysis, kenaf fibre was identified as suitable plant fibre. The fabrication process involved hand lay-up, compression molding, and pultrusion methods to create sandwich structured hybrid composites. Mechanical testing revealed favorable characteristics for

the woven kenaf/glass roving hybrid sequences, particularly the WK/UG alternate configuration, showing promising tensile (404.54 MPa), compressive (417.15 MPa), bending (456.33 MPa), and interlaminar shear (34.90 MPa) strengths. Further investigation into durability demonstrated good fatigue responses (18,630 cycles at 60% ultimate tensile strength, UTS), impact strengths (260 kJ/m²), and specific strengths (2.719×10^5 Nm/kg) for the WK/UG alternate configurations. Integration of kenaf fibres also resulted in significant raw material cost reductions (35.7–50%) and weight reductions (9.6–19.1%) in the pultruded profiles. To showcase practical viability, these profiles were utilized in constructing a single-pole structural ladder exceeding ANSI 14.5 standards in multiple performance tests. This highlights their potential for special-duty ladders with substantial working capacities up to 170.1 kg of working load. Overall, the study establishes the potential of kenaf/glass reinforced hybrid pultruded profiles for diverse industries, contributing valuable insights into mechanical attributes and economic benefits while fostering sustainable and resilient structural solutions.

Keywords: *Hybrid Composites; Plant Fibre Composites; Pultruded Profiles; Structural Composites; Sustainable Materials.*

SDG: GOAL 7: Affordable and Clean Energy

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**PROFIL PULTRUDED HIBRID DIAPLIKASI DENGAN SERAT KENAF
DAN KACA UNTUK TANGGA**

Oleh

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Tesis ini meneroka pembangunan dan penilaian profil pultruded hybrid untuk aplikasi tangga struktur, yang menggabungkan serat tumbuhan dan kaca. Bahan tangga sedia ada, seperti fibreglass dan aluminium, menimbulkan cabaran berkaitan kelestarian, kos-kesan, risiko kesihatan, berat, dan penyaliran elektrik. Selain itu, terdapat jurang dalam penyelidikan mengenai penggunaan serat tumbuhan untuk aplikasi struktur. Oleh itu, terdapat keperluan mendesak untuk meneroka pembangunan profil pultruded hybrid tumbuhan/kaca. Penyatuan serat tumbuhan ke dalam profil pultruded hybrid akan menghasilkan sifat mekanikal yang sebanding dengan profil fibreglass konvensional, sambil mengurangkan kos bahan dan berat, dan memenuhi piawaian industri untuk integriti struktur dan kelestarian. Bermula dengan analisis Hierarchy Proses Analitik (AHP), serat kenaf diidentifikasi sebagai serat tumbuhan yang sesuai. Proses fabrikasi melibatkan teknik hand lay-up, pemampatan molding, dan pultrusion untuk mencipta komposit hybrid

berstruktur sandwich. Ujian mekanikal mendedahkan ciri-ciri yang menggalakkan untuk susunan hibrid benang kenaf/kaca, terutamanya konfigurasi WK/UG alternatif, menunjukkan kekuatan tegangan (404.54 MPa), tekanan (417.15 MPa), lenturan (456.33 MPa), dan ricih antara lapisan (34.90 MPa) yang menjanjikan. Siasatan lanjut ke dalam ketahanan menunjukkan tindak balas keletihan yang baik (18,630 kitaran pada 60% kekuatan tegangan ultimate, UTS), kekuatan impak (260 kJ/m²), dan kekuatan spesifik (2.719×105 Nm/kg) untuk konfigurasi WK/UG alternatif. Penyatuan serat kenaf juga menghasilkan pengurangan kos bahan mentah yang signifikan (35.7–50%) dan pengurangan berat (9.6–19.1%) dalam profil pultruded. Untuk memperlihatkan kebolehan praktikal, profil-profil ini digunakan dalam pembinaan tangga struktur tunggal yang melebihi piawaian ANSI 14.5 dalam ujian prestasi pelbagai. Ini menunjukkan potensi mereka untuk tangga khas dengan keupayaan kerja yang besar sehingga 170.1 kg. Secara keseluruhan, kajian ini menetapkan potensi profil pultruded hibrid yang diperkuat kenaf/kaca untuk pelbagai industri, menyumbang wawasan berharga mengenai sifat-sifat mekanikal dan faedah ekonomi sambil memupuk penyelesaian struktur yang lestari dan tahan lama.

Kata Kunci: *Bahan Lestari; Komposit Hibrid; Komposit Serat Tumbuhan; Komposit Struktur; Profil Pultruded.*

SDG: MATLAMAT 7: Tenaga Murah dan Bersih

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Completing this thesis would not have been possible without the collective efforts and support of everyone mentioned above. I am truly grateful for the invaluable contributions and believe that this research will make a meaningful impact in the field of materials and composites engineering.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ASTM	American Society for Testing Materials
DR	Direct Roving
GF	Glass Fibre
KF	Kenaf Fibre
MCDM	Multi Criteria Decision Making
PaLF	Pineapple Leaf Fibre
PFC	Plant Fibre Composites
PMC	Polymer Matrix Composites
SEM	Scanning Electron Microscope
UG	Unidirectional Glass Fibre Roving
UPR	Unsaturated Polyester Resin
UTS	Ultimate Tensile Strength
WG	Woven Glass Fibre
WK	Woven Kenaf Fibre
wt%	Weightage%

CHAPTER 1

INTRODUCTION

In this chapter, discussions will be on the introduction towards this research. This chapter is divided into five sections which consist of Overview, Problem Statement, Objectives, Scope, and Thesis Layout.

1.1 Overview

In the pursuit of sustainable and resilient structural solutions, the exploration of unconventional materials and manufacturing techniques has become a paramount endeavor. As society increasingly demands environmentally conscious alternatives without compromising structural performance, there arises a pressing need to push the boundaries of innovation in the field of materials engineering. This thesis marks a transformative milestone in the realm of structural profile applications, as it unveils the untapped potential of Plant/Glass Fibre Reinforced Hybrid Pultruded Profiles. Merging the inherent strength of glass fibres with the sustainable attributes of plant fibres, this novel composite promises to redefine the landscape of materials engineering, forging a path towards a greener and more resilient future.

The objective of this research is to develop an in-depth understanding of the mechanical, physical, structural and durability properties of hybrid structural profiles, ultimately unlocking their full potential for a wide range of industries, including domestic applications. Through an exploration of the manufacturing process, an investigation into the fibre-matrix interaction, and comprehensive

performance assessments, this study seeks to shed light on the unexplored capabilities of plant fibres in structural profile applications.



Figure 1.1: Common types of plant fibres

Plant fibres, derived from various sources such as kenaf, hemp, flax, or jute, possess inherent sustainability and renewability attributes (Figure 1.1). They are known for their low carbon footprint, fast growth rates, and ease of cultivation, making them highly attractive alternatives to traditional reinforcement materials. Plant fibre composites have emerged as a promising alternative to traditional materials in various industries due to their renewable nature and environmental benefits (K Hasan, 2020; Kurien et al., 2023; M. Li et al., 2020; Mahmud et al., 2021). These composites combine plant-based fibres, with a polymer matrix to create lightweight and eco-friendly materials. While plant fibre composites offer several advantages, including high specific strength, low cost, and reduced carbon footprint, they also come with certain limitations when it comes to structural applications (Ticoalu et al., 2010). One major limitation is their inferior mechanical properties compared to

conventional materials like steel, glass, and carbon fibre composites. Additionally, there are challenges in achieving consistent and predictable material properties due to plant variations in plant fibres, leading to difficulties in quality control and standardization. The research on plant fibre composites is still evolving, and there are limitations in terms of understanding the long-term durability, degradation mechanisms, and processing techniques. These limitations pose significant challenges that need to be addressed to fully exploit the potential of plant fibre composites in structural profile applications.

Plant/Glass Fibre Reinforced Hybrid Pultruded Profiles represent a novel approach in composite materials, combining the exceptional properties of glass fibres with the sustainable advantages of plant fibres. Glass fibres have long been favored for their outstanding strength, rigidity, and durability, making them ideal for structural profiles that require resilience in harsh environmental conditions (Baeza et al., 2022). However, the widespread use of glass fibres comes at a significant cost to both the environment and production expenses. To address these concerns, researchers and engineers have turned to hybrid composites, which blend the distinct characteristics of different fibres through pultrusion process. By incorporating plant fibres into the mix, the resulting hybrid composite can achieve a balance between mechanical performance and sustainability. This innovative approach enables the creation of pultruded profiles that exhibit improved strength, stiffness, and environmental benefits (Figure 1.2) (Barkanov et al., 2021; Correia, 2023). These hybrid profiles have the potential to revolutionize various industries, offering a viable solution that aligns both performance requirements and ecological responsibility.

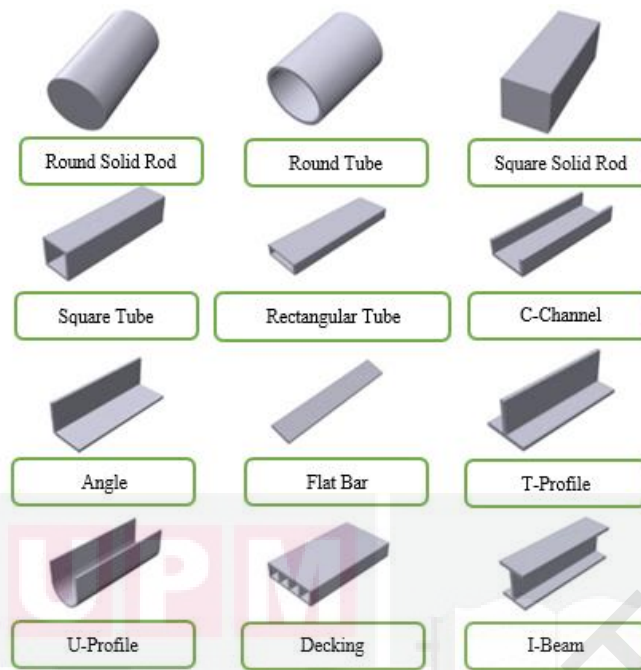


Figure 1.2: Pultruded profiles

As the industry embraces a paradigm shift towards sustainable practices, the potential applications of Plant/Glass Fibre Reinforced Hybrid Pultruded Profiles are vast and far-reaching. From architectural marvels and infrastructure projects to aerospace and marine structures, this plant fibre composites have the capacity to revolutionize the way we build, ensuring a harmonious coexistence between human ingenuity and the environment (Z. Zhang et al., 2020). For instance, Figure 1.3 shows the potential applications of pultruded structural profiles divided into three levels of applied loadings (light, moderate and heavy).

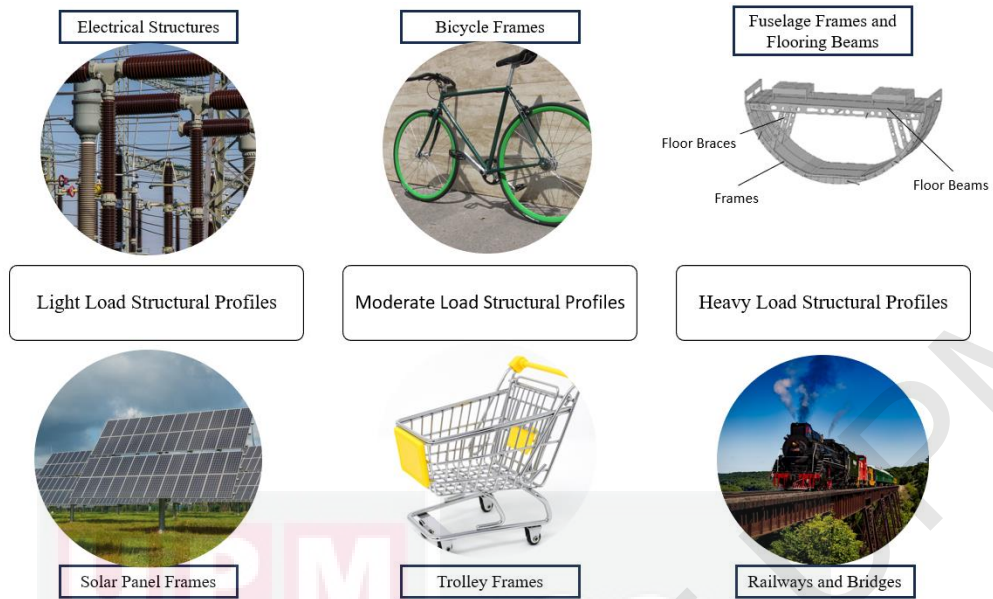


Figure 1.3: Potential applications of pultruded profiles

Through addressing the knowledge gaps surrounding this innovative material, this thesis not only contributes to the scientific understanding of hybrid composites but also charts a course for a new era in sustainable materials engineering. By conducting rigorous analyses, validating through experimental testing, and providing comprehensive assessments, this research aims to equip engineers and designers with the tools necessary to embrace the full potential of Plant/Glass Fibre Reinforced Hybrid Pultruded Profiles in their pursuit of resilient and environmentally responsible structural materials.

1.2 Problem statement

The use of plant fibres as reinforcement materials in composites has gained significant attention in recent years, primarily focusing on non-structural applications such as insulation, packaging, and textiles. However, there exists a considerable research gap in exploring the full potential of plant fibres in structural applications (Abhiram et al., 2021; Chaudhary & Ahmad, 2020; Navaratnam et al., 2023). This section aims to highlight this gap and

emphasize the need for comprehensive investigations into the utilization of plant fibres, particularly in the development of Plant/Glass Fibre Reinforced Hybrid Pultruded Profiles for structural applications focusing on structural ladders. To clarify the research problem and focus on structural applications, the approach involves conducting targeted research that directly addresses gaps identified in the literature. Instead of duplicating existing fundamental work, the study prioritizes practical relevance by designing experiments tailored to structural application requirements. Collaboration with industry partners or experts helps ensure alignment with real-world needs and standards. By utilizing applied research methods and integrating fundamental knowledge with practical findings, the research aims to provide comprehensive solutions for structural applications. This approach enables the investigation of plant fibers' suitability for structural contexts while advancing both fundamental understanding and practical application.

The extensive research on plant fibres has predominantly focused on their application in non-structural contexts. These studies have showcased the unique characteristics of various plant fibres, such as kenaf, hemp, flax, and jute, including their renewable nature, low environmental impact, and potential for reducing carbon emissions. Plant fibres offer promising alternatives to conventional reinforcement materials, such as glass and carbon fibres, due to their sustainability and favorable mechanical properties. However, most research efforts have been directed towards non-structural applications, limiting our understanding of their potential in structural applications. The gap in research becomes evident when considering the vast opportunities that arise from integrating plant fibres into structural components. Structural

components like pultruded profiles rely heavily on materials with high strength, stiffness, and durability to meet demanding performance requirements. Glass fibres have traditionally been the material of choice due to their exceptional mechanical properties and resistance to environmental factors. However, the high energy consumption and carbon emissions associated with the production of glass fibres necessitate the exploration of sustainable alternatives.

Plant fibres offer a promising solution to bridge this gap, as they possess inherent sustainability attributes and can be cultivated with reduced environmental impact. By combining plant fibres with glass fibres through a pultrusion process, Plant/Glass Fibre Reinforced Hybrid Pultruded Profiles can potentially provide a sustainable and high-performance alternative for structural applications. The hybridization of these fibres aims to capitalize on the mechanical strength and rigidity of glass fibres while harnessing the sustainable benefits and renewability of plant fibres. While a significant body of literature exists on the mechanical behavior and performance of glass fibre reinforced composites and plant fibre reinforced composites, there is a lack of comprehensive research specifically targeting the structural potential of plant fibres. This research gap hinders the realization of sustainable and resilient structural solutions that could significantly contribute to the advancement of environmentally conscious construction practices. To address this research gap, it is crucial to conduct systematic investigations into the mechanical properties, bonding characteristics, and long-term performance of Plant/Glass Fibre Reinforced Hybrid Pultruded Profiles. By filling this gap, researchers can gain a deeper understanding of the structural behavior of these hybrid

composites, assess their suitability for different structural applications, and unlock their full potential in sustainable materials engineering.

Besides that, to demonstrate the practical feasibility of plant/glass hybrid pultruded profiles, this study aims to conduct a case study, by employing the profiles in the fabrication of a single-pole structural ladder. Traditional materials used in the fabrication of structural ladders have been wood and metals like aluminium. However, these materials come with certain limitations. Wood, while renewable, may have issues with durability and susceptibility to decay and insect damage, making it less suitable for long-lasting applications. On the other hand, aluminium, while lightweight and strong, is a conductive material that can transfer significant amounts of heat and electricity, making it unsuitable for certain applications where electrical insulation is crucial. To address the limitations of traditional ladder materials, the industry shifted towards using Fibre-Reinforced Polymers (FRP) ladders, where glass fibres were incorporated to enhance strength and rigidity. While FRP ladders offer improvements in terms of durability and strength-to-weight ratio, they come with drawbacks. The incorporation of glass fibres makes the ladder heavier and more expensive, limiting its appeal in certain contexts where weight and cost are critical factors. This problem statement presents an opportunity for innovation in ladder fabrication by exploring the development of Plant/Glass Fibre Reinforced Hybrid Pultruded Profiles for use in structural ladder construction.

Incorporating plant fibers into ladder construction offers significant potential benefits, including increased sustainability, reduced environmental impact,

and lower material costs. However, ensuring the ladder maintains necessary mechanical strength and rigidity necessitates the combination of glass fibers. To address this challenge, industrial collaboration with key players in Malaysia's fiberglass and ladder sectors, such as Mui Fatt Industries Sdn Bhd and Myladder Sdn Bhd has been crucial. Through this collaboration, a prototype ladder has been developed, demonstrating the practical feasibility of hybrid pultruded profiles in real-world applications. By bridging the gap between extensive research on plant fibers for non-structural applications and the underexplored potential of plant fibers in structural contexts, this thesis aims to comprehensively explore Plant/Glass Fiber Reinforced Hybrid Pultruded Profiles. Through rigorous experimentation, analysis, and performance assessments, this research will not only advance sustainable and innovative solutions in structural materials but also validate the industrial viability of these profiles for widespread adoption in various applications including structural ladders.

1.3 Research objectives

The main goal of this study is to develop pultruded profiles intended for structural purposes by identifying the optimal composition of hybrid composites reinforced with plant and glass fibres. The specific objectives of the research are as following:

- i. To identify the most suitable plant fibre using analytical hierarchy process (AHP) for plant/glass fibre reinforced hybrid composite in pultruded profiles.

- ii. To analyse the mechanical properties of different layer sequences of the hybridized composite of the selected plant fibre with glass fibre via tensile test, compression test, bending test, and interlaminar shear stress.
- iii. To investigate the resilience of pultruded composites made from the selected layer sequence of plant/glass composite through impact test and fatigue test.
- iv. To conduct a case study analysis on a ladder prototype made from the selected composition of plant/glass fibre hybrid pultruded composite through structural analysis.

1.4 Scope and limitations

The scope of this research encompasses the development of plant/glass fibre reinforced hybrid pultruded profiles for structural applications. While this research endeavor strives to contribute valuable insights and advancements in the development of plant/glass fibre reinforced hybrid pultruded profiles for structural applications, certain limitations should be acknowledged.

The research focuses on investigating a limited range of plant fibres and their combination with glass fibres. Other types of plant fibres or alternative reinforcement materials may not be included in the scope of this study, limiting the generalizability of the findings. Moreover, the research primarily focuses on the pultrusion process for composite profile production. Other manufacturing techniques or composite processing methods may not be explored within the scope of this study.

The mechanical, durability, and structural performance evaluations will primarily be conducted at the laboratory scale. The influence of larger-scale manufacturing and practical application factors may not be fully captured within the limitations of this research.

The case study on the prototype ladder represents a specific application of the developed profiles. The findings and conclusions may not directly translate to other structural applications, and further investigations are required for their broader applicability.

Despite these limitations, this research aims to make a significant contribution by exploring the development of plant/glass fibre reinforced hybrid pultruded profiles for structural applications, providing valuable insights into material selection, mechanical properties, manufacturing processes, and real-world performance.

1.5 Layout of thesis

This thesis consists of five major chapters which starts with the introduction of the research project, followed by the literature review that are related to this research, the methodology aspects of the project, results, and discussion, and finally the concluding remarks for this research respectively.

Chapter 1: Introduction discusses about the gap of plant fibres in structural applications and provides an overview of the potential of plant/glass fibre reinforced hybrid pultruded profiles for structural profiles. This chapter also consists of the research background, problem statement, objectives, scope of study, and thesis overview.

Chapter 2: Literature review investigates the past research and the fundamental theories related to plant fibre composites, current related research that has been done, insight into plant fibres and pultruded composites, and finally in-depth analysis on the research gap for plant/glass fibre reinforced hybrid pultruded composites.

Chapter 3: Methodology reports detailed description of the material selection, test specimen preparations and experimental testing. The fabrication processes and testing procedures for a working prototype are also discussed.

Chapter 4: Results and discussion, studies the AHP method conducted to select the suitable plant fibres for the research. Besides that, mechanical properties of the plant/glass fibre hybrid composites are analysed to select potential stacking sequences for structural profile application. The selected combination of composite is then fabricated via pultrusion to further study its impact and fatigue properties. In addition, a case study on the application of plant/glass fibre hybrid pultruded profile has been conducted by developing a prototype ladder. Assessment of what was previously written and discussed is made.

Chapter 5: Conclusion and recommendations, briefly explains the summary of all the chapters. Explained important information and feedback from the study. Emphasized the benefits and contribution of this work to the community and society. Future works and recommendations are included.

CHAPTER 2

LITERATURE REVIEW

Plant fibres have gained attention in many industries and increasingly being used as replacement of synthetic fibres. These sustainable alternatives offer low cost, low density, availability in abundance, environmentally friendly, nontoxicity, high flexibility, renewability, and biodegradability. As the focus of this research, it is aimed to characterize and develop plant/glass fibre reinforced hybrid composites for pultruded profile for structural applications. Hence, before doing the experimental and documentation works, it is essential to do some literature review regarding to the topic. This includes the knowledge of composite materials, plant fibres, matrices, processing techniques, and some other related information from previous studies regarding the topic. The literature review conducted for this study is originated from published sources such as books, journals, and trustable online website.

2.1 Introduction

Composites are produced through various manufacturing processes. Each process holds significant characteristics in producing composites that are different from one another. The recent composite processing techniques are categorised as open moulding, closed moulding, cast polymer moulding and additive manufacturing (Rajak et al., 2019). The selection of processing techniques depends on various aspects, such as the resin type, reinforcement type and fibre placement in the composites.

Generally, a method that can be utilised with a large quantity of fibre reinforcements is theoretically responsible for producing composites with increased strength. Pultrusion is one of the most common closed moulding processing methods for producing FRP profiles with high fibre volume and excellent strength, among other manufacturing processes (Pannu et al., 2019). Pultrusion is a continuous moulding method used in numerous manufacturing sectors to produce structures and composite materials with uniform cross-sections. Pultruded structures and profiles used in various industries are mainly made from synthetic fibres like carbon and glass fibres.

However, the excessive use of synthetic materials in composites has raised sustainability issues and adverse environmental effects. This is because synthetic fibres are made by processing petrochemicals and fossil fuels, which are energy sources that are not renewable. In addition, synthetic fibre is expensive, harmful to health, and takes a long time to decompose in materials if used excessively. Therefore, plant based natural fibres are proposed as alternatives to synthetic materials in developing sustainable composites for structural applications via pultrusion in this era of emerging green technology. Haag et al. (Haag et al., 2017) studied and compared flax reinforced composites processed by three manufacturing techniques: twin-screw extrusion and injection moulding, vacuum-assisted resin transfer moulding (VARTM), and pultrusion. The research findings indicate that composites' highest performance was achieved using the pultrusion process compared to the other two techniques. Pultruded flax fibre reinforced composites consisting of high fibre volume fraction, high fibre orientation, and high fibre bundle length

validated better mechanical performance than composites from other manufacturing techniques.

Plant fibres are not just chosen to solve problems with sustainability. Plant fibres are used in various composite manufacturing processes due to their lighter weight, lower cost, and superior strength-to-weight ratio. The properties of the fibres are influenced by factors like the physical and chemical morphology, the growth and structure of the lumens, cells, and cell walls, and cross-sectional dimensions (Brett C. Suddell & William J. Evans, 2005; Juliana et al., 2018; Thomas et al., 2011). Cellulose, hemicelluloses, and lignin typically make up plant fibre's chemical composition (Lu et al., 2012). In the form of cellulosic microfibrils in the inner layer of the primary wall, cellulose is one of the primary components of plant fibres. Cellulose is a linear chain of 1,4-linked D-glucose units. It is the main component of plant cell walls and gives them a stiff and rigid structure. The multiple hydroxyl (OH-) groups on the glucose residues hydrogen bond with one another to form microfibrils, securing the chains in place and contributing to their high tensile strength (Ravindran et al., 2019). Generally, the reinforcing efficiency of plant fibres in composites depends on the cellulose content and their crystallinity (Kim et al., 2016). The crystalline structure in cellulose provides good strength in plant fibres, making it applicable in load bearing composites. Plant fibre composites typically have better tensile properties with high cellulose content and a low fibrillar angle.

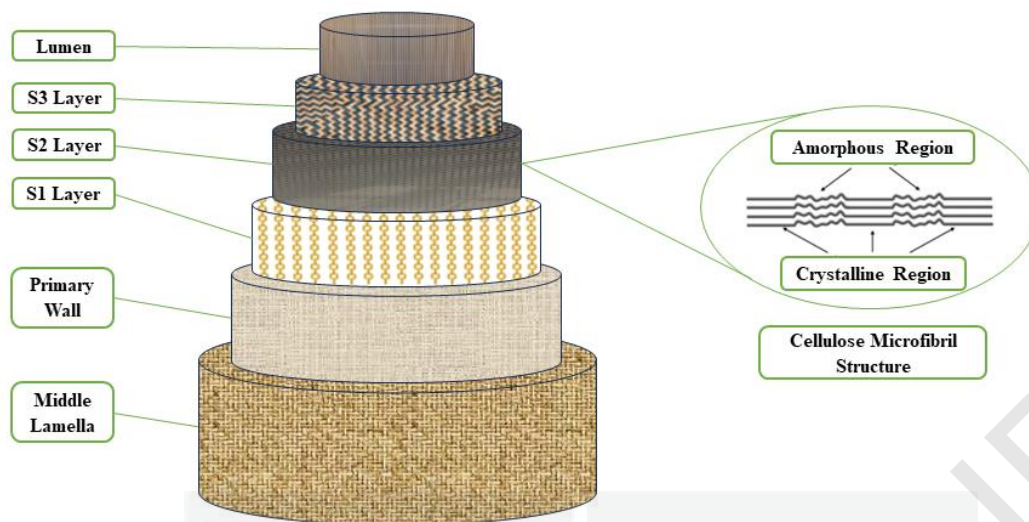


Figure 2.1: Hierarchical structure of plant cell wall and cellulosic structure (Source: Fornari et al., 2022)

As a result of its renewable and sustainable nature, plant fibres are gaining more attention for application in composite materials and structures. Hence, this literature reviews the research progress and potential of plant based natural fibres to be implied in pultruded composite manufacturing to reduce and replace the use of synthetic materials in pultruded structures. In raising awareness of developing environmentally friendly and high-performance materials for structures and infrastructure facilities, this literature aims to provide an overview of the prospects of plant fibres to be applied in pultruded FRP composites.

2.2 Composite materials

Composites have begun to replace conventional materials such as metals, ceramics, plastics and wood in many industries and applications due to their enhanced properties when compared to conventional materials. Composite materials are materials with enhanced properties made by combining two or more material components with different properties (Yang et al., 2019).

Composites were first introduced into aerospace industry in 1970s (Sajan & Philip Selvaraj, 2021). With the current development of composite materials, these materials are being widely used in various engineering structures in industries like aerospace, marine, civil, and automotive. This is because composite materials have good strength to density and hardness to density properties.

There are two classification systems of composite materials. One of the classification systems is based on the matrix material and the other is based on material structure. According to the classification based on matrix material, the commonly used composites are;

- i. Ceramic Matrix Composite (CMC)
- ii. Metal Matrix Composite (MMC)
- iii. Polymer Matrix Composite (PMC)

Another classification is where composites are divided into 3 categories according to its material structure which are (Egbo, 2020);

- i. Particulate reinforced composites
- ii. Fibre reinforced composites
- iii. Structural composites which is a combination of composites, arranged and held together with a homogenous adhesive material. For example, laminate composites and sandwich composites.

2.2.1 Fibre reinforced polymer composites

Among the various types of composite material structures, fibre reinforced composites are the most widely used, and produced in large amounts. Fibre

reinforced composites have low specific gravity, high specific strength, and high specific modulus. These traits can effectively improve the tensile strength and rigidity of the composite material, reduce shrinkage, and increase the heat-distortion temperature and low-temperature impact strength. There are two common types of fibre materials used for composite structures which are synthetic fibres and plant fibres. The common types of synthetic fibre reinforced composites are namely glass, carbon, and aramid fibres (Kevlar). Fibre reinforced composites come in various designs which include continuous fibre composites, chopped fibre composites, woven fibre composites, and hybrid composites (Balasubramanian et al., 2018). These composites are fabricated according to the length of the fibres as listed below.

- i. Short-fibre reinforced composites. Short-fibre reinforced composites consist of a matrix reinforced by a dispersed phase in form of discontinuous fibres
- ii. Composites with random orientation of fibres.
- iii. Composites with preferred orientation of fibres.
- iv. Long-fibre reinforced composites. Long-fibre reinforced composites consist of a matrix reinforced by a dispersed phase in form of continuous fibres.
- v. Unidirectional orientation of fibres.
- vi. Bidirectional orientation of fibres (woven).

A matrix used in composite materials has relatively high ductility and low fracture strength that surrounds the other constituent, often known as the inclusion or the dispersed phase. The matrix system in a composite material assists the reinforcements by aligning and stabilizing them to assure stress

transfer from one fibre to another. Hence, the mechanical performance of fibre reinforced composites relies on the bond strength between the matrix and fibre. Polymer matrix composites can be further divided into two types which are thermoplastics and thermosets. Thermoset composites are significantly good in resisting corrosion and fatigue. Hence, maintenance requirements can be significantly reduced by using thermoset composites (Rubino et al., 2020).

2.2.2 Glass fibre reinforcements

Glass fibre is a non-metallic material in which prepared by blowing its molten state into a very fine fibrous material by external force. Glass fibres have excellent application prospects due to its high specific strength, high-temperature resistance, corrosion resistance, chemical stability, electrical insulation, and thermal insulation properties (Yang et al., 2019). According to Table 2.1, there are several types of glass fibres with different alkali metal oxide contents.

Table 2.1: Types of glass fibres

Type	Description	Composition
E-CR Glass	High electrical/chemical resistance	Alumino-lime silicate with less than 1%w/w alkali oxides,
E-Glass	Good electrical insulation and mechanical properties	Calcium aluminum borosilicate
C-Glass	Used for glass staple fibres and insulation	Alkali-lime glass with high boron oxide content
A-Glass	Used to prepare glass fibre felt and glass wool	Alkali-lime glass with little or no boron oxide
D-Glass	Low dielectric constant	Borosilicate glass
R-Glass	High mechanical properties	Alumino silicate glass without MgO and CaO
S-Glass	High tensile strength	Alumino silicate glass without CaO but with high MgO content

(Source: S. Prashanth et al., 2017; Yang et al., 2019)

As the most common type of glass fibre, E-glass which is alkali free and is the first glass prescription used in continuous filament formation for electrical resistant applications, is chosen as reinforcement material in this research (Jing et al., 2019). Several research works have been reported on E-glass composites and hybridized E-glass/plant fibre composites. In EL-Wazery et al.'s research work (EL-Wazery et al., 2017), an E-glass fibre with random oriented reinforced polymer composite was developed by hand lay-up technique with varying fibre percentages (15%, 30%, 45%, and 60% by weight percentage). The results showed enhancement in the mechanical properties of the fabricated composite with an increasing in the glass fibre contents. Mahalle et al. (Mahalle et al., 2017) has compared the mechanical properties of E-glass and coconut fibre reinforced with polyester and epoxy resin matrices. From the investigation, coconut fibre reinforced composites show good stiffness, but with a limitation in strength. However, E-glass reinforced epoxy resin composites showed better mechanical properties than other samples.

Arphita et al. (Arpitha et al., 2017) has found that E-glass and silicon carbide filler can reduce the voids in Sisal/E-glass hybrid composites and enhances the physical and bending properties. The researcher also found that the tensile properties enhance with increasing proportion of E-glass fibres through the study. Nurazzi et al. (Nurazzi et al., 2020) has investigated the effects of alkaline treatment and hybridization on the thermal properties of sugar palm yarn/E-glass fibre. From the research, they found that hybridization of the glass fibre with treated sugar palm fibre enhances the thermal properties of the hybrid composites for structural applications. A study on the properties of

hybrid Ramie/E-glass fibre reinforced composite fabricated by hand layup method (Giridharan, 2019). The researchers stated that hybrid Sisal/E-glass, Siugar Palm/E-glass and Ramie/Eglass, fibre reinforced epoxy composites exhibited better mechanical properties than the individual samples.

2.2.3 Plant fibre reinforcements

Besides sustainability and lightweight, one of the advantages of using plant fibres as reinforcement in composites is to create jobs in agricultural sectors and to reduce the wastages contributing to a healthier environment (Ramesh et al., 2018). Their environmental aspects such as biodegradability, renewability, recyclability, and low toxin emission when processed make them environmentally friendly. Additionally, plant fibres also provide several advantages with their outstanding properties such as abundance in nature, relative low cost, light weight, and high strength to weight ratio (Alhijazi et al., 2020). However, their disadvantages such as high moisture absorption, short service life, and degradation requires some modifications to their morphology using some chemical and physical treatments to enhance their application in various industries. Table 2.2 explains the advantages and limitations of applying plant fibres as reinforcements in composites.

Table 2.2: Advantages and limitations of plant fibres in composites

	Advantages	Limitations
Mechanical properties	Higher specific strength and stiffness than glass fibre	Lower tensile, bending and impact strength compared to glass fibre. Mechanical properties of the plant fibres are greatly affected by many factors such as fiber length, fiber aspect ratio and fiber-matrix adhesion.
Physical properties	Lower density than glass fibre	Fibres absorb moisture resulting in swelling and presence of voids
Processing	Non-harmful processing, hence reduced health risk Lower energy required compared to glass fibre composite production	Requires additional processing such as chemical treatments to decrease the water absorption of fibres and increase the interface adhesion between the fibre and matrix
Environmental	Sourced from renewable resources, hence preventing carbon footprints. Lower energy consumption at production Recyclable	Prone too fungal attack and weathering
Costing	Lower price rate when compared to glass fibre	Price fluctuations depending on the harvest results and availability

(Source: S. Kumar et al., 2022)

Poor dimensional stability and high hydrophilic nature are the major drawbacks that restrict the use of plant fibres in different applications. Therefore, it is essential to perform a treatment to improve the surface properties of plant fibres before being used in the composites (Godara, 2019). Interfacial bonding between the fibre and matrix plays a vital role in deciding the mechanical characteristics of composites. Various chemical cures are applied for enhancing the fibre-matrix adhesion which ends up in better mechanical characteristics of the composites (Bhuvaneshwaran et al., 2019; Gholampour & Ozbakkaloglu, 2020; Lee et al., 2021). A study on the effect of chemical treatment on the thermal properties of hybrid plant fibre-reinforced composites was conducted by Neto et al. (J. S. S. Neto et al., 2019) and it was found that

the chemical treatments have increased the thermal stability of the composites.

2.3 Processing techniques

Composites can be manufactured using various manufacturing processes. The selection of processing techniques depends on various aspects such as the resin type, reinforcement type and fibre placement in the composites. The common fabrication methods for composites are hand lay-up, compression molding, resin transfer molding (RTM), Vacuum infusion process (VARTM/ SCRIMP/ RIFT), extrusion, and injection molding (Mahmud et al., 2021).

Table 2.3: Composites manufacturing techniques

Manufacturing techniques	Description	Advantage	Disadvantage
Hand Lay-up	Each ply is handled only by hand and stacked layer-by-layer up to the desired thickness.	• Cost effective • Good design flexibility • Cured at room temperature	• Labor intensive • Requires high skill work
Spray Lay-up	A handgun is used to spray resin and chopped fibre and cured at room temperature.	• Cost effective • Fast deposition rates • Suitable for large products	• Requires high skill work
Compression Molding	Plies are compressed between two steel dies during fabrication.	• High volume production • Provides excellent surface finish • Good mechanical, and chemical properties.	• Time consuming • High labor cost • Not suitable for complex molding

Table 2.3: Continued

Resin Molding	Transfer	The process involves placing the fibre mat at the mold's bottom and subsequently thoroughly filling the mold with resin through low-pressure pumping.	• Better surface finishing and productivity	• Critical mold designs require high skill work and good tools. • Requires proper venting and gating to avoid defects in the composites.
Injection Molding		Molten materials are forced into the mold, where the material will be left until cured.	• Provides high volume production at faster rate. • Cost effective • Design flexibility • Low labor cost	• Tooling cost is high. • Limitations in fibre length.
Vacuum Processing	bag	During the process, the materials will be placed onto the mold in desired sequence and covered by a film layer, air breeder layer, blocked film layer, breather layer, and vacuum bag layer. Vacuum is used to remove excess resin and air that has been trapped in the mold.	• High volume of fibre can be used • Lower void content	• Requires high skill work • Low volume production rate
Pultrusion		Pultrusion technique involves pulling of the continuous fibre materials through a die which contains a resin bath during composite fabrication.	• Low labor cost • Production at continuous rates	• High tooling cost • Limited to constant or near constant cross-section components.
Filament winding		Circular shaped components such as pipes can be produced using the filament winding process. The mold is a rotating mandrel, and an open mold is used for fabrication process.	• High fibre volume • Good resin distribution. • High strength to weight ratio.	• Applicable to limited design. • High cost of mandrel.

(Source: Balasubramanian et al., 2018; Mahmud et al., 2021)

Table 2.3 presents brief explanation on the commonly used composite manufacturing techniques in various industries. The final product consistency of composite processing techniques can be achieved by monitoring the fibre volume, thickness, and lay-up directions. These aims can be achieved by considering the tooling used during the process, the composite configurations, and the whole manufacturing process (Balasubramanian et al., 2018). A lot of consideration is required to choose the suitable manufacturing process for any type of composites. Theoretically, a process that can be used with high volume of fibre will produce composites with better strength. Overall, manufacturing techniques affect the properties of the composite produced since the process is also related to fibre size, fibre orientation, fibre direction and length, and type of matrix used for the composite fabrication.

2.3.1 Pultrusion process

Among the various types of composite manufacturing processes, pultrusion is one of the widely used closed moulding processing techniques to produce FRP profiles with high fibre volume and excellent strength. Pultrusion is a continuous moulding process commonly used in many manufacturing industries to fabricate composite materials and structures of uniform cross-section.

By replacing conventional metals and alloys, pultruded FRP components are used in designing and building simple to complex structures for a wide range of applications. Pultrusion is chosen by many industries to manufacture parts that are strong, lightweight, and continuous which include the aerospace, marine, military, electrical, transportation, as well as infrastructure, chemical,

and construction sectors. The profiles can be fabricated in any desired length with uniform cross-section. Besides that, pultruded products can also be cut, painted, drilled, and connected using screws, rivets, bolts, and adhesives which make them more user-friendly. Surface veils and UV-resistant coatings are typically applied to profiles which protect them from harmful radiations and corrosive environmental effects.

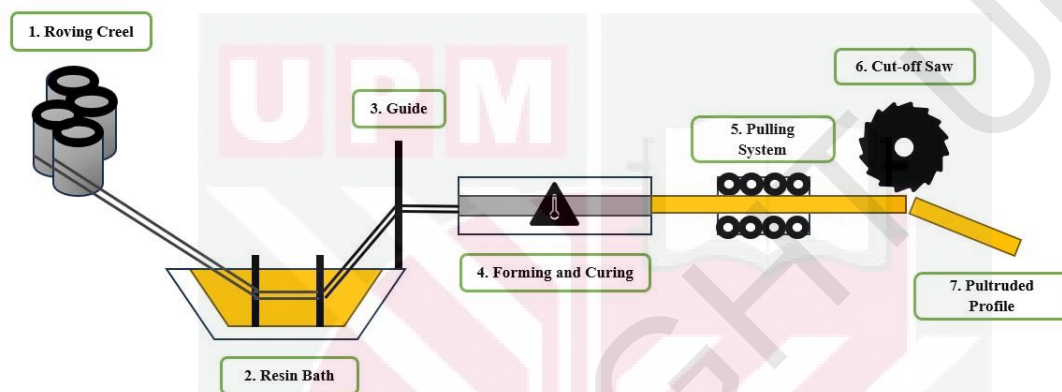


Figure 2.2: Pultrusion process
(Source: Riedel, 2012)

There are two steps in the pultrusion processing: impregnation and curing (Landesmann et al., 2015). The process starts with the fibre creel to easily pull the fibres without a knot. The fibre reinforcement is then drawn into a resin bath and thoroughly impregnated with the resin mixture. The impregnated fibres will be pulled through a pre-former into a heated die. The die configuration determines the product's shape, and the resin is then cured. Conventionally, the heating zones varied along with the die and were controlled depending on the type of resin, pulling speed, and the length of the die. The pultruded parts are pulled throughout the process using a pulling device which controls the processing speed. A sawing system is equipped at

the end of the pultruder to cut off the cured continuous profiles at the desired length.

Generally, several process control parameters are essential in producing pultruded composites, such as the pull speed, resin viscosity, fibre volume fraction, heating temperature in the die, and preform plate area ratio (Gadam et al., 2000; J. Li et al., 2002; Paciornik et al., 2003). For instance, the viscosity of the matrix determines the processing temperature and speed to ensure a high quality of the fully cured product (P. Li et al., 2023; Sandberg, Yuksel, Baran, Hattel, et al., 2021; Tian et al., 2023). Typically, thermosets, such as unsaturated polyester resin, vinyl ester resin, epoxy resin, and phenolic resin, are used as the matrix system. However, thermoplastic composites are also gaining significant attention in the pultrusion industry (Bechtold et al., 2016; Esfandiari et al., 2022; Wilson & Buckley, 2016; P. Zhang et al., 2023). Pultrusion technology and pultruded FRP composite have steadily emerged in many development areas and are still open to market challenges.

2.3.2 Pultruded FRP composites

Utilising reinforcing fibres, resin, a catalyst, fillers, pigments, and a release agent, pultrusion is known for producing fibre-reinforced polymer composite profiles with a uniform cross-section, such as flat bars, rods, beams, channels, and solid and hollow sections (Qi et al., 2023). The highly automated process can produce continuous and high fibre volume composites, making it ideal for structural profile production with an excellent strength-to-weight ratio. The pultrusion process does not only limit its scope in producing open-section geometries, but also single- or multi-celled close-shaped profiles can be

manufactured through this process (Strauss et al., 2023). Moreover, besides producing conventional linear profiles, efforts and research have also been carried out in developing curved parts using modified pultrusion technologies (Aranberri et al., 2021; Liu et al., 2021; Struzziero et al., 2021; Tang et al., 2022; Tonatto et al., 2021; Zhao et al., 2022). Figure 2.3 shows examples of commonly fabricated and applied structural components made by pultrusion.

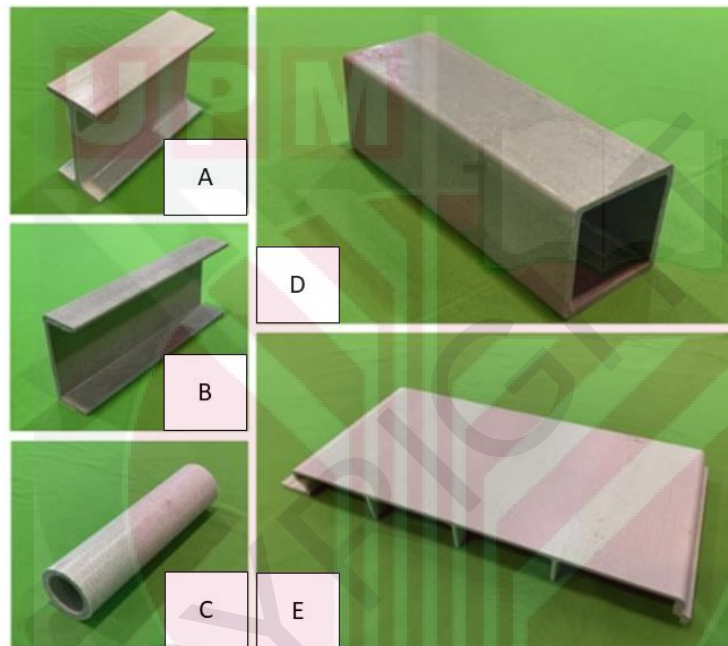


Figure 2.3: Pultruded components: (A) I beam (B) C channel (C) Round tube (D) Square tube (E) Deck
(Source: *Top FRP Manufacturer and Supplier in Malaysia - Mui Fatt Marketing Sdn Bhd*, n.d.)

This technology is emerging in the composites industry due to continuous production at a high rate and low labour cost, which leads to cost-effective manufacturing (Volk et al., 2022). Composites with glass and carbon fibre reinforcements of synthetic fibres are frequently made using pultrusion (Correia, 2023; Hofmann et al., 2023). Commercially, the reinforcing materials usually used in pultruded FRP composites are fibreglass continuous strand mats, continuous fibreglass roving and chopped strand mats. The

unidirectional roving provides longitudinal reinforcement of the profile, while woven fabrics give transverse strength (Pirchio et al., 2023). A surfacing mat enhances the composite surface appearance and protects the layer from chemical and weather conditions. The fibre arrangement and stacking sequence vary according to the pultruded composite's application. Figure 2.4 shows an example of a stacking sequence in a C-channel pultruded profile.

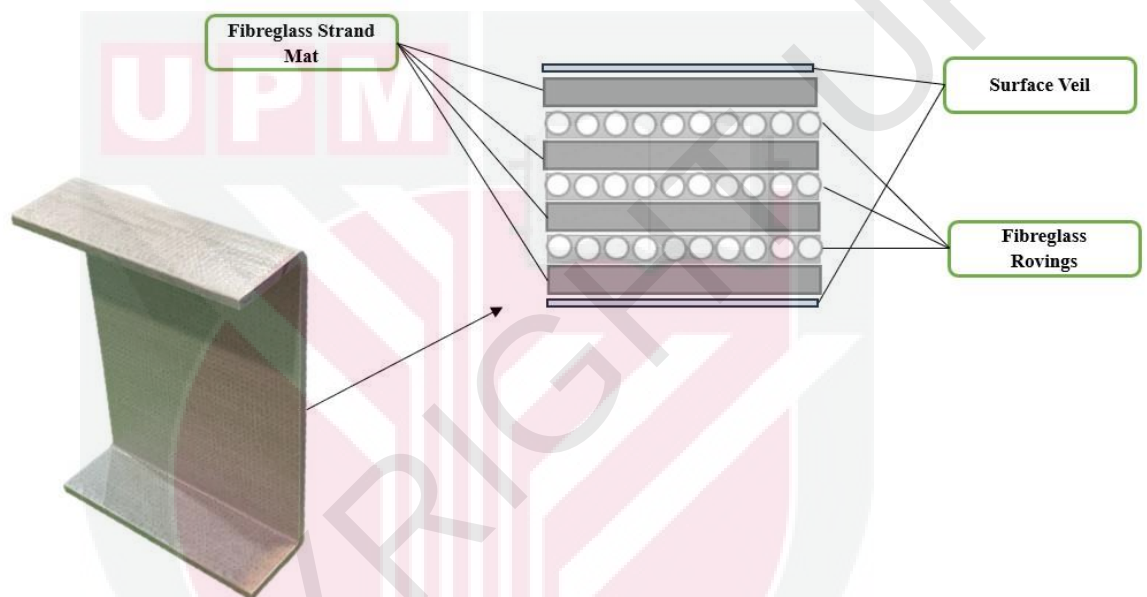


Figure 2.4: Stacking configuration in pultruded profile

Excessive use of synthetic materials in composites have been leaving some negative environmental impacts and awakening sustainability issues. This is due to the use of petrochemicals and dependency on non-renewable energy resources. Besides that, excessive use of synthetic fibre is also harmful to health, and it takes a long time to decompose its constituents. Hence, in this era where green technology is emerging vastly, plant fibres are proposed to be a superior alternative to synthetic materials in developing green composites for structural applications especially in pultruded structural profiles. However, there is still a huge gap present in the scope of developing pultruded structural

products using plant fibres as reinforcement. For instance, characterization using different types and forms of plant fibres (woven and yarns), analysis on stacking sequences, structural analyses on various types of cross sections of pultruded profiles, and product development is remaining as a gap to make bio-based pultrudes applicable in practical real-life applications.

2.4 Plant fibres in pultrusion

Plant fibres can be classified as plant fibres, animal fibres and minerals. Among these types, plant fibres have been widely used as reinforcing fibres in composites lately (M. R. Sanjay et al., 2019). Generally, plant fibres can be classified into bast fibers, core fibres, seed fibers, leaf fibers and reed fibers (Keya et al., 2019; Nurazzi et al., 2021). Popular plant fibres are extensively researched and applied in various composite applications such as bast and core fibres (flax, jute, hemp, ramie, kenaf). Plant-based natural fibres offer several advantages to reducing and replacing conventional synthetic fibres in pultruded FRP composites. Besides providing good relative mechanical and lightweight properties, plant fibre-reinforced composite (PFC) also solves sustainability issues by reducing the energy required for production (Roy et al., 2019; Shalwan & Yousif, 2013).

According to Wu et al. (Y. Wu et al., 2018), 20% of environmental issues were reduced by producing kenaf-reinforced composite compared to the fibreglass-reinforced composite. Although plant fibre offers several advantages, such as low weight, low cost, abundant availability, and sustainable and environmentally friendly properties, it comes with some limitations, such as high moisture absorption (S. Kumar et al., 2022; Madhu et al., 2019).

Generally, the property of PFC depends on the constitution of plant fibres such as cellulose, hemicellulose, lignin, fibre distribution and fibre surface roughness (Rajesh et al., 2021). Besides that, the mechanical characteristics of PFCs highly depend on interfacial bonding between the fibre and matrix. Chemical processing is often applied to plant fibres to reduce the hydrophilic properties of fibres and enhance the fibre-matrix adhesion to improve the mechanical properties of PFC, which can be applied to pultruded structural applications (Karthi et al., 2020). The poor dimensional stability and high hydrophilic nature are the significant disadvantages limiting plant fibre use in different applications. Therefore, chemical treatments are essential to improve the surface properties of plant fibres before being applied to composites (Koohestani et al., 2019; Setswalo et al., 2021). The common chemical treatments applied are alkaline, silane, acetylation, and maleate coupling treatments (Edeerozey et al., 2007; Koohestani et al., 2019).

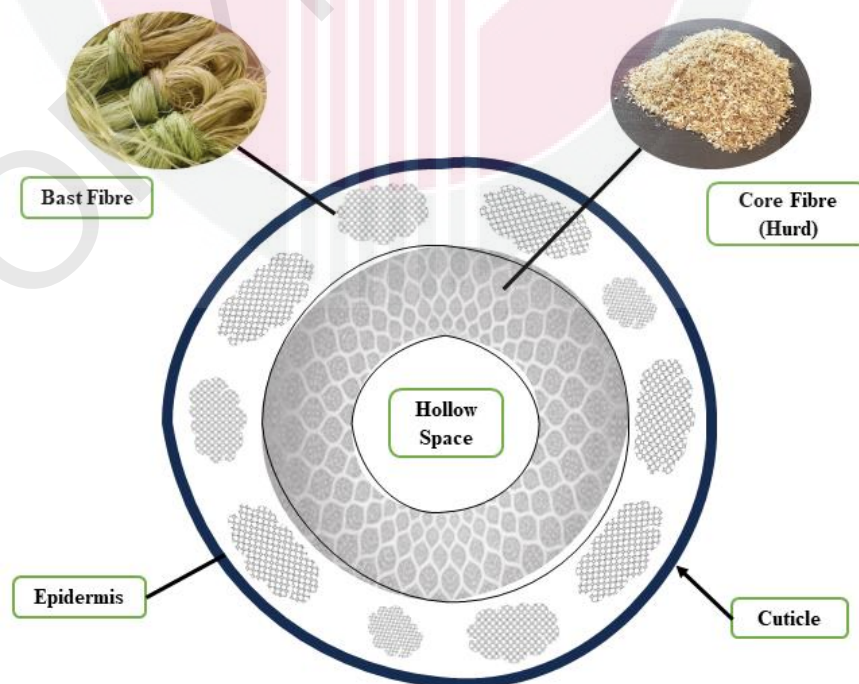


Figure 2.5: Anatomy bast and core fibres
(Source: El-Abbassi et al., 2020; Khoo et al., 2023)

To produce pultruded profiles from reinforced plant fibres with similar properties to GFRP, the processing parameters, fibre preforms in yarns and woven fabrics, and resin must be adapted to each other. Hence, research on optimum processing parameters, fibre size and loadings, and characterisation of pultruded plant fibre composites is important to develop eco-friendly pultrudes for commercial structural applications. To limit investments in new machinery, producing plant fibre profiles should be made possible in the same production plants and manufacturing setups as conventional GFRP profiles. For instance, parameters such as pulling speed, preheating conditions, the heating temperature in the die, and the cooling rate need to be adapted for the pultrusion of PFC profiles in the manufacturing industry (Joshi et al., 2003).

Angelov et al. (Angelov et al., 2007) have conducted a study on pultruded flax/polypropylene yarn, and their findings indicated that under certain conditions of speed and temperature, the pultruded profiles show good mechanical performance similar to composites fabricated using compression moulding. Linganiso et al. (Linganiso et al., 2013) stated that at higher die temperatures (290°C) and lower pulling speeds (0.5 m/min) during the process, the mechanical properties of pultruded flax-reinforced thermoplastic composites have improved. The improvement is due to the increased penetration within the reinforcement resulting from better melting and lower matrix viscosity at high temperatures and low pulling speed during the process.

Similarly, efforts have been taken by Fairuz et al. (Fairuz et al., 2015) to find the optimum process parameters for the pultrusion of kenaf reinforced composite through analysis of variance. The findings revealed that a pulling

speed of 0.4m/min, gelation temperature at 120°C and curing temperature at 180°C were the best combination of processing parameters for kenaf fibres. During pultrusion, it is essential to ensure that a low-viscosity resin is used to facilitate ease of resin penetration into fibre yarn. Besides that, voids inside pultruded PFCs are generally higher than pultruded synthetic fibre composites (Fairuz et al., 2015). It occurs due to high moisture content and poor wetting of plant fibres. Hence, the resin is formulated to contain the filler to reduce the use of resin and to fill in the porosity inside the composites. Table 2.4 shows several research works using plant fibres such as kenaf, jute and hemp. The significant findings based on the various test parameters used to study the properties of pultruded PFCs are highlighted in the literature review. According to the table, characterisation in mechanical and physical properties has been analysed on pultruded PFCs. Mechanical properties such as tensile, compressive, and bending studies have been conducted, while moisture absorption has been studied for physical properties.

2.4.1 Mechanical properties of pultruded plant fibre composites

Researchers investigating the mechanical properties of plant fibre composites have stated that the composites are suitable for low-load applications (Parbin et al., 2019; Saba et al., 2015). Hence, introducing plant fibres in conventional pultrusion manufacturing would lead to cost-effective and sustainable products for low-load structural applications. Generally, several factors affect the mechanical properties of plant fibre composites, such as moisture absorption, fibre alignment, fibre treatments, fibre distribution and the use of additives (Vedernikov et al., 2021). According to Table 2.4, plant-based fibres such as

jute, kenaf, flax and hemp are studied in developing pultruded composites. However, studies on pultruded kenaf and jute fibre composites have been extensively researched. From the literature study, different plant fibre reinforcement types have demonstrated different mechanical and physical properties. Such a circumstance is due to the difference in plant fibre properties such as cellulose content, degree of polymerisation and microfibrillary angle, which results in the different interface between the fibre and matrix. In this context, Omar et al. (Omar et al., 2010) found comparable dynamic mechanical properties between two different types of plant fibre reinforcements by analysing the dynamic compressive strength and strain rate properties of pultruded kenaf fibre reinforced composites and pultruded jute fibre reinforced composites. Jute fibre reinforced composites recorded higher dynamic compressive properties and better performance at high strain rate loading than kenaf fibre reinforced composites due to higher cellulose content and lower microfibril angle in jute fibres. However, kenaf reinforcements recorded higher values at low strain rate loading.

Osman et al. (Osman et al., 2014) studied the effect of alkali treatments at different concentrations of sodium hydroxide (3%, 6%, and 9% M) on the mechanical properties of pultruded kenaf fibre reinforced polyester composites. The researchers recorded that 6% of sodium hydroxide as the best treatment parameter as the tensile and bending properties of the composites have significantly improved. Chemical treatments improve the surface roughness of the fibres for better mechanical interlocking (Ahmad et al., 2019). It also enhances cellulose exposure on the fibre surface, increasing the number of possible reaction sites. Safiee et al. (Safiee et al., 2011)

analysed the compressive and bending properties of jute fibre-reinforced unsaturated polyester rods fabricated using pultrusion. The pultruded jute rods with 70% fibre content recorded 149 MPa and 890 MPa for compressive strength and bending strength, respectively. The composite rod demonstrated major failure modes: matrix yield, shear failure, fibre micro buckling, and pure fibre compressive failure. Another study was conducted by Velis et al. (Hedayati Velis et al., 2018) where jute, high-density polyethene, wood flour and starch were used as raw materials to develop pultruded tube profiles. The researchers compared the tensile properties by varying the matrix systems using jute fibres as reinforcement. The study introduced thermoplastic starch as a biopolymer matrix system and compared it with a high-density polyethene (HDPE) matrix system. The study revealed that jute/HDPE tubes have higher tensile strength and modulus when compared to other jute/thermoplastic starch tubes. Additionally, wood flour was tested as a filler in jute-reinforced HDPE composites. Adding 10% of wood flour filler to jute/HDPE improved the tensile modulus up to 8.27 GPa. However, the tensile strength of jute/HDPE decreases when wood flour is added due to the weak interface between the filler and matrix.

Research on filler loading, filler composition, fibre loading, yarn size, matrix system and immersion environment as tested parameters in pultruded PFCs has been demonstrated, and the best parameters from the tests are also highlighted. Similar findings on the optimum fibre loading (70%) for kenaf fibre reinforced pultruded composites were recorded by Zamri et al. (Zamri et al., 2016) and (Akil et al.) where the composites recorded the highest mechanical performance. Velde et al. (van de Velde et al., n.d.; van de Velde & Kiekens,

2001) studied thermoplastic pultruded profiles using flax fibre as reinforcement and compared its mechanical properties with pultruded Glass/Polypropylene composites. The bending and tensile properties of pultruded Flax/PP round profiles showed good values, although lower than those of Glass/PP rectangular profiles. The findings have proven the possibility of developing pultruded plant fibres using a thermoplastic matrix with good mechanical properties at a lower density ($0.08 \pm 0.04 \text{ g/cm}^3$).

Peng et al. (Peng et al., 2012) stated that hemp/wool fibre reinforced pultruded composite using a polyurethane resin system had higher tensile and compressive properties than vinyl ester and polyester resin systems. However, polyester composites show better bending strength. The study gave an overview of the importance of fibre impregnation and fibre–matrix adhesion between plant fibres and different matrix systems to ensure better mechanical and physical properties for applications of pultruded PFC as structural components. Additionally, studies on filler loadings and filler composition in pultruded PFCs were also conducted by Fairuz et al. (Fairuz et al., 2016) and Gupta et al. (Gupta et al., 2019) respectively. Typically, fillers are used in composites to reduce costs and improve properties. This is proven by Fairuz et al. when the tensile, compressive, and bending properties of kenaf-reinforced pultruded composites have improved with the increase of filler loading in the composite. However, the optimum amount of added filler loading is also necessary to avoid the resin getting too viscous with too high filler composition, resulting in voids and poor wettability in the composites

Table 2.4: Research on the characterisation of plant fibre reinforced pultruded composites

Year	Author	Raw materials	Tested variable	Parameters of variable	Test analysis	Obtained data		Volume percentage of eco-friendly material content
						Best parameter composition	Results	
Mechanical properties								
2023	Zakaria et al.(N. A. Zakaria et al., 2023)	Kenaf	Fibre orientation and fabrication method	0° fibre orientation (pultrusion)/ 45° fibre orientation (filament winding)	Tensile strength	0° orientation via pultrusion	39.16 MPa	-
2019	Gupta et al.(Gupta et al., 2019)	Jute + Unsaturated Polyester	Composition of hybrid filler	Bagasse/ Carbon black/CaCO3 (g)	Tensile strength Bending strength	Bagasse 25 g/ CB 5 g/ CaCO3 5 g Bagasse 35 g/ CB 5 g/ CaCO3 50 g	61.39 MPa 155.48 MPa	40-50% of jute fibres
2018	Velis et al. (Hedayati Velis et al., 2018)	Jute + Thermoplastic starch and high-density polyethene (HDPE)	Matrix system and filler	Jute/ thermoplastic starch, Jute/ HDPE, & Jute/ HDPE/ wood flour	Tensile strength Tensile modulus	Jute/ HDPE Jute/ HDPE/ 10% wood flour	81.9 MPa 8.27 GPa	35-40% of jute fibres
2016	Fairuz et al.(Fairuz et al., 2016)	Kenaf + Vinyl Ester	Filler loading (%)	20/30/40/50/60 (%)	Tensile strength Tensile modulus Bending strength Bending modulus Compressive strength	50% 50% 30% 50% 40%	150-155 MPa 10000 MPa 180 MPa 2000 MPa 80-85 MPa	40% of kenaf fibres

Table 2.5: Continued

2016	Zamri et al.(Zamri et al., 2016)	Kenaf + Unsaturated Polyester	Yarn (Tex) Fibre loading (%)	size 1400/2200/3300 (Tex) 60/65/70 (%)	Bending strength Bending modulus Compressive strength Compression modulus	Tex 1400/ 70% Tex 1400/ 70% Tex 1400/ 70% Tex 1400/ 70%	350-400 MPa 35-40 GPa 70-80 MPa 3.5-4.0 GPa	70% of kenaf fibres
2014	Osman al.(Osman et al., 2014)	Kenaf	Concentration of chemical treatment (%)	3%, 6% and 9% M Sodium hydroxide (NaOH)	Tensile strength Tensile modulus Bending strength Bending modulus Bending strength	6% of NaOH 6% of NaOH 6% of NaOH 6% of NaOH 70%	200-250 MPa 14-16 GPa 250-300 MPa 14-16 GPa 225-250 MPa	70% of kenaf fibres
2011	Akil et al. (Akil et al., 2011)	Kenaf + Unsaturated polyester	Fibre loading (%)	50/60/65/70/75 (%)	Bending strength	70%	225-250 MPa	70% of kenaf fibres
2011	Safiee et al. (Safiee et al., 2011)	Jute + Unsaturated polyester	Jute-reinforced unsaturated polyester pultruded rod	PJFRC	Compressive strength Compressive modulus Bending strength Bending modulus	-	149 MPa 7.4 GPa 890 MPa 2.6 GPa	70% of jute fibres
2010	Omar al.(Omar et al., 2010)	Kenaf and Jute + Unsaturated polyester	Dynamic mechanical properties	Pultruded kenaf and jute composites	Dynamic compressive strength Strain-rate sensitivity at lower strain-rate condition Strain-rate sensitivity at higher strain-rate condition	Jute reinforced composite Kenaf reinforced composite Jute reinforced composite	150.6 ± 5.9 MPa 4.2 MPa 150.6 MPa	70% of kenaf and jute fibres
2012	Peng al.(Peng et al., 2012)	Hemp (wool)	Matrix system	Polyester/ Ester/ Vinyl	Tensile strength	Polyurethane	122.66 MPa	30% of hemp and 5% of wool fibres
2001	Velde et al. (Velde et al., 2001)	Flax + Polypropylene	Comparison of mechanical properties	Polyurethane Pultruded Flax/PP and Glass/PP composites	Compressive strength Bending strength Tensile strength Bending strength	Polyurethane Polyester Flax/PP Glass/PP Flax/PP Glass/PP	50-60 MPa 180 MPa 145 MPa 515 MPa 101 MPa 135 MPa	38% of flax fibres

Table 2.6: Continued

<i>Physical properties</i>						
2012	Peng et al. (Peng et al., 2012)	Hemp (wool)	Matrix system	Polyester/ Ester/ Polyurethane	Vinyl water/ water / acidic solution	Highest percentage of water absorption (%)
2009	Akil et al. (Akil et al., 2009)	Jute + Unsaturated polyester	Immersion environment	Distilled water/ Sea water / acidic solution	Distilled water (bending)	17.83%
				Distilled water (compressive)	Distilled water (bending)	10.71%
				Distilled water (compressive)	Distilled water (compressive)	14.32%
				Distilled water (bending)	Distilled water (bending)	6.54×10^{-6} (mm ² /s)
				Distilled water (compressive)	Distilled water (compressive)	2.67×10^{-5} (mm ² /s)
2010	Nosbi et al. (Nosbi et al., 2010)	Kenaf + Unsaturated polyester	Immersion environment	Distilled water/ Sea water / acidic solution	Highest moisture content, Mm (%)	70% of kenaf fibres
				Diffusion coefficient, D (mm ² /s)	Diffusion coefficient, D (mm ² /s)	19.83×10^{-3} (mm ² /s)

2.4.2 Physical properties of pultruded plant fibre composites

The physical properties of plant fibre composites must be investigated to ensure the composites' longevity and durability. For instance, a high moisture absorption would lead to poor interfacial bonding between the fibre and matrix, resulting in mechanical failure in composites (Zakikhani et al., 2014). Besides analysing the mechanical properties of different resin systems, Peng et al. (Peng et al., 2012) also studied the physical properties by investigating the water absorption properties. As a result, hemp/wool fibre-reinforced polyurethane samples recorded the highest water absorption rate due to the presence of voids. Nosbi et al. (Nosbi et al., 2010) researched the water absorption properties of pultruded kenaf-reinforced unsaturated polyester composites. The composites displayed the highest absorption in distilled water, followed by acidic solution and seawater. The findings also indicated the decay in compressive properties with an increased water absorption rate. The failure properties of the composites were explained due to the formation of hydrogen bonding between the water molecules and cellulose presence in kenaf fibres.

Similarly, Akil et al. (Akil et al., 2009) evaluated the physical properties of pultruded jute fibre reinforced composites by testing the water absorption properties of the composites. The results revealed maximum water absorption in the samples immersed in distilled water, followed by acidic solution and seawater. They also recorded that the bending and compressive properties decreased with an increasing water absorption rate. However, compared to the study conducted by Nosbi et al., pultruded jute fibre composites show a

lower water absorption rate than pultruded kenaf-reinforced composites. This condition could be attributed to the better fibre matrix interface in jute-reinforced composite than kenaf-reinforced composite. Overall, the studies indicated that pultruded PFCs have limitations in application in aqueous environments, resulting in swelling and failure of the structure. However, further research on coatings and surface engineering on pultruded PFCs could widen the prospects of the material for outdoor applications.

The literature review has given an overview of research progress on pultruded PFCs over the years. The efforts taken by researchers to study the process parameters and characterisation in mechanical and physical properties of pultruded PFCs have validated the prospects and limitations for the development of commercial low load-bearing structural and non-structural products. Although the properties offered by pultruded PFCs are not as good as those of conventional fibreglass profiles, the composites showed better mechanical properties than some of the conventional plastics used in low-load structural and non-structural applications. Besides that, the optimum amount of plant fibres used in pultrusion could reach as high as 70% compared to other composite fabrication methods. This also shows that a large portion of synthetic materials (glass fibre reinforcements and plastics) in structures could be potentially replaced by plant fibre reinforcements via pultrusion. PFC pultruded profiles can be used in architectural and construction applications with relatively low loads. For instance, they can be used in window and door frames, curtain wall systems, decorative elements, handrails, and lightweight structural components that do not carry significant loads. Besides that, various types of plant fibres offer different properties that can be studied in the future

by implementing them into pultruded FRP composites. Hence, there is still a massive scope in designing and manufacturing pultruded products with PFCs. The world's concern to "go green" encourages researchers and industrialists to develop eco-friendly materials with good performance and sustainable properties.

2.5 Hybridizing plant fibres with synthetic fibres via pultrusion

Composites using two or more types of reinforcement or matrix are known as hybrid composites (M. Sanjay & Yogesha, 2017), which can be made from a combination of plant and synthetic fibres, synthetic and synthetic fibres, or plant fibre and carbonaceous materials (Nurazzi et al., 2021). Although plant fibres have advantages in pultruded composite production, the combination of plant fibres alone is insufficient to provide good mechanical properties. PFCs have several disadvantages, such as their low impact strength, high moisture absorption, low fire resistance and high temperature when compared with synthetic fibre reinforced composites, requiring them to be combined with synthetic fibres to enhance the mechanical performance and water-resistant properties. The hybridisation of plant fibres with synthetic fibres could reduce the limitations of both plant and synthetic fibres individually while producing materials with eco-friendly and durable advantages (Safri et al., 2018).

Multiple studies have been conducted on pultruded hybrid PFC to improve their properties through hybridisation with glass fibres to achieve materials with desired properties and improved performance. The three main factors affecting the properties of the hybrid composites are the selection of materials, preparation methods and the interaction between fibre and matrix (Mochane

et al., 2019). Other factors that should be considered while designing hybrid PFCs are the mechanical and physical properties, recyclability, environmental sustainability, disposability, cost, treatments, and test methods according to the intended applications. The three most used hybrid configurations are interlayer (layer by layer), interlayer, and inter yarn (Prabhu et al., 2021). Lackey et al. (Lackey et al., 2007) have successfully fabricated hemp/glass-reinforced pultruded composites using unidirectional hemp yarn and woven hemp fabrics. The study used pull speeds of 2.03 cm/s (48–60 in/min) and a die temperature of 177°C (350°F) to process hemp fibre without damage, as hemp could withstand 177°C processing temperature during pultrusion. The researchers also stated that the processing temperatures during the pultrusion of plant fibres are limited. Hence, a suitable process temperature is essential to avoid damage to the plant fibres.

Volumetric composition, such as volume fractions of fibres, matrix and porosity, is also one of the factors affecting the performance of the pultruded hybrid composites, such as mechanical, physical and thermal properties. Typically, the volumetric composition of composites is controlled during manufacturing of composites. However, a different approach has been conducted by Madsen et al. (Madsen et al., n.d.) to control the volumetric composition in pultruded hybrid composites. The researchers studied the volumetric composition in pultruded kenaf/glass-reinforced hybrid composites by developing a generic model and validating it with experimental data. The model can be used to control and design the volumetric composition in pultruded hybrid composites. This method effectively saves time and cost in finding the best composition in pultruded composites.

Most of the research on plant/synthetic fibre reinforced hybrid composite involves finding the best parameters to improve its mechanical and physical properties as a function of fibre loading, fibre preforms (length, shape and size), fibre orientation, stacking sequence, chemical treatments, fibre and matrix selection and adhesion between fibre and matrix (Karthi et al., 2020). The mechanical properties of hybridised composites depend on factors such as fibre loading, fibre orientation, stacking sequence, hybrid ratio and fibre-matrix interfacial strength (J. Neto et al., 2022; J. S. S. Neto et al., 2019). Research has been carried out on the hybrid plant/glass fibre composites using pultrusion processing, presented in Table 2.5. Mechanical, physical and tribological properties have been investigated on pultruded plant/glass fibre reinforced hybrid composites. Glass fibres have been used as the synthetic component, whereby kenaf and jute as plant fibres develop pultruded composites.

2.5.1 Mechanical properties of pultruded hybrid plant/glass fibre composites

All studies have validated that hybrid composites demonstrate better mechanical properties than pure PFCs. Zakaria et al. (K. Z. Zakaria et al., 2020), Hashemi et al. (Hashemi et al., 2015), and Malek et al. (Malek et al., 2014) have compared the mechanical properties of pultruded hybrid glass/plant fibre reinforced composites with pure pultruded PFCs. Pultruded hybrid glass/kenaf reinforced composites have outperformed pure pultruded PFC and GFC by recording higher bending strength and bending modulus at ratios of 60:40 and 80:20, respectively. According to Zakaria et al. (K. Z. Zakaria et al., 2020) and Akil et al. (Akil et al., 2010), hybridised composites

have shown better bending strength and modulus than pure pultruded PFCs. Hashemi et al. (Hashemi et al., 2015) have proven that at 0.09 β of glass/kenaf-hybrid-fibre mixing ratio, the composite has improved its interlaminar shear strength. However, as the hybrid fibre mixing ratio increases, the ILSS of composites decreases due to the moisture absorption properties of kenaf fibre that limit the impregnation of the fibres in the composites, hence forming voids.

A different approach was conducted by Memon et al. (Memon & Nakai, 2013) when jute in the form of tubular spun yarn and polylactic acid (PLA) resin fibres were commingled and hybridised with glass fibres to fabricate pultruded composites. The bending properties were analysed on the hybrid thermoplastic composites by varying the braided preforms and finding the composites' best processing temperature and filler ratio. The results revealed that the best bending properties were found at 205°C and 120% of processing temperature and filler ratio, respectively, for GF720 preform. Kumar et al. (N. Kumar et al., 2021) studied the influence of hybrid filler loading on jute/glass fibre reinforced hybrid pultruded composites. In their findings, the researchers stated that 9 Wt.% of hybrid filler loading is the optimum loading as the highest tensile and compressive strength is achievable by the composition. However, the highest impact strength is recorded when no filler is added to the hybrid composite.

2.5.2 Physical properties of pultruded hybrid plant/glass fibre composites

To analyse the physical properties of pultruded hybrid composites, Osman et al. (Osman et al., 2013) studied the moisture absorption properties of

pultruded glass/kenaf composites and compared the data with pure kenaf, and pure glass-reinforced pultruded composites. The findings indicated hybrid samples show lower moisture absorption properties than pure kenaf-reinforced composites. Although the hybrid composites were proven to absorb water at a slightly higher rate than pure glass composites, the difference was minimal. Zamri et al. (Zamri et al., 2012) analysed the water absorption properties of jute/glass fibre reinforced unsaturated polyester pultruded hybrid composites. They found that the composites show maximum absorption rate in distilled water followed by acidic solution and seawater. They also validated that hybrid composites show significantly higher mechanical and water absorption performance than pure plant fibre composites. The investigation highlighted that through glass fibre hybridisation, plant fibres tend to reduce their water absorption capacity. Both studies show that the bending and compressive properties tend to decrease with increased water uptake. Therefore, a lower water absorption capacity is highly preferred for applying pultruded hybrid PFCs outdoors.

Bassam et al. (Bassam et al., 2020) mentioned that the dielectric strength of kenaf/glass-reinforced unsaturated polyester hybrid composites was higher than that of pure glass-reinforced UPE composites. Bundled kenaf close together raised dielectric strength because plant fibres have better insulating properties, as evidenced by the burning effect. Moreover, the researchers also conducted another study analysing the effect of moisture absorption on the bending properties of kenaf/glass/UPE rods (Alaseel et al., 2022). The study highlighted that the bending strength of pultruded hybrid composites was

retained by the arrangement of kenaf fibre in a composite when the hydrophilic fibre was concentrated at the centre of a cross-section of the composite rod.

2.5.3 Tribological properties of pultruded hybrid plant/glass fibre composites

Tribological properties are the wear and friction properties of a material. Researchers recorded that plant fibres demonstrated less abrasive damage to processing equipment due to the high cellulose content of the soft fibres. Nasir et al. (Nasir et al., 2014) conducted a different approach to unidirectional glass-pultruded-kenaf (UGPK) composites by comparing their tribological properties with paddy straw-reinforced polypropylene, pure polypropylene, and pultruded glass fibre. The findings show that hybrid glass/kenaf pultruded composites scored the lowest wear rate and highest coefficient of friction compared to other samples, including pure glass fibre pultruded composites. It validates the strong bonding between fibre and matrix in pultruded kenaf/glass hybrid composites, making them a suitable alternative to conventional fibreglass profiles.

According to researchers, optimum fibre loading, and fibre treatment of plant fibres could result in better wear and friction properties (Nirmal et al., 2015; Sumithra & Sidda Reddy, 2018). Another study on the wear resistance of hybrid pultruded composites was conducted by Kumar et al. (N. Kumar et al., 2021) when tested with different loading parameters of hybrid fillers. From the experiments, 9 Wt.% loading of hybrid fillers recorded the highest wear resistance, scoring the lowest coefficient of friction (COF) in hybrid jute/glass

pultruded composites. The low coefficient of friction improved the wear resistance in the composites.

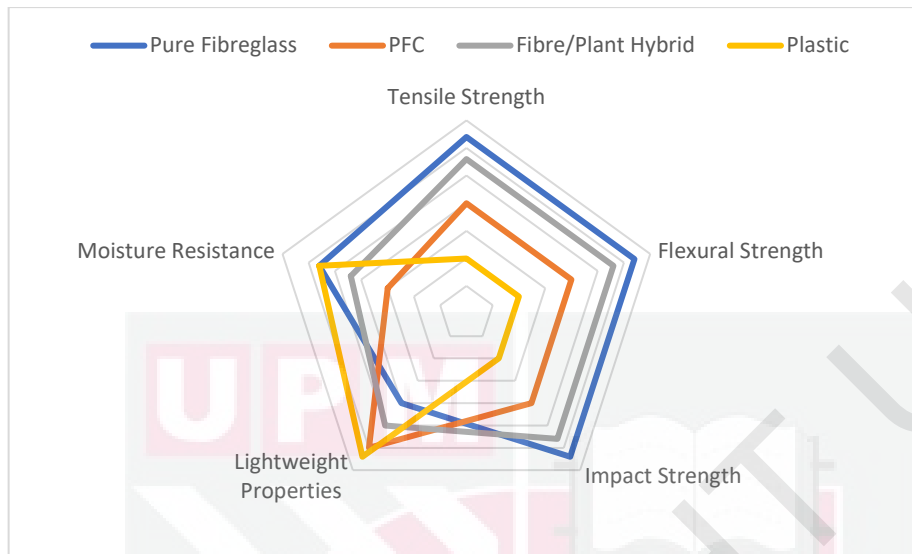


Figure 2.6: Graphical comparison of properties between synthetic materials and pultruded PFCs

In general, hybridisation of composites is known to be a method for overcoming the limitations of both plant and synthetic materials by combining multiple materials to utilise and enhance the individual characteristics of each material (Naga Kumar et al., 2019). Applying the hybridisation of plant and synthetic fibres into pultrusion will open opportunities in manufacturing high-performance structural profiles with advantages from both types of fibres. In most cases, the mechanical and physical properties of pultruded hybrid glass/plant fibre composites were not as high as pure fibreglass composites. However, they performed better than pure pultruded PFCs (Figure 2.6). However, pure plant fibre reinforced pultruded composites and hybrid glass/plant fibre hybrid composites demonstrate better properties than petroleum-based plastic materials. Pure pultruded PFCs are suitable for low load-bearing structural applications. In contrast, hybrid composites could replace pure

fibreglass composites in moderate load-bearing pultruded profiles in various industries such as aerospace, civil, marine, automotive and sporting goods. For instance, bicycle frames, seat frames, ladders, stairs, gratings, flooring beams and mezzanine floors are some examples of moderate load-bearing structural applications in which glass/plant hybrid pultruded profiles can be potentially applied. Overall, it can be concluded that hybridising plant fibres with synthetic fibres via pultrusion has shown impressive, improved properties compared to pure plant fibre and reinforced pultruded composites. Hence, it is crucial to analyse the application suitability of pultruded plant fibre reinforced composite profiles to match the product design criteria in terms of mechanical and physical performance

Table 2.7: Research on the characterisation of plant/synthetic fibre reinforced hybrid pultruded composites

Year	Author	Composite materials	Tested variables	Parameters variables	of	Test analysis	Obtained data Best composition	parameter	Results
<i>Mechanical properties</i>									
2021	Kumar et al. (N. Kumar et al., 2021a)	Jute/Glass + Polyester	Hybrid filler loading (Wt.%)	0/3/6/9/12/15		Impact strength Tensile strength Compressive strength	0 Wt. % 9 Wt. %		731.91 J/m 88.37 MPa
2020	Zakaria et al. (K. Z. Zakaria et al., 2020)	Kenaf/Glass + Unsaturated Polyester	Various types of pultruded composites	KFRP/ HFRP/ KFRPO4	GFRP/ KFRPC4/	Bending strength retention and recovery (Room Temp) Bending strength retention and recovery (Hygrothermal)	9Wt% HFRP		56.13 MPa 73.83% and 79.08% 46.04% and 47.90%
2019	Kumar et al. (N. Kumar et al., 2019)	Jute/Glass + Polyester	Variation in weight percentage of filler (Wt.%)	Coconut carbon eggshell ash	ash/ black/	Tensile strength Compressive strength	9% carbon black filler 15% egg shell filler		76 MPa 99.44 MPa
2015	Hashemi et al. (Hashemi et al., 2015)	Kenaf/Glass	Hybrid fibre mixing ratio (β)	0.00/ 0.09/ 0.22/ 0.38/ 0.63/ 1.00		Interlaminar shear strength	0.09 β		14.5 MPa
2014	Malek et al. (Malek et al., 2014)	Kenaf/Glass + Resol phenolic type	Different ratios of glass/ kenaf hybrid FRP composites with and without additives	Glass: Kenaf, 0:100/ 20:80/ 40:60/ 60:40/ 80:20/ 100:0		Bending strength Bending modulus	60:40 (With additives) 80:20 (With additives)		110-120 MPa 900-1000 MPa
2013	Memon et al. (Memon & Nakai, 2013a)	Jute Spun Yarn/PLA/Glass	Different braided preforms, pultrusion temperature, filling ratio	GF520/ GF720/ GF1150		Bending strength Bending modulus	Braided preform = GF720 Temperature = 205°C Filling Ratio = 120%		31.83 MPa 10.40 GPa

Table 2.8: Continued

2010	Akil et al. (Akil et al., 2010)	Jute/Glass + Polyester Kenaf/Glass + Polyester	Type of glass/plant fibre composites	Pultruded jute/glass and kenaf/glass hybrid polyester composites	Bending strength Bending modulus	Jute/Glass Jute/Glass	325-350 MPa 20-25 GPa
<i>Physical properties</i>							
2022	Bassam et al. (Alaseel et al., 2022)	Kenaf/Glass + Polyester	Volume fraction of kenaf and glass fibres	20KGPE/ 40KGPA/ 30KGPE/ GUPE	Reduction of bending properties due to water absorption (%)	30KGPE hybrid	24%
2020	Bassam et al. (Bassam et al., 2020)	Kenaf/Glass + Polyester	Volume fraction of kenaf and glass fibres	20KGPE/ 40KGPA/ GUPE	Dielectric strength (kV/mm)	30KGPE hybrid	2.73 kV/mm
2013	Osman et al. (Osman et al., 2013)	Kenaf/Glass	Type of glass/plant fibre composites	PKRC/ PKGRC	Maximum moisture content (%)	PKGRC (Bending sp.) PKGRC (Compression sp.)	3.789% 6.47%
					Diffusion coefficient (m ² /s)	PKGRC (Bending sp.) PKGRC (Compression sp.)	2.256 x10 ⁻¹¹ m ² /s 3.290 x10 ⁻¹¹ m ² /s
2011	Zamri et al. (Zamri et al., 2012).	Jute/Glass + Unsaturated polyester	Immersion environment	Distilled water/ Sea water/ Acidic water	Maximum moisture content (%)	Distilled water (Bending sp.) Distilled water (Compression sp.)	4.46% 5.16%
					Highest diffusion coefficient (m ² /s)	Distilled water (Bending sp.) Distilled water (Compression sp.)	7.14 x10 ⁻¹² m ² /s 2.68 x 10 ⁻¹¹ m ² /s

Table 2.9: Continued

<i>Tribological properties</i>						
			Hybrid filler loading (Wt.%)	0/3/6/9/12/15	Coefficient of friction (COF)	9 Wt.%
2021	Kumar et al. (N. Kumar et al., 2021b)	Jute/Glass + Polyester	Type of pultruded hybrid plant fibre composites	Polypropylene/PSRP composite/pultruded glass-fibre/ unidirectional glass-pultruded-kenaf	Lowest wear rate Coefficient of friction (COF)	Unidirectional pultruded kenaf
2014	Nasir et al. (Nasir et al., 2014)	Kenaf/Glass				glass 4.02 × mm ³ /Nm 3 - 4.5
						glass 3 - 4.5
						Unidirectional pultruded kenaf

2.6 Future scope of plant fibre reinforced pultrusion

Pultruded composites have gained significant traction across a multitude of industries and market sectors due to their exceptional versatility and performance capabilities (*Pultruded Composites Market Growing, Says EPTA* | *CompositesWorld*, n.d.; Vedernikov et al., 2020). The Asia Pacific region is poised to emerge as a dominant player in the pultrusion market, primarily driven by its surging demand for pultruded products (*Key Development Opportunities for the Pultrusion Market*, n.d.; *Pultrusion Market Size, Share, Industry Forecast 2029*, n.d.; *Pultrusion Products Market Size, Trends - Industry Outlook Report 2028*, n.d.). These versatile pultruded profiles find extensive use in various sectors, including construction, automotive, aerospace, maritime, utilities, and energy. Their appeal lies in the ability to serve both straightforward and complex structural applications. Notably, pultruded profiles offer the advantage of uniform cross-sections and the flexibility to be manufactured in varying lengths, making them adaptable to diverse project requirements. Furthermore, the ease of working with pultruded profiles, whether cutting, painting, drilling, or attaching them to other materials using adhesives, rivets, screws, or bolts, enhances their practicality in diverse applications.

As the utilisation of pultruded profiles continues to expand across industries, the imperative for sustainable materials becomes increasingly apparent. This is where plant fibres come into the spotlight, serving as cost-effective, eco-friendly, and lightweight alternatives. They offer a promising solution for developing sustainable structural profiles, particularly in low to moderate load-

bearing applications. Integrating plant fibre yarns and woven plant fibre mats into the conventional pultrusion process requires minimal modification to the existing setup (Figure 2.7), making it a feasible and eco-conscious transition (Baley et al., 2020). This innovation aligns with sustainability goals and capitalises on the inherent benefits of plant fibres to create more environmentally responsible and efficient structural solutions for a wide range of applications.

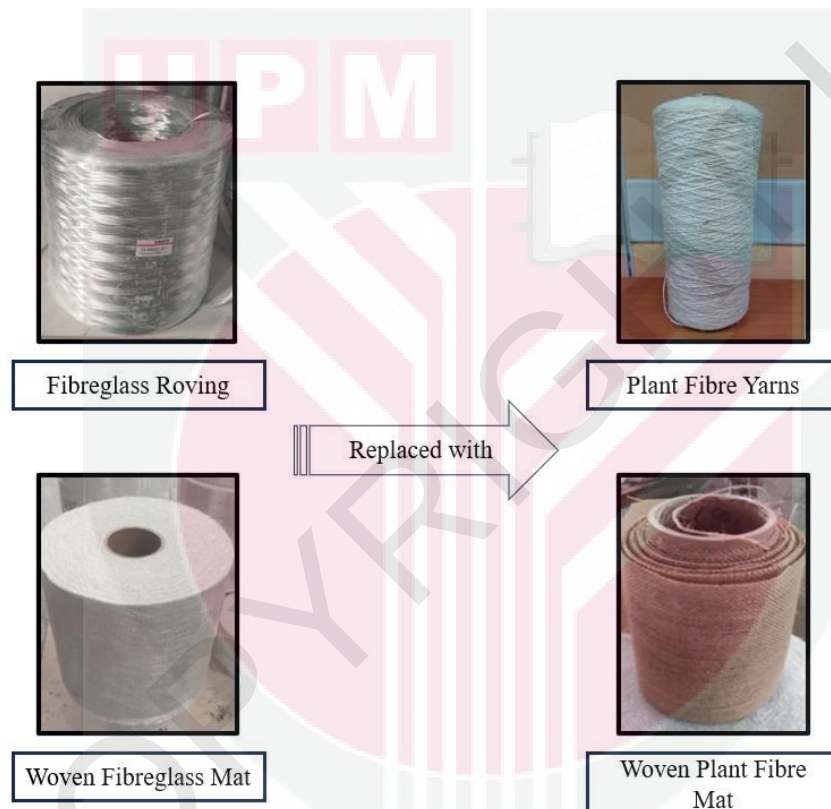


Figure 2.7: Plant Fibres in yarn and woven form as sustainable alternatives in pultrusion

While pultruded Plant Fibre Composites (PFCs) exhibit commendable mechanical properties well-suited for low to moderate-load applications, it is essential to acknowledge their inherent limitations. These limitations, including high water absorption, limited flame retardancy, and low chemical and UV resistance properties, render them less suitable for deployment in harsh

outdoor and aqueous environments (Bourmaud et al., 2020). To unlock the full potential of PFCs in such challenging settings, it is imperative to delve into further research focused on enhancing their performance.

One promising improvement avenue lies in exploring advanced coatings and surface engineering techniques tailored explicitly for pultruded PFCs (Ding et al., 2022; Pourhashem et al., 2020; Wang et al., 2019; S. Da Wu et al., 2023). These innovations aim to mitigate the limitations and bolster their applicability in extreme conditions. For instance, integrating surfacing veils represents a crucial area of investigation. These veils can enhance temperature stability, fire resistance, chemical resistance, abrasion resistance, and moisture resistance in pultruded profiles reinforced with plant fibres. PFCs can become more resilient and adaptable to demanding outdoor and aqueous environments by addressing these key attributes. An investigation by Kandare et al. (Kandare et al., 2014) demonstrated that the fire-retardant properties of balsa-flax/epoxy laminates significantly improved when a thin glass fibre veil impregnated with ammonium polyphosphate was used as a surfacing veil. The researchers mentioned that applying fire retardant surfacing veils in plant-fibre composites proves their potential in semi-structural engineering applications threatened by fire. Studies have also been carried out on fibre coatings for plant fibres in composites to enhance their compatibility with the surrounding matrix material, improving adhesion and overall composite performance (Arulvel et al., 2021; Mysamy & Krishnasamy, 2022). These fibre surface coatings can mitigate moisture absorption and fibre-matrix bonding issues, leading to stronger and more durable PFCs for structural profile

applications. According to Page et al. (Page et al., 2021), linseed oil coating on flax fibre reinforcement improved the bending strength of the composites.

In addition to examining fibre reinforcements, an equally crucial aspect deserving of attention lies in selecting matrix systems used in pultruded Plant Fibre Composites (PFCs). This facet has seen a notable shift in focus, driven by the emergence of bio-based resins and innovative thermoplastic pultrusion techniques. Bio-based resins have risen to prominence as they enhance the sustainability quotient of these profiles and seamlessly align with broader eco-friendly objectives. Researchers and industrialists have developed resins derived from plant oil and starches, a distinct departure from conventional petrochemical-based options (Cataño et al., 2023). Notably, this shift toward bio-based resins has encompassed various renewable alternatives, including olive oil, sunflower oil, soybean oil, corn oil, castor oil, rapeseed oil, and linseed oil (Bassett et al., 2016; Latif et al., 2020). The research landscape is ripe for exploring abundant renewable alternatives, such as cellulosic plant fibres and vegetable oil-based bio-resins, which promise to achieve 100% sustainable pultruded profiles.

Additionally, using thermoplastic pultrusion allows for more excellent recyclability of the composites, minimising their environmental footprint (Awais et al., 2021; Chen et al., 2019; Lessard et al., 2022). This approach fosters a holistic approach to materials development, ensuring that PFCs meet performance demands and align with sustainability and environmental considerations. Several studies on thermoplastic pultrusion have been recorded by Minchenkov et al. (Minchenkov et al., 2021, 2022). The

researchers stated that replacing thermosets with thermoplastics in pultrusion benefits in improved impact strength, recyclable, and allows welded joints in pultruded profiles. However, thermoplastic resin has a significant problem for its application in pultrusion. Due to its high melt viscosity, which hinders fibre impregnation, prepregs such as tow pregs, commingled yarns, and preconsolidated tapes are used in thermoplastic pultrusion (Minchenkov et al., 2023; Vedernikov et al., 2022). To facilitate plant fibre reinforcement in thermoplastic pultrusion, plant fibre prepregs are another unexplored scope of research which needs significant attention. Parameters such as the resin flow, impregnation, crystallisation, heat transfer, and pulling speed must be investigated when different resin systems are used (Alsinani et al., 2021; Alsinani & Laberge Lebel, 2022).



Figure 2.8: Moderate and low load application possibilities of pultruded PFCs

Expanding upon the review, it becomes evident that further investigation into various mechanical properties is imperative for harnessing the full potential of

plant fibres in pultruded structural profiles. While the existing research has shed light on essential aspects, such as tensile strength and stiffness, it is equally essential to explore properties like fatigue resistance, creep behaviour, damping properties, and thermomechanical attributes (M. Z. Rahman, 2021; Yu et al., 2023). The determination of glass transition temperatures is of particular significance, which can provide valuable insights into the temperature ranges within which these profiles can perform optimally. In addition to the considerations mentioned earlier, it is crucial to emphasise the need to develop novel methodologies for determining the optimal parameters in the pultrusion process of Plant Fibre Composites (PFCs) through numerical modelling and machine learning (A. Safonov et al., 2020; A. A. Safonov et al., 2018; Sandberg et al., 2020; Sandberg, Yuksel, Baran, Spangenberg, et al., 2021; Tucci et al., 2020). This entails leveraging computational tools and simulations to fine-tune various processing parameters, such as temperature profiles, pulling speeds, and resin formulations. By utilising computer predictive methods, researchers and manufacturers can achieve greater precision and efficiency in the pultrusion of PFCs, ultimately leading to improved product quality, reduced material waste, and enhanced sustainability (Duchet-Rumeau et al., 2022).

Researchers are actively contributing their findings to address the inherent limitations of pultruded Plant Fibre Composites (PFCs), aiming to position them as a viable and eco-friendly choice for manufacturing profiles across diverse sectors. The trajectory for the adoption of both pure and hybrid pultruded composites derived from PFCs is expected to experience significant

growth on a global scale (Johnson et al., 2016). As researchers and industrialists continue to refine the selection of reinforcements and optimise processing techniques, there is a tangible opportunity to design and develop structural materials that prioritise environmental sustainability and offer economic advantages (Kamarudin et al., 2022). Figure 2.8 and Table 2.6 illustrate a range of potential applications for pultruded PFCs across various industries, focusing on applications involving low to moderate loads.

Table 2.10: Potential industrial applications of pultruded PFCs

Industries	Applications
Aerospace	Maintenance platforms and ladders, aircraft interior profiles, satellite components, drone components, upper deck floor beams.
Construction	Residential and commercial windows, doors, frame profiles, electrical supports, roll-up door panels, construction board, insulation board.
Electrical and Electronics	Switch boxes, cored tubing, cable trays, static arrestors, trunking.
Transportation	Automotive components, fittings, enclosures, chassis rails, bumper beams, roof beams.
Utilities and other applications	Utility poles, tool handles, demisting blades, cross arms, line markers, non-conductive ladders and rails, fibre optic cabling, fishing rods, ski poles, tennis rackets.

(Source: Ramasubbu & Madasamy, 2020)

Overall, implying plant fibres into pultruded composites represents a significant step in manufacturing high-performance and environmentally friendly materials for structural and non-structural applications that can potentially replace and reduce the use of synthetic fibres and plastic materials in numerous applications and industries. Besides being a sustainable alternative, PFCs could also potentially reduce the carbon emissions from the petrochemical production plants of synthetic fibres and plastics, causing numerous negative environmental issues in the past few decades. Developing

sustainable materials is related to the environment's social and economic status, which ensures a carbon-free environment while improving the standard of life (Agan & Balcilar, 2022; Du et al., 2019). Hence, the implication of plant fibres in uplifting green technology serves numerous advantages economically, socially, and environmentally. These efforts are believed to uplift the agricultural industry for composite manufacturing and create more job opportunities among the farmers and labours in the agricultural sectors. Besides, waste materials such as pineapple leaf fibres, coir, sugarcane, and oil palm fibres can be innovated efficiently into producing pultruded PFCs, which can be used in various applications. The innovations in eco-friendly materials do not significantly contribute to solving sustainability issues for the economies with low-income levels. At the same time, the mitigation effect becomes significant for those with developed economies (Agan & Balcilar, 2022; Du et al., 2019; Yi et al., 2019). Therefore, the government and private agencies of the developed economies should encourage the R&D sectors and industry players to make green materials emerge in the near future.

2.7 Summary

From the review conducted, the following conclusions can be drawn:

- i. The implication of plant fibres such as kenaf and jute in pultruded plant fibre composites and pultruded hybrid glass/plant fibre composites show good properties, proving the capability as alternatives to conventional pultruded fibreglass in low load and moderate load bearing structural, and non-structural applications.

- ii. Potential applications of plant fibres in pultruded FRP composites and their limitations are identified based on the mechanical and physical characterisation of pure and hybrid pultruded PFCs.
- iii. The application of plant fibres in developing pultruded products with their excellent low weight, low cost, good mechanical properties, and environmentally friendly properties will improve the sustainability and environmental issues. Besides that, applying plant fibres in developing pultruded products will also improve the agricultural sector and open more job opportunities to farmers, industrialists, and industrial employees, who could bring numerous economic, environmental, and social benefits.
- iv. There is still a huge scope of work ranging from process parameters optimisation and material characterisation to product development for pultruded PFCs to make them competitive with synthetic fibres in commercial applications.

Analyzing the literature review, Table 2.7 demonstrates the gap in previous research, and it is addressed in this research. While previous research has primarily centered on pultruded rods, there is a recognized need to explore alternative cross-sections to broaden the applicability of the findings. Additionally, despite achieving notable strength, it is acknowledged that the attained levels may be insufficient for certain structural profile applications. To address these gaps, this research endeavors to investigate open and closed wall structural profile geometries beyond conventional rod shapes, potentially uncovering profiles better suited for structural purposes.

Table 2.11: Table of gap

Gap identified	How research addresses gap
Limited exploration of alternative cross-sections	The research aims to investigate alternative cross-sectional geometries beyond conventional rod shapes to broaden applicability.
Insufficient strength for structural profile applications	The study acknowledges the need to achieve higher strength levels for structural profile applications and seeks to optimize material composition and manufacturing processes accordingly.
Utilization of plant fibers in the form of yarns	While yarns have been utilized, the research recognizes the importance of further exploring diverse forms and configurations of plant fibers to enhance composite performance.
Limitation in practical validation for structural applications	The research plans to conduct real-world testing and validation of developed structural ladder in collaboration with industry partners, bridging the gap between theory and application.

Moreover, while plant fibers in the form of yarns have been utilized, the study recognizes the importance of further exploring plant fibers in woven mat which provides bidirectional strength in composites. To overcome the limitation of practical validation for structural applications, this research plans to conduct a case study of the developed structural ladder. By leveraging collaborations with industry partners and conducting rigorous performance testing, this study aims to bridge the gap between theoretical research and practical implementation.

CHAPTER 3

METHODOLOGY

In this chapter, the flowchart, materials used and methodology that were applied throughout this experimental research is explained. The procedures and methods applied during the research is indicated in methodology.

3.1 Introduction

Glass fibre and plant fibres chosen from AHP methodology were used to fabricate the hybrid composites with different compositions. Overall, this study was divided into six main stages as indicated below.

- i. Selection of plant fibre using AHP methodology.
- ii. Fabrication of hybrid composites with different stacking sequences.
- iii. Mechanical characterization is carried out on the hybrid composites with different stacking sequences.
- iv. Fabrication of hybrid pultruded profiles
- v. Izod, Fatigue and density tests are carried out on the hybrid pultruded composites.
- vi. Designing, fabrication and testing of working prototype ladder from the identified best composition of hybrid composite material.

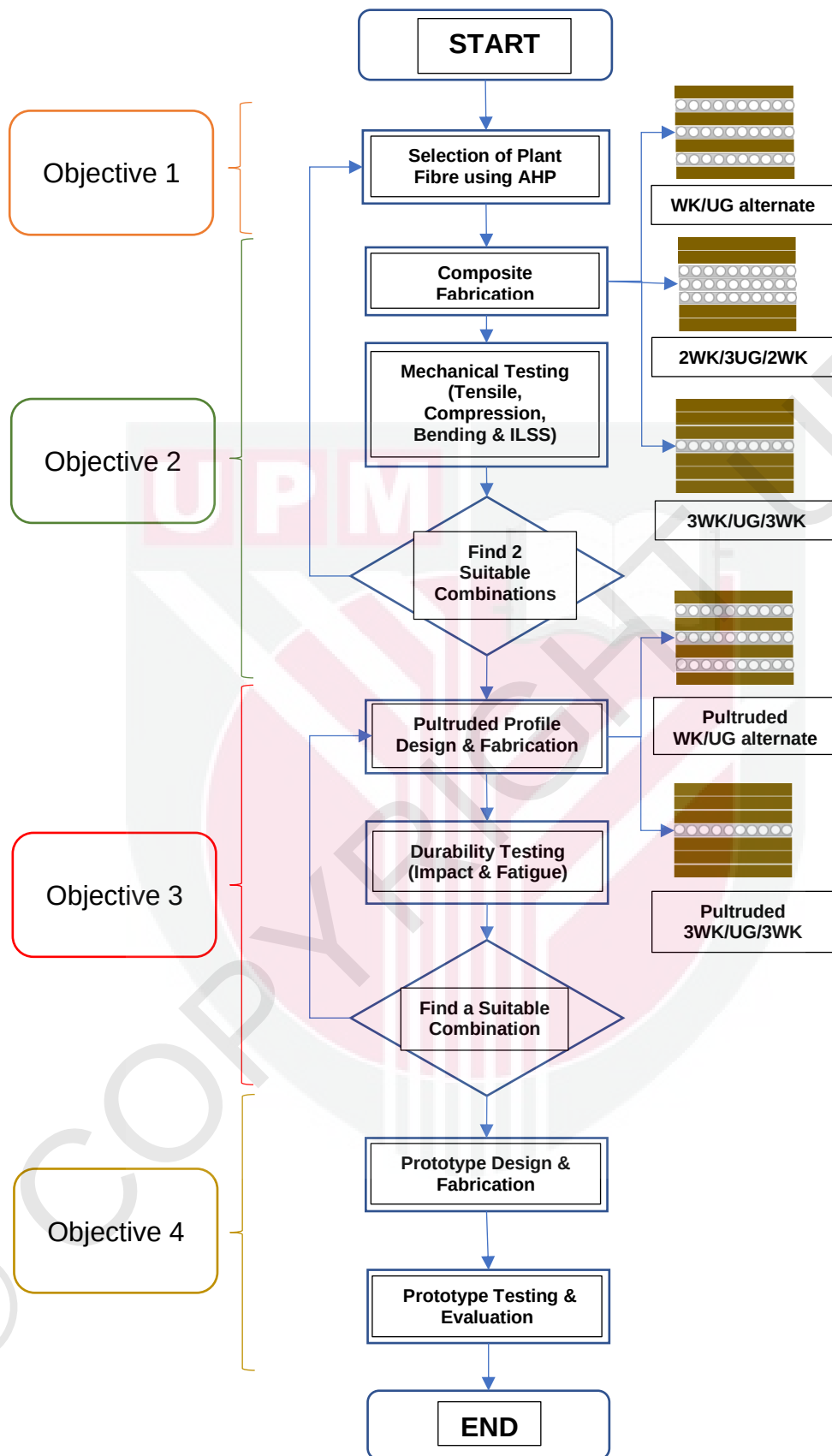


Figure 3.1: Research flowchart

The fabrication and testing process for the experiment was carried out in Institute of Tropical Forestry and Forest Product (INTROP), UPM. Figure 3.1 shows the flowchart of the experiment. The methodology section of this thesis begins with an overview of the research flow chart, which outlines the sequential progression of activities conducted to achieve the research objectives. The flow chart serves as a visual guide, illustrating the key steps involved in the design process and providing clarity on the overall research framework.

Objective 1 involved the selection of plant fiber using the Analytic Hierarchy Process (AHP) methodology. This objective aimed to identify the most suitable plant fiber for integration into the hybrid composites. Objective 2 focused on the fabrication of hybrid composites with varying stacking sequences. Following the selection of plant fiber, this objective aimed to create plant/glass hybrid composites with different compositions for open and closed wall structural profiles with 6 mm thickness. Subsequently, mechanical characterization tests were conducted to assess the performance of these hybrid composites. Objective 3 in methodology includes the fabrication of hybrid pultruded profiles and the conduct of Izod, fatigue, and density tests on these profiles. Finally, Objective 4 culminates in the design, fabrication, and testing of a working prototype ladder using the optimal composition of hybrid composite material identified through earlier experimentation. Through this structured approach, the methodology section provides a comprehensive overview of the research methodology employed in this study, ensuring transparency and clarity in the research process.

3.2 Selection of suitable plant fibre using AHP

As the first objective of the study, Analytic Hierarchy Process (AHP) methodology is used in determining a suitable plant fibre to be applied in structural profile applications.

3.2.1 Criteria in the selection of plant fibre for pultruded structural application

Setting the criteria plays a big role in the selection of plant fibres. Generally, the primary design factors to be considered to develop pultruded glass/plant fibre composites in structural applications are mechanical performance, weight, sustainability, and availability. In this study, the mechanical properties, physical properties, chemical properties, and availability were considered in setting the criteria. Table 3.1 shows the mechanical, physical, and chemical properties of plant fibres used in the AHP analysis. The six selected criteria are listed as follows.

i. Tensile strength

Tensile strength is the maximum load a material can withstand before failure. It is one of the basic requirements in developing structural components to withstand the forces applied before breaking under tension. Fibre strength is associated with improved tensile properties in the yarns and hence the composite (Mathangadeera et al., 2020). Besides, tensile properties are also important to avoid fibre breakage during pultrusion processing which causes defects in the finished product. This is due to the higher pulling force exerted on the pulling fibres during pultrusion processing. Therefore, it is important to

select a fibre with higher tensile strength to avoid any failure during the pultrusion process and structural applications. Plant fibres have recorded an acceptable tensile strength to be applied in composites although glass fibres recorded higher tensile strength of around 3400 MPa. Hence, hybridizing glass fibres with moderate strength plant fibres are expected to produce sustainable, cost and weight saving composites without sacrificing much tensile properties when compared to conventional pultruded fibreglass composites. The maximum intensity scale value was given to fibres with high tensile strength and the least scale was given to fibres with low tensile strength. Flax, kenaf, pineapple leaf, jute, and hemp fibres offer good tensile properties and hence were given a high intensity scale value.

ii. Tensile modulus

Tensile modulus, which is also known as young's modulus, is a measure of elasticity. Tensile modulus is the ratio of stress to strain applied along the longitudinal axis of the material. In that context, materials with high tensile modulus are stiffer than materials with low modulus. Fibres with higher modulus ensure good load transfer between the fibre and matrix, hence, improving the modulus of the composite (R. Rahman & Putra, 2019). In this study, reinforcements with high tensile modulus were preferred to ensure a rigid composite for structural members. Flax, hemp, kenaf, and pineapple leaf fibres have high tensile modulus, hence were given the maximum intensity scale value.

iii. Density

Plant fibres typically have a lower density, hence resulting in lower weight composites when compared to synthetic fibre in reinforced composites. Another criterion in the fibre selection is the fibre density as it is directly related to the weight of structures, whereby the fibre's density highly affects the ratio of strength-to-weight of the composites. The hybridization of glass/plant fibre reinforced composites has led to better mechanical properties and higher strength-to-weight ratio. Fibres with lower density are preferred to reduce the overall weight of the composites, thereby achieving structural components with light weight. Hence, higher priority vector after tensile properties was given to the density criteria in respect of the goal as hybrid glass and plant fibre in reinforced composites provide significant effects on the structural weight of composites when compared to conventional synthetic fibre reinforced composites. A maximum relative intensity scale value was given to fibres with lower density while a minimum scale was set for fibres with higher density.

iv. Elongation at break

Elongation at break is used to determine the ductility of the material. Hence, the higher the elongation at break percentage, the higher the ductility of composites. High ductility composites will be more likely to deform and not break, whereas low ductility makes it brittle and fractures before deforming much under a tensile load (Tcharkhtchi et al., 2015). Materials with good elongation properties aid in dissipating the kinetic energy of the structure upon plastic deformation. Therefore, by absorbing the impact before breaking,

ductile materials reduce the safety risks. Additionally, fibres with a high degree of elongation produce fabrics with superior properties such as tensile, tearing strengths, and flex resistance (Mathangadeera et al., 2020). Generally, synthetic fibres such as glass fibres show better mechanical and physical properties compared to plant fibre. However, the specific modulus and elongation at break are better in plant fibres than the synthetic fibres (Djafari Petroudy, 2017). These advantages of plant fibre properties serve as an important factor in developing plant/synthetic fibre reinforced hybrid composites which eliminates the weakest aspects from both plant and synthetic fibres while producing environmentally friendly materials with superior properties than conventional materials in structural applications. Alternatives with higher elongation were focussed on the analysis by setting them at a higher relative intensity scale.

v. Cellulose content

The chemical composition of plant fibre typically consists of cellulose, hemicelluloses, and lignin (Lu et al., 2012). Cellulose is one of the main components in plant fibres present in the form of cellulosic micro fibrils in the inner layer of primary wall. Cellulose is crystalline with good strength whereas hemicelluloses have random, amorphous structure with lower strength. Cellulose is made up of a linear chain of β -1, 4 linked D-glucose units which serves as the main element in the plant's cell walls by providing a stiff and rigid structure to the plants. Generally, the reinforcing efficiency of cellulose fibres in plant fibre composites depends on the cellulose content and their crystallinity. A high cellulose content and low fibrillary angle improve the tensile

properties in composites. Cellulose chains link to form micro fibrils, in which the multiple hydroxyl (OH-) groups on the glucose residues hydrogen bond with each other, holding the chains firmly together and contributing to their high tensile strength (Ravindran et al., 2019). Typically, crystallization in cellulose can reach up to 50–60% (Kim et al., 2016). The crystallized structure of cellulose can result in better mechanical properties, such as a modulus of elasticity at approximately 150 GPa. Therefore, fibres with higher cellulose content are desirable to the application and have been rewarded a maximum intensity scale compared to fibres with lower cellulose content.

vi. Local availability

The availability of plant fibres locally in Malaysia was also considered in the AHP analysis. Availability plays a vital role in developing structural parts and products so that the raw material supply is sufficient during production. Kenaf fibres and pineapple leaf fibres are widely available locally and hence given the most priority scale compared to other fibres. However, a minimum intensity scale value was given to 'local availability' in respect of the goal compared to other criteria included in this study. Technical criteria (tensile strength, tensile modulus, density, elongation, cellulose content) were given more weightage than availability.

Table 3.1: Mechanical, physical and chemical properties of fibres (Data used in AHP software)

Fibres	Tensile strength (MPa)	Tensile modulus (GPa)	Density (g/cm ³)	Elongation (%)	Cellulose content (%)	References
Bagasse	20-290	19.7-27.1	1.2	1.1	52.4	(Jawaid & Abdul Khalil, 2011; John & Anandjiwala, 2008)
Bamboo	230-295	17	1.1	11	54.6	(Abdul Khalil et al., 2012; Javadian et al., 2019; John & Anandjiwala, 2008; Shah et al., 2016)
Banana	355	33.8	1.35	5.3	65	(Jawaid & Abdul Khalil, 2011)
Coir	220	6	1.25	15-25	43	(Jawaid & Abdul Khalil, 2011)
Cotton	400	12	1.51	3-10	82.7	(Jawaid & Abdul Khalil, 2011)
Flax	500-1500	60-80	1.4	1.2-1.6	64.1	(Jawaid & Abdul Khalil, 2011)
Hemp	550-900	70	1.48	1.6	74.4	(Jawaid & Abdul Khalil, 2011)
Jute	400-800	10-30	1.46	1.8	64.4	(Jawaid & Abdul Khalil, 2011)
Kenaf	930	53	1.2	2.7-6.9	53.4	(Jawaid & Abdul Khalil, 2011)
Oil Palm	248	3.2	1.55	2.5	65	(Jawaid & Abdul Khalil, 2011)
Pineapple leaf (PALF)	170-1627	53	1.5	1-3	70	(Jawaid & Abdul Khalil, 2011; Todkar & Patil, 2019)

Table 3.2: Continued

Ramie	500	44	1.5	2	68.6	(Jawaid & Abdul Khalil, 2011)
Sisal	600-700	38	1.33	2-3	65.8	(Jawaid & Abdul Khalil, 2011)
E-glass	2000-3500	70	2.5	2.8	-	(Mansor et al., 2013)



3.2.2 AHP methodology

Typically, there are several stages in carrying out an analytical hierarchy process (Hambali et al., 2010; Mansor et al., 2013). The steps in an analytical hierarchy process are demonstrated in a flowchart (Figure 3.2).

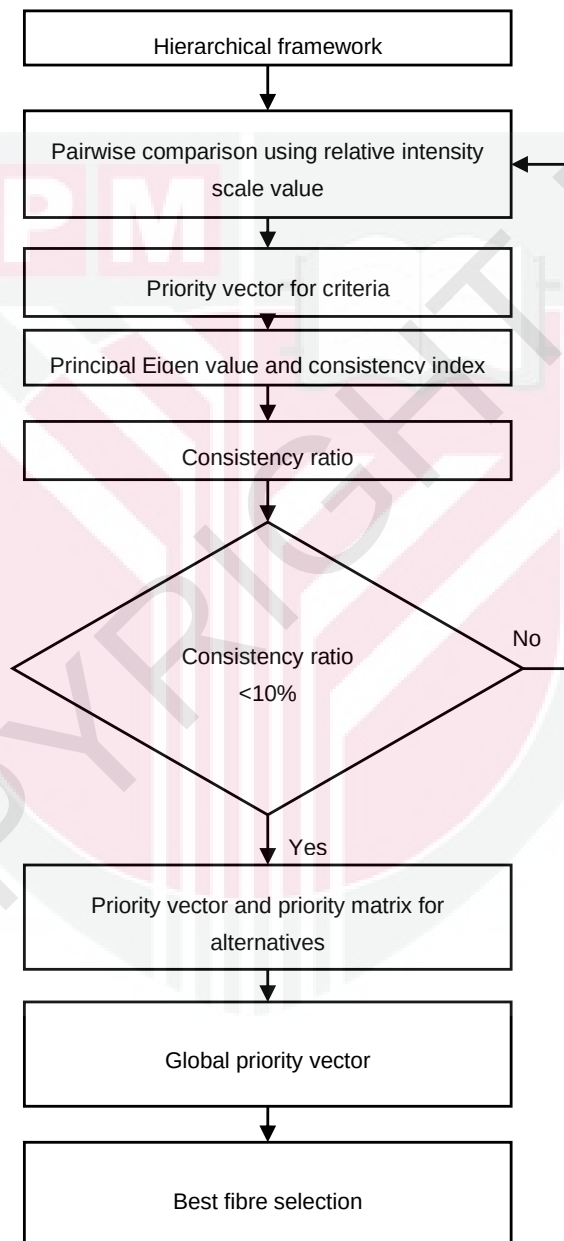


Figure 3.2: AHP methodology flowchart

A hierarchical structure was developed to define the goal, criteria, and alternatives. The hierarchical structure of the AHP methodology is presented in Figure 3.3. The first level shows the overall goal for Analytical Hierarchy Process. Based on the requirements to develop pultruded FRP profiles, six criteria were determined as the selection parameters, as shown in the second level of the hierarchical structure. The third level lists the plant fibres (alternatives) considered as candidate materials for hybridization with glass fibre for pultruded composites in structural applications.

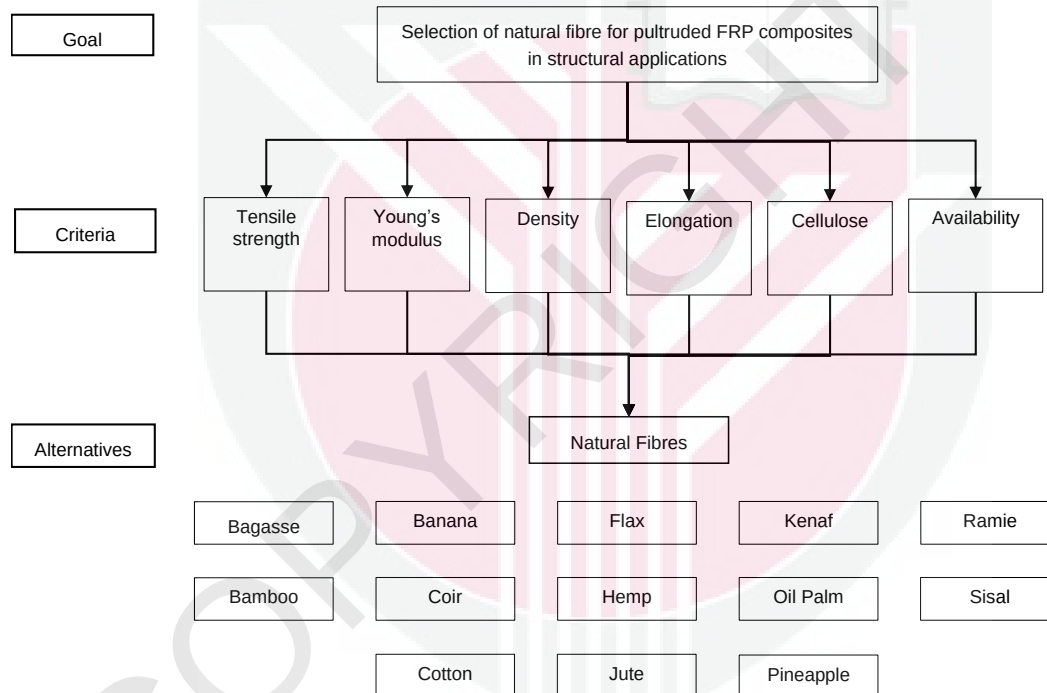


Figure 3.3: Hierarchical structure

Secondly, a pair-wise comparison matrix (PCM) was constructed for the criteria in respect of the goal using relative intensity scale. The intensity scale in Table 3.2 was used to indicate and compare the importance of one criterion

in relation to another (Dos Santos et al., 2019). The intensity scale value varied from 1 to 9 to indicate the level of importance among the criteria.

Table 3.3: Importance scale for PCM analysis

Relative intensity scale	Definition
1	Equal importance of i and j
3	Slightly more importance of i over j
5	High importance of i over j
7	Very high importance of i over j
9	Extreme importance of i over j
2, 4, 6, 8	Intermediate values between two adjacent judgements

(Source: Yahaya, Sapuan, Leman, et al., 2014)

Calculation of Eigen vectors

The PCM data from Step 2 was used to determine the relative priority vector of each attribute. The priority vector, w , was calculated as follows:

$$w = \frac{1}{n} \sum_{j=1}^n \frac{a_{ij}}{\sum_{i=1}^n a_{ij}}, i, j = 1, 2, \dots, n \quad (1)$$

where a_{ij} is the importance scale (i.e. 1, 3, 5, ...) and n is the number of criteria.

3.2.3 Consistency

In the third stage, judgments consistency was validated using consistency ratio (CR). The consistency ratio was made sure to be less than 0.1 to ensure the judgments made were consistent and valid. However, the judgments are unreliable if the consistency ratio was more than 0.1. Hence, as shown in the flowchart in Figure 3.2, if the consistency ratio was more than 0.1, the PCM was required to be performed again until a ratio of less than 0.1 was obtained. The consistency ratio was calculated using the following equations.

Principal Eigen Value ($\lambda_{\max}$)

$$\lambda_{\max} = \sum_{i=1}^n \frac{\sum_{j=1}^n a_{ij} w_j}{w_i} \quad i, j = 1, 2, \dots, n \quad (2)$$

where w is Eigen vector, a_{ij} is the importance scale (i.e. 1, 3, 5, ...) and n is the number of criteria.

Consistency index (CI)

$$\text{Consistency Index, CI} = (\lambda_{\max} - n) / (n - 1) \quad (3)$$

where n is the number of criteria.

Consistency ratio (CR)

$$\text{Consistency ratio, CR} = \text{CI/RI} \quad (4)$$

where CI is the consistency index and RI is the random consistency index as in Table 3.3.

Table 3.4: Average random consistency

Size of matrix	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

(Source: Naveen et al., 2018)

3.2.4 Formulating and synthesizing PCM of the proposed materials in respect of criteria

PCM for the alternative materials in respect of all the criteria was formulated in the fourth stage. Then, the alternative materials priority vector, (w), in respect of each criteria was calculated. The PCMs for the alternative materials in respect of the criteria were formulated using the data from previous research works on mechanical, physical, and chemical properties of each type of plant fibre illustrated in Table 3.1.

3.2.5 Identifying the best alternative according to global prioritization

As the final step, the global priority vector was generated by multiplying PCM for the alternative materials and the criteria's priority vector. The ranking of global priority vector obtained from this test determines the most suitable proposed material (Rashid et al., 2017). The alternative material that yielded the highest priority vector is selected as the most suitable plant fibre to be implemented in the development of pultruded hybrid FRP composites.

3.2.6 Pairwise Comparison Matrix (PCM) using AHP software

Expert Choice v.11.5 software was used to formulate the PCM to identify the relative importance of criteria in respect of the goal and alternatives in respect

of the criteria. Black coloured values indicate that the row member is relatively given higher priority than the column number. Whereas red coloured values indicate that higher priority is given to the column member than the row member. Figure 3.4 (a) shows the PCM of the criteria versus the goal. The criteria were ranked according to the following order: Tensile strength > Tensile modulus > Density > Elongation at break > Cellulose content > Availability. Higher weightage was given to the criteria with more importance in designing the pultruded composites for structural applications. In that context, tensile strength followed by tensile modulus were the most important factors considered to produce structural profiles with better strength and good stiffness, whereas density was considered third in the ranking to produce structural products with lower weight. Elongation at break which came after density aims to ensure good ductility, hence, improving the safety risks upon failure. The PCM of alternatives with respect to each criterion is generated using the data collected on the parameters of each fibre respectively as listed in Table 3.1. Generally, a range of values were collected from previous studies for each property of plant fibres due to the variations in the fibre quality affected by different plantation regions and processing methods. Hence, the most common values obtained from several previous research were considered as fixed values to generate the PCM in this study. Figures 3.4 (b) and 3.4 (c) show the PCM of the alternative materials in respect of the tensile strength and tensile modulus criteria, respectively. The relative importance scale values were obtained by calculating the ratio between the tensile values of individual fibres. For instance, in 3 (b), the tensile strength given for Bagasse and Bamboo were 290MPa and 230MPa, respectively. Hence, by calculating

their ratio (290/230), the relative importance scale value of 1.26 was obtained. The scale is indicated in black showing that the row member (Bagasse) was relatively given higher priority than the column number (Bamboo). Similarly in 3 (c), the tensile modulus of Bagasse and Bamboo were 27.1 GPa and 17 GPa, respectively, where the corresponding ratio (27.1/17) was 1.59. The obtained value is indicated in black showing that bagasse is 1.59 times better than bamboo for the intended application. According to Figure 3.4 (d), the corresponding ratio of 1.09 indicated in red shows that bamboo has lower density than bagasse at 1.1 and 1.2 g/cm³, respectively. Hence, the value 1.09 was obtained from the ratio of (1.2/1.1). The same rule was applied in obtaining the relative importance scale of fibres in respect of the elongation at break and cellulose content as shown in Figure 3.4 (e) and Figure 3.4 (f), respectively.

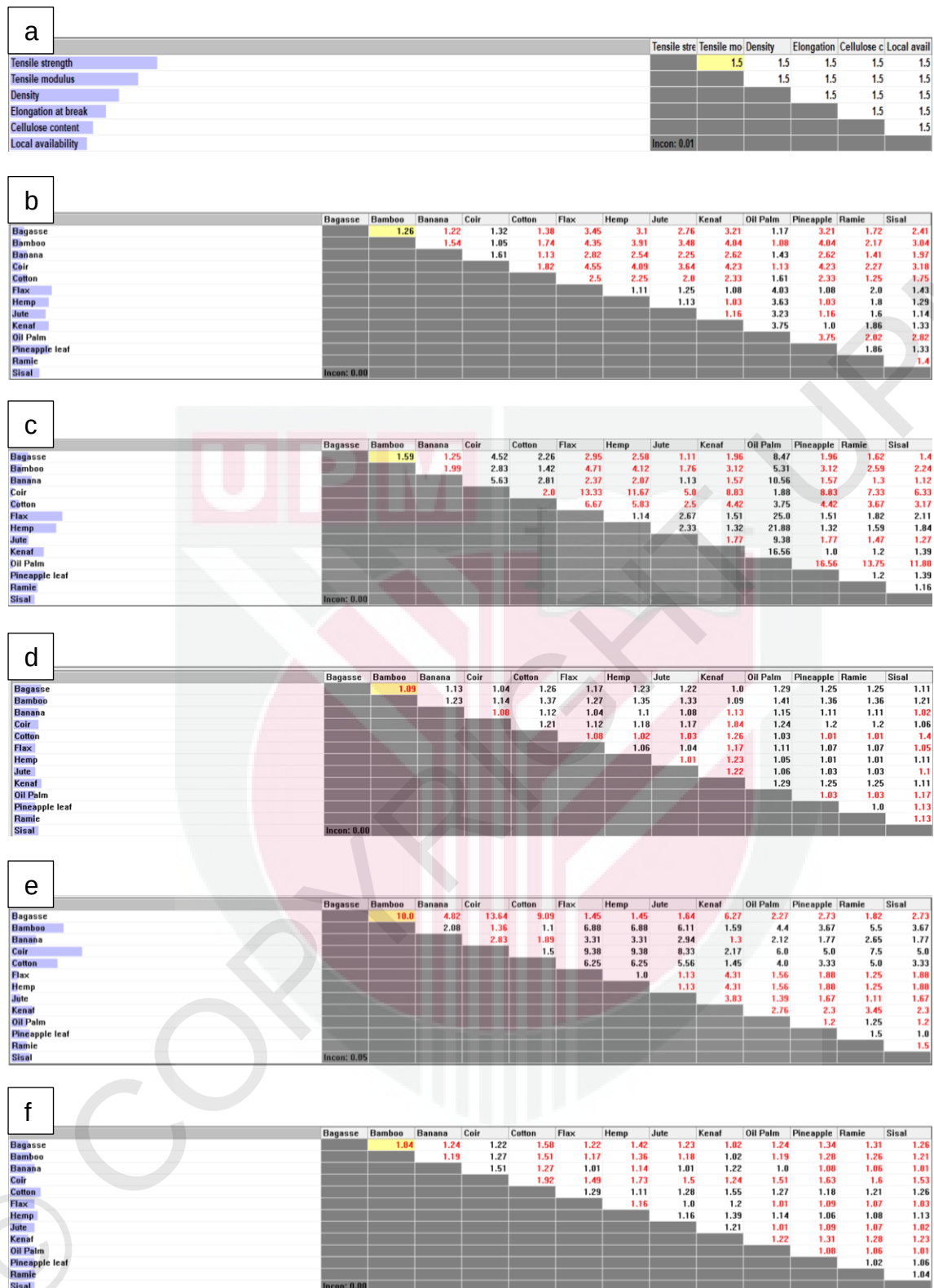


Figure 3.4: (a). Relative importance in respect of the goal; (b). Relative importance in respect of the tensile strength; (c). Relative importance in respect of the tensile modulus; (d). Relative importance in respect of the density; (e). Relative importance in respect of the elongation; (f). Relative importance in respect of the cellulose content

3.3 Preparation of materials

The materials used in this research comprise reinforcing fibres, thermoset resin, and surfacing veils. For the reinforcing fibres, chosen kenaf fibres were hybridized with E-glass fibres. Kenaf fibres were purchased locally in Malaysia whereby glass fibres were purchased from China. The matrix material used for the study is selected to be unsaturated polyester resin which is curable at room temperatures. By combining the robustness of E-glass fibres with the eco-friendly characteristics of kenaf fibres, our research aimed to create a composite material with enhanced mechanical properties and sustainability.

3.3.1 Kenaf

To fabricate plant/glass fibre reinforced hybrid composites, kenaf fibres are purchased in woven form from Lembaga Kenaf dan Tembakau Negara (LKTN), Kota Bharu, Malaysia. Kenaf fibres are abundantly available in Malaysia, making them a readily accessible and sustainable reinforcement material for composite manufacturing. The kenaf fibres were chemically treated with 5% concentration of Sodium Hydroxide (NaOH) solution to enhance the fibre-matrix adhesion. The fibres were treated at room temperature for 8 h, washed in clean water, and dried under hot sun for 48 hours. Figure 3.5 displays the woven kenaf fibre mat utilized in this study.



Figure 3.5: Kenaf fibres (woven)

The use of woven kenaf fibres ensures a well-organized and uniform distribution of the plant fibres within the composite, which is essential for enhancing mechanical properties and overall structural performance. Besides that, one of the main goals of this research is to ideally replace the use of woven glass fibre mats used in the pultruded composites industry. By incorporating locally sourced kenaf fibres, the composite fabrication process benefits from reduced transportation costs and supports the domestic agricultural industry, making it an eco-friendly and cost-effective approach to composite production.

3.3.2 E-Glass

E-glass fibres in the form of both woven mats and direct roving were procured from Shandong Fiberglass Group Co., Ltd., Linyi, China. These fibreglass materials are commonly employed in the pultrusion industry to fabricate a wide range of cross-sections for pultruded profiles, primarily targeting structural applications. Figure 3.6 illustrates the E-glass fibres in direct roving form,

which are continuous bundles of untwisted fibres. On the other hand, Figure 3.7 showcases E-glass fibres in woven mat form, where the fibres are arranged in an organized and interlocked pattern.



Figure 3.6: E-glass fibres (direct roving)



Figure 3.7: E-Glass fibres (woven)

The availability of both direct roving and woven mat forms of E-glass fibres provides flexibility in the manufacturing process, allowing to produce various composite profiles with specific mechanical properties and performance characteristics. The use of high-quality E-glass fibres ensures consistency and reliability in the composite manufacturing process, contributing to the production of robust and durable structural components suitable for a wide range of industries.

3.3.3 Unsaturated Polyester Resin (UPR)

Unsaturated polyester resin is widely recognised for its economic viability in composite manufacturing applications. Unlike other thermoset resins, such as vinyl esters and epoxies, unsaturated polyester resin stands out due to its highly cost-effective nature. The affordability of this resin makes it a preferred choice for a wide range of industries seeking economical solutions for their composite needs. The type of UPR used in this study is Isophthalic, purchased from Eternal Materials Sdn Bhd, Pasir Gudang, Malaysia. Isophthalic UPR provides good mechanical, chemical-resistant, and water-resistant properties. The resin and hardener are mixed in the weight ratio of 10:1, as per the manufacturer's specification. This precise mixing ratio ensures the resulting composite's optimal curing and mechanical properties. By using unsaturated polyester resin in conjunction with plant and glass fibres, the research aligns to develop environmentally sustainable and economically viable pultruded hybrid composites suitable for structural applications. This resin system's cost-effectiveness and favourable mechanical properties make it a promising candidate for enhancing advanced composite materials' commercial viability and widespread adoption.

3.3.4 Surfacing veil

Surfacing veils are well-regarded in composite applications for their unique benefits in enhancing the surface finish and performance of composite materials. Figure 3.8 shows the polyester surfacing veils, purchased from Utek Composite Co., Ltd., Changzhou, China, that were applied in the fabrication

of pultruded composite in this study. Surfacing veils act as a protective layer, reducing surface defects, such as porosity and fibre print-through, which are common in pultruded composites. These veils also provide added UV resistance, preventing premature degradation and color fading due to prolonged exposure to sunlight.

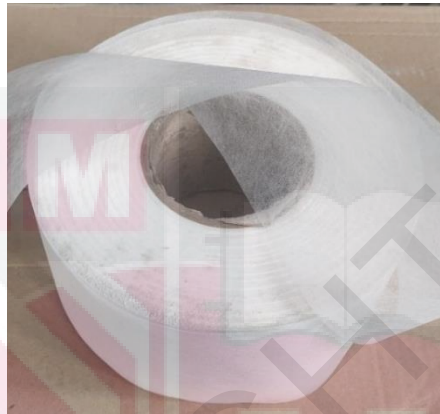


Figure 3.8: Surfacing veil

3.4 Selection of woven kenaf/glass roving hybrid composites

As the second objective of this research, the selected plant fibre from AHP is used to fabricate kenaf/glass reinforced hybrid composites of various stacking sequences. The composites are evaluated for their mechanical properties to select suitable stacking sequences for structural profile fabrication and analysis. Tensile, compression, bending, and interlaminar shear strength (ILSS) tests were chosen to evaluate the mechanical properties of the hybrid composites as they provide comprehensive insights into different aspects of material behavior under various loading conditions. Tensile testing, for example, allows for the measurement of the material's resistance to stretching or elongation, which is crucial for assessing its strength and ductility.

Compression testing evaluates the material's ability to withstand forces pushing inward, simulating real-world scenarios where the material may be subjected to compressive loads. Bending tests provide information on the material's flexural strength and stiffness, essential for applications where the material needs to support bending or flexing forces. Finally, ILSS testing assesses the bond strength between individual layers or plies within the composite structure, which is critical for evaluating the overall integrity and durability of the composite material. By utilizing these specific testing methods, the research ensures a comprehensive understanding of the mechanical properties of the hybrid composites, enabling informed decision-making in their application for structural purposes.

3.4.1 Fabrication of composites with varying stacking sequences

Woven glass fibres and unidirectional glass rovings are conventionally used to manufacture fibreglass structural profiles. The costly and highly denser woven fibreglass are used by industrial players with the stacking sequence of WG/UG alternate. Therefore, in this research, woven kenaf fibres are used as a substitute to woven glass fibres to develop lighter, cheaper and sustainable hybrid composites for structural applications. However, in this objective, hand layup followed by compression molding is used to prepare the samples instead of pultrusion to reduce the manufacturing cost and time. Hence, 3 different stacking sequences of woven kenaf/unidirectional glass fibre composites are fabricated by considering the traditional pultrusion setup. The overall best performing hybrid sequence will be used to develop structural profiles for further investigation. The overall fibre/matrix ratio was fixed at 55/45. Calcium

Carbonate and Aluminium Hydroxide were used as filler at 40% of total resin weight, in the process to improve the mechanical properties of the composites. All the samples are controlled with 7 numbers of plies and a thickness of about 6 mm.

Table 3.5: Stacking sequence of kenaf/glass hybrid composites and pure fibreglass composites

Samples	Stacking sequence	Weightage (wt.%)	
		Kenaf	Glass
WK/UG alternate	WK/UG/WK/UG/WK/UG/WK	45	55
2WK/3UG/2WK	WK/WK/UG/UG//UG/WK/WK	45	55
3WK/UG/3WK	WK/WK/WK/UG/WK/WK/WK	81.7	18.3
WG/UG alternate	WG/UG/WG/UG/WG/UG/WG	0	100

WK = Woven Kenaf

UG = Unidirectional Glass

WG = Woven Glass

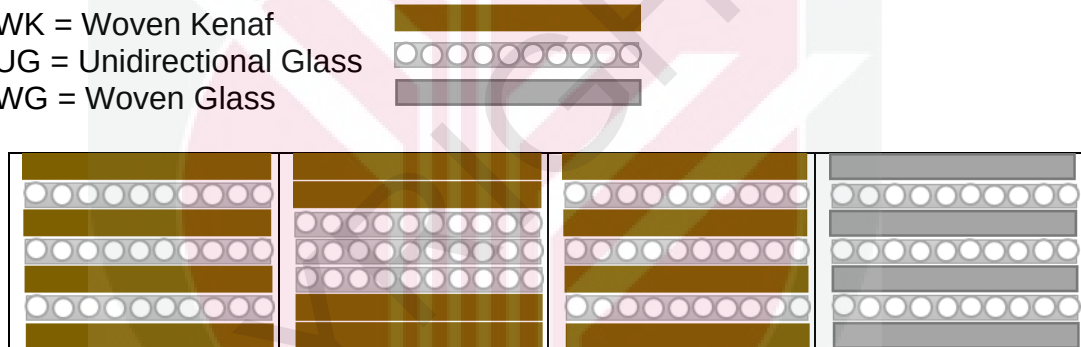


Figure 3.9: Stacking Sequence of Kenaf/Glass Hybrid Composites and Pure Fibreglass Composites

3.4.2 Tensile and compressive test

Tensile and compression tests were conducted for each group of kenaf/glass fibre hybrid composites and glass fibre composites (control). The tensile samples preparation and testing procedure was followed according to ASTM D-638 with a crosshead speed of 5 mm/min, while compression samples and test follow ASTM D-695 with a crosshead speed of 1.3 mm/min. Tensile tests were conducted using universal testing machine Zwick/Roell Z400. The tensile

specimen dimensions were 165 mm x 19 mm x 6 mm. Compression tests were carried out using universal testing machine Instron 5582. The specimen dimensions for compression testing were 79.4 mm x 19 mm x 6 mm. In both tests, five samples from each composite variation were tested, and the average value was determined and recorded as a result. The tensile strength and tensile modulus are recorded from tensile test whereby the compressive strength and compressive modulus data is obtained from compression test.

Tensile Strength was calculated as per the following equation:

$$\tau_t = \frac{F_{max}}{l*b} \quad (5)$$

where τ_t represents tensile-shear strength along the fibres (MPa), F_{max} is the maximum force at breaking point (N), l is the length of shear area (mm), and b is the width of shear area (mm).

Tensile Modulus was calculated as per the following equation:

$$E_t = \frac{F_{max}}{\Delta l*b} \quad (6)$$

where E_t represents tensile modulus (GPa), F_{max} is the maximum force at breaking point (N), Δl is the change in length/ elongation of shear area (mm), and b is the width of shear area (mm).

Compressive Strength was calculated as per the following equation:

$$\tau_c = \frac{F_{max}}{l*b} \quad (7)$$

where τ_c represents compressive-shear strength along the fibres (MPa), F_{max} is the maximum force at breaking point (N), l is the length of shear area (mm), and b is the width of shear area (mm).

Compressive Modulus was calculated as per the following equation:

$$E_c = \frac{F_{max}}{\Delta l * b} \quad (8)$$

where E_c represents compressive modulus (GPa), F_{max} is the maximum force at breaking point (N), Δl is the change in length/ elongation of shear area (mm), and b is the width of shear area (mm).

3.4.3 Bending test

Utilizing INSTRON 5567 (Institute of Tropical Forestry and Forest Products (INTROP)'s Biocomposite Laboratory, Universiti Putra Malaysia, Malaysia), the bending strength properties test was carried out. The samples were subjected to a three-point bending test using the ASTM D 790 standard. At 2.5 mm/min, the crosshead speed remained constant. The standard specimen length is 120 mm for a thickness of approximately 6 mm, and the standard specimen width is 25 mm, with the specimen length being approximately 20% longer than the support span. The standard span-to-thickness ratio is 32:1.

Modulus of rupture was calculated as per the following equation:

$$MOR_{b3} = \frac{3 * F_p * l_0}{2 * b * h^2} \quad (9)$$

where MOR_{b3} is the modulus of rupture (MPa), F_p is the maximum force at breaking point, l_0 is the axial distance between supports (mm), b is the test piece width (mm), and h is the test piece thickness (mm).

Modulus of elasticity was calculated as per the following equation:

$$E_{w3} = \frac{(F_2 - F_1) \cdot l_0^3}{4 \cdot b \cdot h^3 \cdot (a_2 - a_1)} \quad (10)$$

where E_{w3} is the modulus of elasticity (GPa), l_0 is the axial distance between supports (mm), b is the test piece width (mm), h is the test piece thickness (mm), and $F_2 - F_1$ is the loading increase in the loading/deflection curve linear section (N). The value of F_1 should be approximately 10% and F_2 approximately 40% of the breaking load. The difference between $a_2 - a_1$ is the deflection increase in the half of the test piece length (corresponding to the loading increase $F_1 - F_2$).

3.4.4 Interlaminar shear stress test

Interlaminar shear strength properties of the composites were tested using ASTM D-2344 with a crosshead speed of 1 mm/min. The samples were prepared with dimensions of 40 mm x 13 mm x 6 mm. The test was conducted using universal testing machine Instron 5967.

Inter Laminar Shear Strength was calculated as per the following equation:

$$F_{sbs} = 0.75 * \frac{P_{max}}{b * h} \quad (11)$$

where F^{sbs} is the short-beam strength (MPa), P_{max} is the maximum load observed during the test (N), b is the measured specimen width (mm), and h is the measured specimen thickness (mm).

3.4.5 SEM analysis

The laminated tensile fractured composites' morphology was examined with a scanning electron microscope. The tested samples, which measure 3–4 mm, were cut from the fractured zone. The specimens were subjected to high-resolution scanning electron microscopy (SEM) analysis on the fracture surface using a COXEM EM-30AX PLUS with a 20 KV voltage acceleration from the Institute of Tropical Forestry and Forest Products (INTROP) Biocomposite Laboratory at Universiti Putra Malaysia, Malaysia. To enhance sample imaging, a gold coating was applied to the samples.

The mean values and standard deviations were calculated for each set of experimental data, and error bars were incorporated in graphical representations to visually depict the variability and uncertainty associated with the measurements.

3.5 Testing of kenaf/glass roving hybrid pultruded composites

In the third objective, the selected stacking sequences are fabricated into kenaf/glass hybrid pultruded profiles to analyse its durability properties.

3.5.1 Fabrication of pultruded profiles

The pultruded profile fabrication was done in Mui Fatt Sdn Bhd, a local composites manufacturing company based in Port Klang, Malaysia. A

hydraulic pultrusion machine was used to fabricate woven glass/unidirectional glass composites and woven Kenaf/Unidirectional Glass hybrid pultruded square profiles. Woven glass fibres and unidirectional glass rovings are conventionally used to manufacture fibreglass pultruded products. This research uses woven kenaf fibres to substitute conventional glass fibres and develop hybrid composites for pultrusion applications. The process parameters for the pultruded profile fabrication are depicted as shown in Table 3.5.

Table 3.6: Pultrusion process parameters

Parameters	Values
Pull speed	30 cm/min
Pull Force	6 Bar
Die Temperature	159°C

The overall fibre/matrix ratio was fixed at 55/45. The profiles were controlled with seven layers of plies and a thickness of about 6 mm. The unsaturated polyester resin was used as the matrix, while Dibenzoyl Peroxide (BPO) and Tert Butyl Peroxy Benzonate (TPBP) were used as hardeners to form the composite profile matrix. Pigments were added at 3% of the total resin weight. Calcium Carbonate and Aluminium Hydroxide were used as fillers at 40% of the total resin weight, in the process to improve the mechanical properties of the profiles. The fabricated profiles are shown in Figure 3.10, and stacking sequences are demonstrated in Figure 3.11.

Table 3.7: Stacking sequence of pultruded kenaf/glass hybrid composites and pure fibreglass composites

Samples	Stacking sequence	Weightage (wt.%)	
		Kenaf	Glass
Pultruded alternate	WK/UG	45	55
Pultruded 3WK/UG/3WK	WK/WK/WK/UG/WK/WK/WK	81.7	18.3
Pultruded alternate	WG/UG	0	100

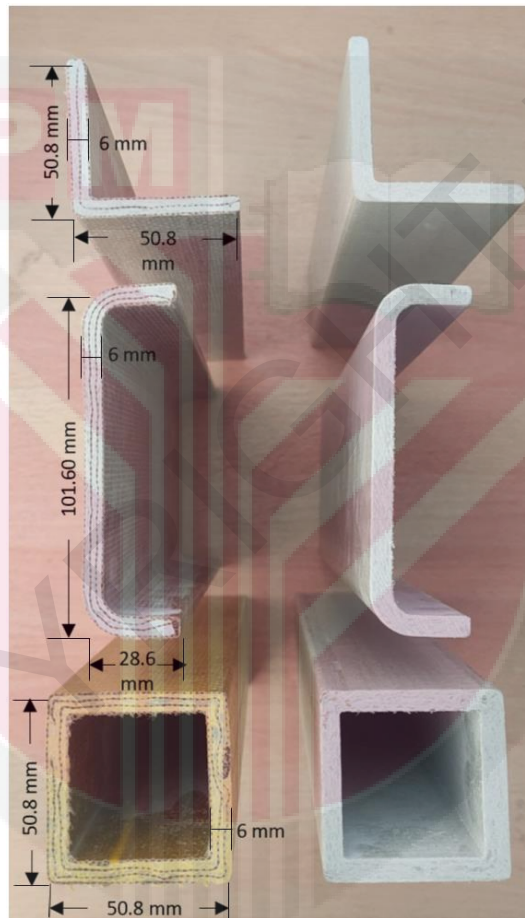


Figure 3.10: Pultruded WK/UG alternate profiles (left) and Pultruded WG/UG alternate profiles (right) fabricated in 3 different cross-sections (angle bars, c-channels, and square tubes)

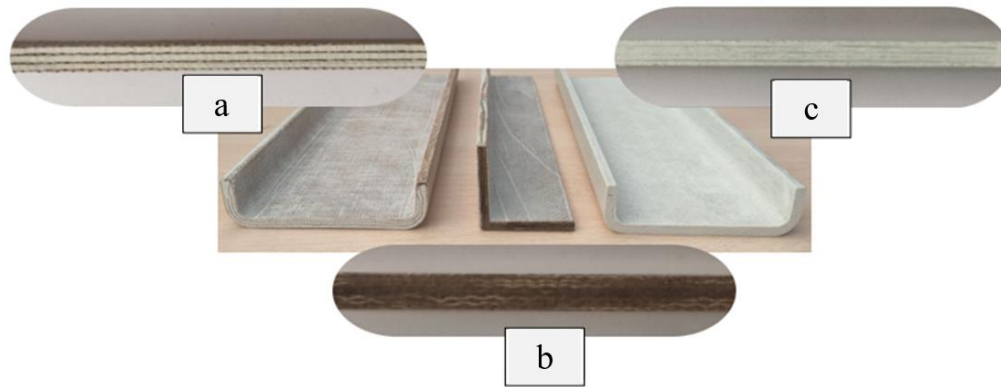


Figure 3.11: Stacking sequences of hybrid and non-hybrid pultruded profiles; (a) WK/UG alternate; (b) 3WK/UG/3WK; (c) WG/UG alternate

3.5.2 Static test

A tensile test was conducted for each group of pultruded kenaf/glass fibre hybrid composites and pultruded glass fibre composites (control). The tensile samples preparation and testing procedure was followed according to ASTM D-638 with a crosshead speed of 5 mm/min. Tensile tests were conducted using the universal testing machine Zwick/Roell Z400 with 100 kN of load cell. The tensile specimen dimension was 165 mm x 19 mm x 6 mm. Five samples from each composite variation were tested, and the average value was determined and recorded. Tensile strength and tensile modulus were recorded. The ultimate tensile strength (UTS) values were used for fatigue analyses.

3.5.3 Fatigue test

Uniaxial fatigue test was carried out by using a Fatigue Test Machine 8801, INSTRON (Figure 3.12) Two specimens were prepared for each level of % ultimate tensile strength (UTS) for all variations.



Figure 3.12: Fatigue testing

The testing procedure of the fatigue tests used in this study was based on ASTM D7791 (Type I) where the specimens were loaded under tension-tension stress. The test was conducted at stress ratio, $R = Q_{\min}/Q_{\max} = 0.1$ with a sinusoidal wave of a frequency at 20 Hz at a different level of applied stress. Analysis was carried out at $23 \pm 2^\circ\text{C}$ and relative humidity of $50 \pm 5\%$ room condition. The stress levels were set to 80%, 70%, 60%, and 50% of the UTS. Table 3.7 shows the applied minimum and maximum stresses in fatigue testing.

Table 3.8: Applied stress on fatigue testing

Type of composites	Ultimate Tensile Strength (UTS), MPa	Percentage of applied load with respect to UTS, %	Maximum stress (Q_{max}), MPa	Minimum stress (Q_{min}), MPa
Pultruded WK/UG alternate	404.54	80	323.63	32.36
		70	283.18	28.32
		60	242.72	24.27
		50	202.27	20.23
		80	141.46	14.15
Pultruded 3WK/UG/3WK	176.82	70	123.77	12.38
		60	106.09	10.61
		50	88.41	8.84
		80	352	35.2
Pultruded WG/UG alternate	440	70	308	30.8
		60	264	26.4
		50	220	22

3.5.4 Izod test

The procedure of this test was conducted based on ASTM D256, Test C (Figure 3.12).



Figure 3.13: Izod impact testing

Five notched specimens of each variation were prepared, with 20 pieces as shown in Figure 3.13. The specimens were then conditioned at 23 °C for 48 h

after notching before testing. The test was then conducted at a laboratory temperature of 21°C. The average value of the five repetitions was then recorded.

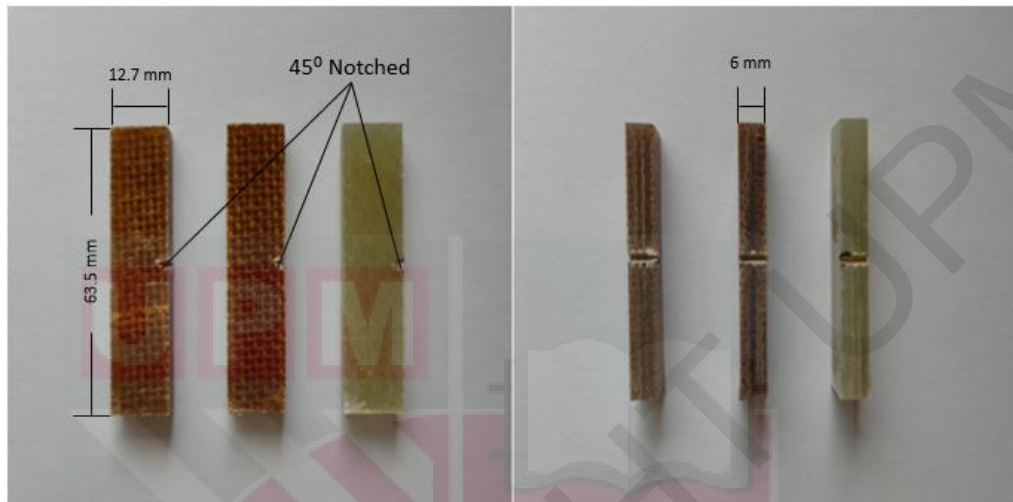


Figure 3.14: Izod samples

3.5.5 Density test

The density test was carried out according to ASTM D792 (Figure 3.15). Three square specimens were prepared for each variation with the dimension size of 20 mm x 20 mm x 6 mm. The specimens were conditioned at room temperature for two days before the density test was carried out. The testing was carried out by using distilled water as its immersion liquid at room temperature (27°C). The mass of the specimen in air was first determined before immersing the specimen into the liquid. After immersion into the distilled water, its apparent mass upon immersion was determined, and its specific gravity was calculated and recorded. The experiment was repeated three times, and the average value was recorded.

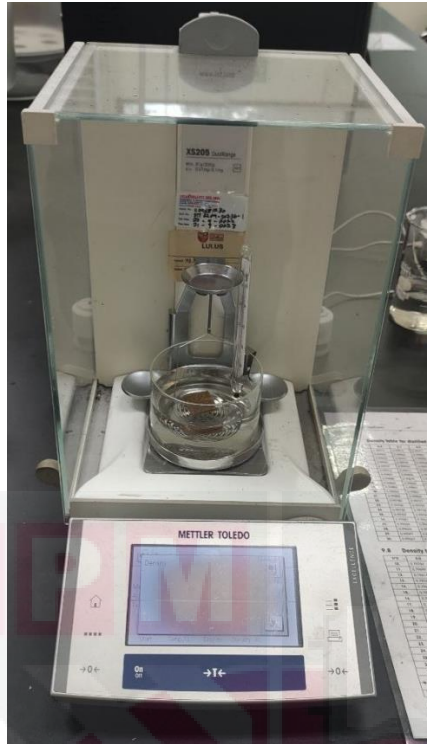


Figure 3.15: Density testing

Density was calculated as per the following equation:

$$\rho_c = \frac{w_c}{w_c - w_w} * 0.997 \quad (12)$$

3.5.6 Specific strength, cost and weight analysis

The weight of 1ft square hollow pultruded profile of the hybrid and non-hybrid composites is compared and analysed. The weight is obtained by simply multiplying the profile's volume ($3.277 \times 10^{-4} \text{ m}^3$) by the material's density. The raw material cost of reinforced fibres in 1ft square hollow pultruded profile were calculated and compared. The cost of reinforcing fibres in Malaysia are listed in Table 3.8.

Table 3.9: Cost of reinforcing fibres in Malaysia

Reinforcing fibres	Cost per kg (RM)
Glass Fibre Direct Roving	3.50
Woven Glass Fibre Mat	5.20
Woven Kenaf Fibre Mat	2.50

3.6 Case study

In the fourth objective, plant/glass fibre reinforced hybrid pultruded profiles are fabricated and applied into a working prototype ladder as the case study of this research. The working prototype is then tested for its structural integrity according to the ladder standards.

3.6.1 Ladder design and assembly

A single-pole ladder was designed and fabricated with a height of 7 ft and 16 inches wide. 6 solid rods were used to in between 2 side rails made up of pultruded kenaf/glass reinforced hybrid profiles (Figure 3.16). The solid rods were made in full fibreglass material. To assemble the ladders smaller fibreglass pultruded round tubes were used. Figure 3.17 shows the assembly process of the ladder.



Figure 3.16: Kenaf/glass reinforced hybrid square hollow pultruded profiles



Figure 3.17: Assembly of working prototype ladder

The ladder was then painted as a protective coating as shown in Figure 3.18.

Figure 3.19 shows the pin-support used to join the side-rails and rungs. Anti-

slip rubber foot is also attached to the ladder as per safety requirements

(Figure 3.20).



Figure 3.18: Working prototype ladder after surface finishing



Figure 3.19: Pin support between side rails and rungs



Figure 3.20: Anti-slip rubber

3.6.2 Testing of ladder

The ladder has been tested according to ANSI 14.5. The ladder is then rated from the testings conducted. Table 3.9 shows the allowed working load for different types of ladders according to the standard. Loads of 10 pounds were used in the testing (Figure 3.21).

Table 3.10: Duty rating of ladder

Duty rating	Working load, lb (kg)
Special Duty	375 (170.1)
Extra Heavy Duty-	300 (136.1)
Heavy Duty	250 (113.4)
Medium Duty	225 (102.1)
Light Duty	200 (90.7)



Figure 3.21: Test load (10 lb)

i. Horizontal Bending Test

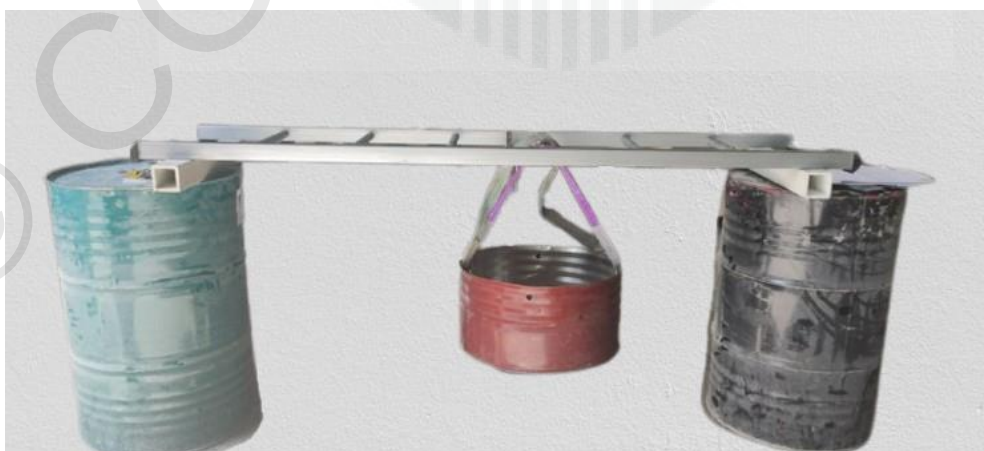


Figure 3.22: Horizontal bending test

The ladder is placed in a flat horizontal position as shown in the Figure 3.22. The end support bars are made sure to permit longitudinal translation of either one or both supports during loading as the test unit deflects. The unit is loaded with a preload initially at the centre of its rung nearest to the midpoint of the test span. The load is ensured that it is applied equally to both the side rails. The preload was held for a minimum period of one minute and then unloaded. Vertical measurements are taken for each rail. The deflection of each side rail is determined as the difference in the vertical measurements. For a 7ft ladder, the maximum average deflection shall not exceed 3.6 inches (91 mm) according to Ansi 4.5.

Table 3.11: Test load for horizontal bending test

Duty rating and type	Working load and deflection test load, lb (kg)	Preload, lb (kg)	Ultimate test load, lb (kg)
Special Duty	375 (170.1)	280 (127)	470 (213.2)
Extra Heavy Duty	300 (136.1)	225 (102.1)	375 (170.1)
Heavy Duty	250 (113.4)	188 (85.3)	310 (140.6)
Medium Duty	225 (102.1)	169 (76.7)	280 (127)
Light Duty	200 (90.7)	150 (68)	250 (113.4)

For the ultimate load testing, the ladder is subjected for at least 1 minute to an increased load, equal to the ultimate test load in accordance with Table 3.10.

The ladder shall sustain the ultimate test load without ultimate failure.

ii. Side Sway Test



Figure 3.23: Side sway test

A preload of 30 pounds (13.6 kg) is applied at the centre of the span, held for a period of 1 minute and unloaded. This establishes the zero reference for deflection measurements. A test load according to Table 3.11 is applied for a minimum period of 1 minute to the centre of the span. The load is applied by hanging weight from the bottom of the lower rail as shown in Figure 3.20. The deflection of the midpoint shall not exceed 0.96 inches (2.4 cm).

Table 3.12: Deflection test loads for side sway test

Duty rating and type	Deflection test load, lb (kg)
Special Duty	85 (38.6)
Extra Heavy Duty	70 (31.8)
Heavy Duty	60 (27.2)
Medium Duty	55 (25)
Light Duty	50 (22.7)

iv. Static Side-Rail Cantilever Bending Test



Figure 3.24: Static side-rail cantilever bending test

The test unit is placed on edge with rungs in the vertical plane as shown in Figure 3.24. The lower side rail is clamped to a support and unsupported from the bottom end to the midpoint of the lower rung. The load is applied to the extreme bottom end of the side rail. The test load is applied according to Table 3.12 for a minimum period of 1 minute. The allowable permanent deformation of the lower side rail shall not exceed 0.25 inch (6 mm).

Table 3.13: Test load for static side-rail cantilever bending test

Duty rating and type	Working load, lb (kg)	Test load, lb (kg)
Special Duty	375 (170.1)	600 (272.2)
Extra Heavy Duty	300 (136.1)	500 (226.8)
Heavy Duty	250 (113.4)	400 (181.4)
Medium Duty	225 (102.1)	300 (136.1)
Light Duty	200 (90.7)	200 (90.7)

v. Inclined Load Test



Figure 3.25: Inclined load test

The ladder is positioned and supported as shown in the Figure 3.25. The load is applied equally to both side rails and at the first rung at midspan and above. The full load is applied for a period (1 minute) before release. The ladder shall sustain this load without ultimate failure.

Table 3.14: Simulated in-use inclined test loads

Duty rating and type	Working load, lb (kg)	Test load, lb (kg)
Special Duty	375 (170.1)	1200 (544.3)
Extra Heavy Duty	300 (136.1)	1000 (453.6)
Heavy Duty	250 (113.4)	1000 (453.6)
Medium Duty	225 (102.1)	900 (408.2)
Light Duty	200 (90.7)	800 (363)

3.7 Summary

In this study, a meticulous and systematic approach was undertaken to explore the development and evaluation of hybrid pultruded profiles specifically designed for structural applications, with a primary focus on their potential in ladders. The methodology commenced with a strategic selection process for plant fibres, employing AHP analysis to guide subsequent fabrication procedures. Through a combination of hand lay-up and compression molding techniques, hybrid composites were intricately fabricated for structural profiles with a precisely defined wall thickness of 6 mm.

Mechanical testing formed a cornerstone of the evaluation process, encompassing a comprehensive analysis of tensile, compressive, and bending behaviors. These assessments not only provided valuable insights into the performance of the panels but also highlighted their distinct advantages over conventional fibreglass composites. Furthermore, fatigue and impact testing played pivotal roles in assessing the durability and resilience of the hybrid pultruded composites, shedding light on their suitability for real-world structural applications. Through meticulous evaluations of strength, cost, and weight, the study underscored potential cost efficiencies in raw materials, while showcasing the practical viability of the hybrid profiles, particularly in lightweight ladder applications. The successful construction and subsequent testing of a single-pole structural ladder, exceeding ANSI standards, stood as a tangible testament to the efficacy of the methodology employed.

While certain testing equipment may offer high precision and accuracy, there may be inherent limitations in sample preparation techniques or environmental conditions that could introduce variability or error into the data. To mitigate these challenges, rigorous quality control measures are implemented, such as standardized protocols for sample preparation and calibration of equipment. Additionally, variations in sample dimensions or testing parameters could impact the consistency and reproducibility of results. By carefully controlling experimental variables and conducting sensitivity analyses, the impact of these factors on the reliability of the data can be minimized. Through proactive identification of potential limitations and mitigation strategies, the study ensures a balanced interpretation of the results, thereby strengthening the overall credibility of the research methodology.

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, the collected results and data are analysed and discussed. This chapter is divided into four sections according to the objectives of the research.

4.1 Selection of suitable plant fibre using AHP

As the first objective of this research, suitable plant fibre is selected using Analytic Hierarchy Process (AHP). With the aid of “Expert Choice” v.11.5 software, AHP was carried out to select the most suitable plant fibre as reinforcement in the pultruded hybrid FRP composites for structural applications.

4.1.1 Synthesis of criteria with respect to goal and alternatives with respect to criteria

As the first step, PCM of the six criteria was made followed by PCM of the 13 alternatives with respect to the criteria. The criteria weightage was given in the following order: tensile strength > tensile modulus > density > elongation > cellulose > availability as shown in Figure 4.1 (a). According to the criteria ranking, the main factors in selecting the suitable plant fibre for structural applications is tensile strength, tensile modulus, followed by density. This is because materials with higher tensile strength, tensile modulus, and lower density are preferable in making structural profiles to improve its strength-to-weight ratio and stiffness-to-weight ratio. It is also clear that the strength of the

material plays a vital role when selecting plant fibres for structural applications.

Hence, high tensile strength in fibres is given the most priority among other criteria to ensure the application of the fibres in load bearing applications.

Figure 4.1 (b) shows the synthesis of the plant fibres with respect to the tensile strength. The alternatives were ranked in the following order: flax > kenaf >

PALF > hemp > jute > sisal > ramie > cotton > banana > bagasse > oil palm >

bamboo > coir. Figure 4.1 (c) demonstrates the synthesis of candidate

alternatives with respect to the tensile modulus where the ranking was ordered as follows: flax > hemp > kenaf > PALF > ramie > sisal > banana > jute >

bagasse > bamboo > cotton > coir > oil palm. Based on the results obtained

on tensile strength and tensile modulus, fibres such as flax, kenaf, pineapple leaf, and hemp have scored significantly higher priority vector which proves

their potential in load bearing applications. Although the mentioned plant fibres

have lower mechanical properties compared to glass fibres which are

conventionally used in producing high load bearing structural profiles, the

moderate mechanical property in plant fibres widens the opportunities to

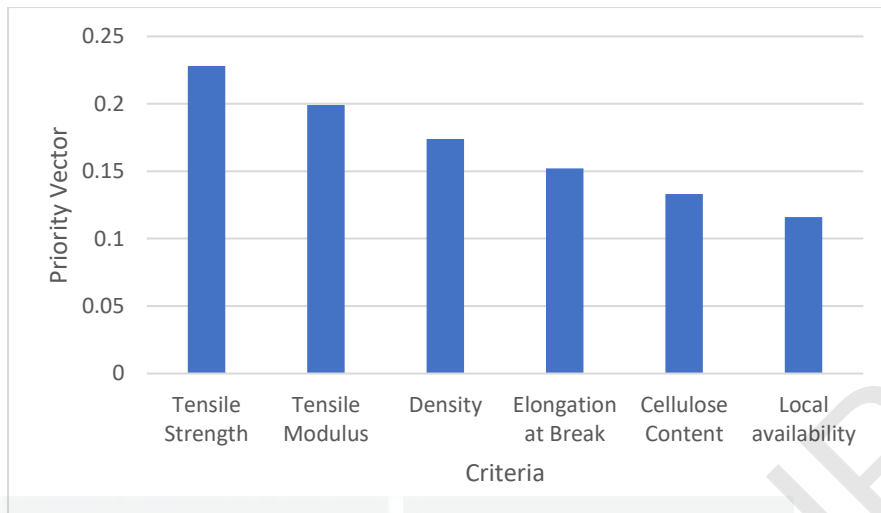
develop moderate load bearing structural applications by greatly cutting down

the cost and reducing sustainability issues. Hence, structural products such as

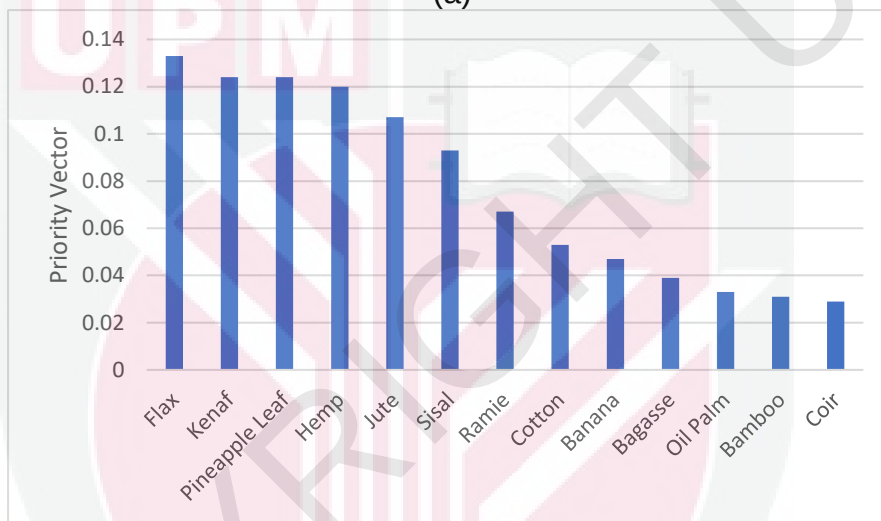
frames, ladders, aerospace and automotive interior elements, and sports

equipment can be manufactured with good strength property via pultruded

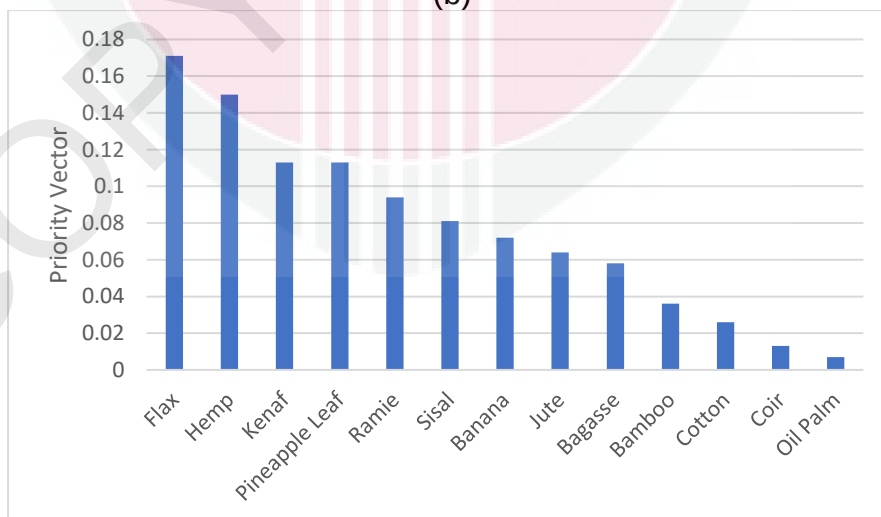
plant/glass fibre reinforced hybrid composites.



(a)



(b)

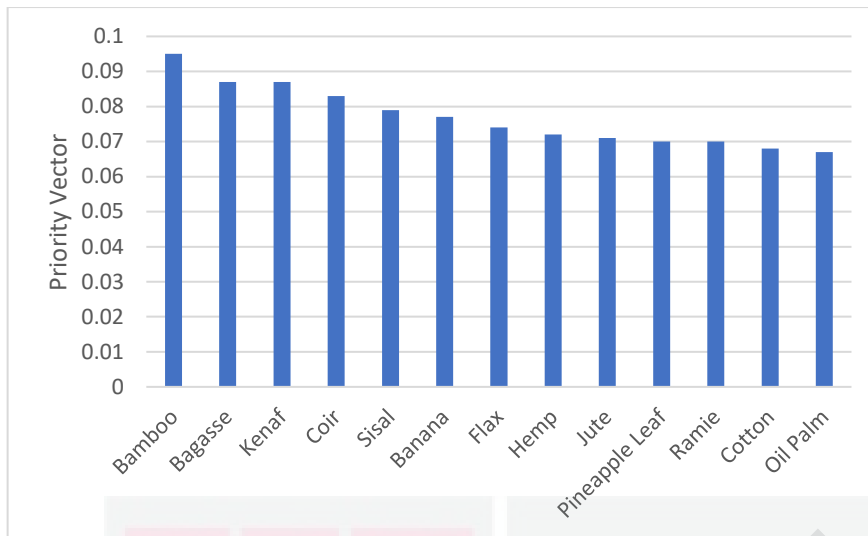


(c)

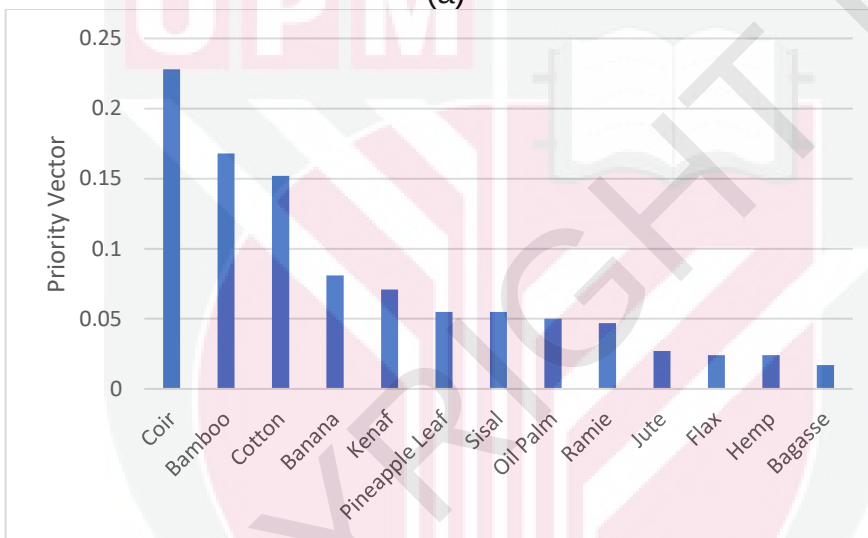
Figure 4.1: (a) Synthesis of criteria with respect to the goal; (b) Synthesis of plant fibres with respect to the tensile strength; (c) Synthesis of plant fibres with respect to the tensile modulus

Figure 4.2 (a) shows the synthesis of the alternatives with respect to the density where the fibres were ranked in the following order: bamboo > bagasse > kenaf > coir > sisal > banana > flax > hemp > jute > PALF > ramie > cotton > oil palm. The ranking highlights that values for priority vector scored by alternatives are close to each other and the differences are only at a minor level. Based on the ranking given, bamboo, bagasse, kenaf, and coir have lower density (ranging up to 0.08 to 0.09) than the average values shown by other candidate fibres (ranging about 0.07 to 0.08). The lower density in fibres is also important in developing profiles at much lower weight. However, by considering the tensile properties in Figure 4.1 (b), (c), kenaf shows the potential to develop profiles with higher strength-to-weight ratio and stiffness-to-weight ratio compared to other candidates. Figure 4.2 (b) shows the synthesis of the candidate fibres with respect to the elongation at break. The fibres ranking was in the following order: coir > bamboo > cotton > banana > kenaf > PALF > sisal > oil palm > ramie > jute > flax > hemp > bagasse. Fibres such as coir, bamboo, and cotton have shown significantly higher priority vector (more than 0.15), whereby banana, kenaf, pineapple leaf, and sisal scored moderate priority vector (more than 0.05) with respect to the elongation at break. These materials add ductility to the structural products by dissipating the kinetic energy of the structure upon plastic deformation. Hence, the safety risk is significantly improved. Figure 4.2 (c) shows the synthesis of the alternatives with respect to the cellulose content. The ranking obtained from the results were in following order: cotton > hemp > PALF > ramie > sisal > banana > oil palm > flax > jute > bamboo > kenaf > bagasse > coir. Cellulose is crystalline which provides good strength and rigidity to the fibres. Almost all

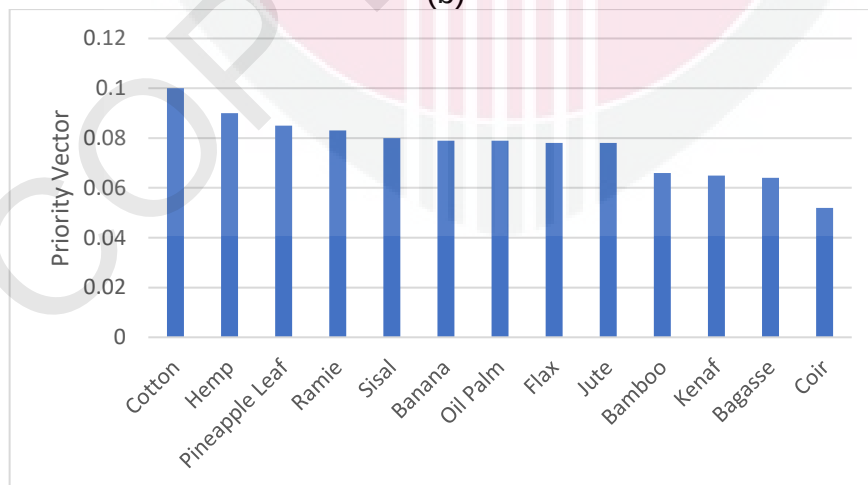
the alternatives demonstrated values for cellulose content near to each other. However, the highest cellulose content is present in cotton and the lowest cellulose content is present in coir fibres. Similarly, the synthesis of fibres with respect to availability was done and evaluated. To ensure a consistent supply to the production of materials, fibres which are made available locally were given higher priority scale compared to other alternatives. Among the fibres available in Malaysia include kenaf, pineapple leaf, bamboo, bagasse, coir, banana, and oil palm. Kenaf fibres and pineapple leaf fibres are widely available locally and hence given the most priority scale compared to other fibres.



(a)



(b)



(c)

Figure 4.2: (a) Synthesis of plant fibres with respect to the density; (b) Synthesis of plant fibres with respect to the elongation at break; (c) Synthesis of plant fibres with respect to the cellulose content

The priority vector of the alternative materials with respect to the criteria was obtained by synthesizing the PCM, which is shown in Figure 4.3. The Figure shows that kenaf fibre is the most suitable alternative to be hybridized with glass fibre in pultruded FRP composites for structural application. The top four potential alternatives for light load bio-based pultruded profile application are listed in order as kenaf, flax, pineapple leaf, and hemp fibres. Kenaf scored the highest priority vector (0.1), followed by pineapple leaf (0.096), flax (0.096), and hemp (0.091). However, oil palm fibre has recorded the least value (0.053). This shows that oil palm fibre is least suitable to be chosen for hybrid composites in pultruded profiles. The overall consistency ratio recorded was 0.01, which proves that the judgements made during the AHP procedure were consistent and valid.

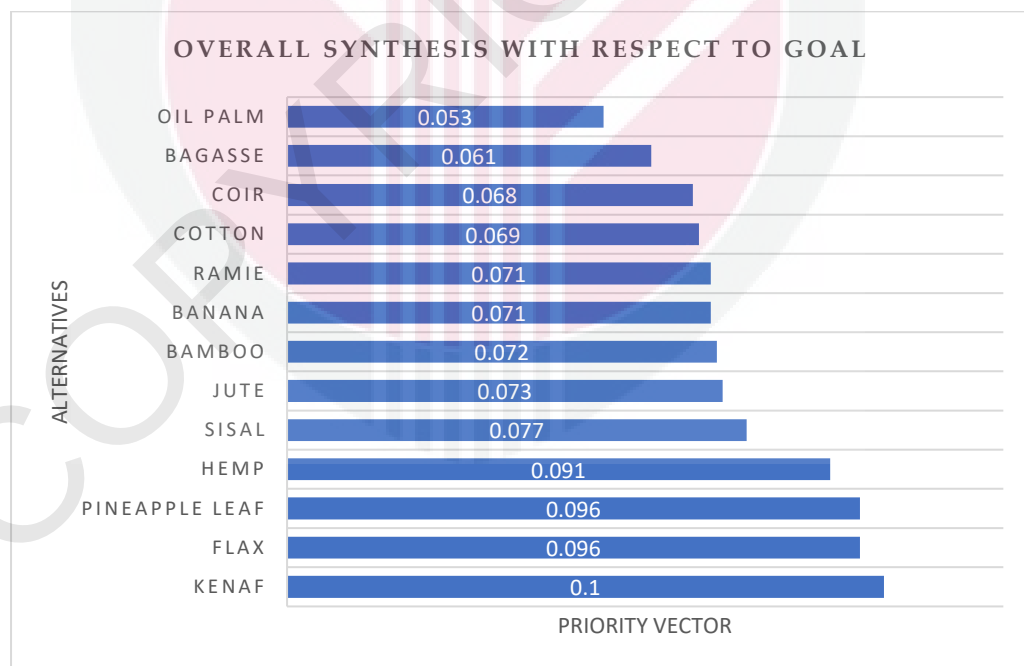


Figure 4.3: Overall synthetis result

Sensitivity analysis was used to get the verification and validation of the overall results of the AHP process. Figure 4.4 (a) shows the performance chart

demonstrating the priority vector yielded by the plant fibres with respect to the criteria.

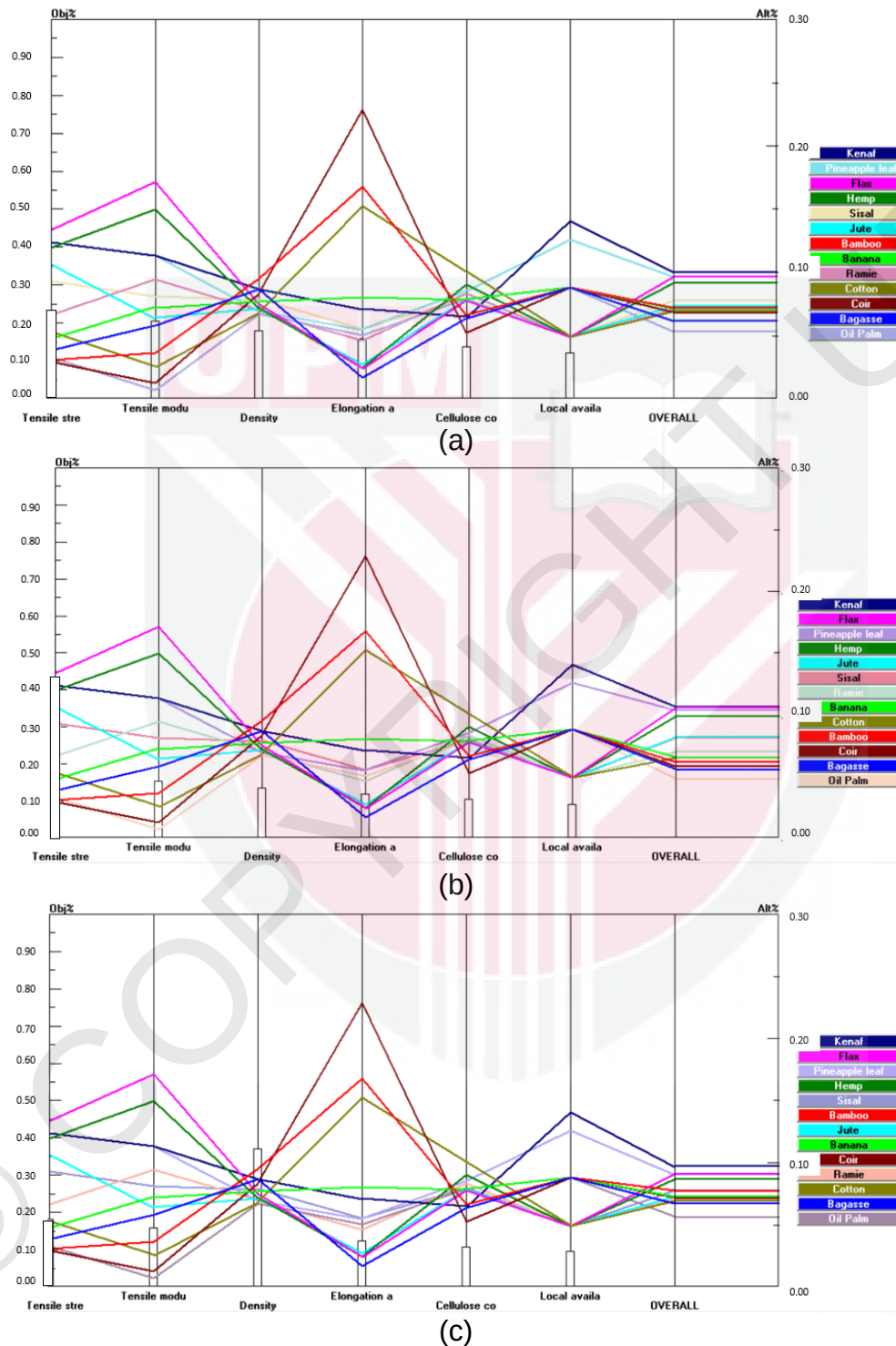


Figure 4.4: (a) Performance chart of the priority vector; (b) Performance chart with the priority vector increased to 20% for tensile strength; (c) Performance chart with the priority vector increased to 20% for density

As the final step, the variation on the ranking scenarios of the plant fibres corresponding to each criterion was validated by increasing the priority vector of each criterion by 20% weightage. Figure 4.4 (b), (c) demonstrates the performance charts of the alternatives varied with respect to the tensile strength and density, respectively, when the priority vector was increased by 20%. Performance charts were obtained for other criteria as well and the obtained results are summarized in Table 4.1.

Table 4.1: Fibre ranking when priority vector increased by 20% for each criterion

Rank	Tensile strength	Tensile modulus	Density	Elongation	Cellulose	Availability
1	Kenaf	Flax	Kenaf	Coir	Kenaf	Kenaf
2	Flax	Hemp	Flax	Kenaf	Palf	Palf
3	Palf	Kenaf	Palf	Bamboo	Flax	Flax
4	Hemp	Palf	Hemp	Cotton	Hemp	Hemp
5	Jute	Sisal	Sisal	Palf	Sisal	Bamboo
6	Sisal	Ramie	Bamboo	Flax	Jute	Banana
7	Ramie	Banana	Jute	Hemp	Cotton	Coir
8	Banana	Jute	Banana	Banana	Ramie	Sisal
9	Cotton	Bamboo	Coir	Sisal	Banana	Jute
10	Bamboo	Bagasse	Ramie	Ramie	Bamboo	Bagasse
11	Coir	Cotton	Cotton	Jute	Coir	Ramie
12	Bagasse	Coir	Bagasse	Oil Palm	Bagasse	Cotton
13	Oil Palm	Oil Palm	Oil Palm	Bagasse	Oil Palm	Oil Palm

Sensitivity analysis is carried out to study the impact on the results when the weightage of the priority vector for each criterion is varied. Typically, the result of the analysis is considered robust when the changes are not significant due to variations in underlying assumptions. From the sensitivity analysis, kenaf

fibre is ranked as the best alternative in four out of six criteria (tensile strength, density, cellulose, and availability). However, for tensile modulus and elongation, kenaf holds the third and second position, respectively, when compared to other alternatives. Therefore, the selection of kenaf as the suitable alternative using AHP is proven to be robust as consistent results were obtained on kenaf fibre when the weightage of priority vector in each criterion was altered. The sensitivity analysis validates the results obtained earlier by providing results on kenaf fibre as the most suitable fibre in the application of pultruded hybrid FRP composites for structural applications.

4.1.2 Summary

Overall, the AHP method serves researchers and engineers as one of the effective multi-criteria decision-making tools to perform selection and problem-solving tasks systematically for various applications. Based on the study, kenaf fibre is selected as the suitable alternative using AHP analysis, satisfying the basic design objectives and criteria of the application intended.

Consistency analysis was performed to validate the judgements made in the development of PCM. The overall inconsistency ratio obtained was 0.01, which is lower than the maximum CR value (0.1). Hence, it is proven that the judgements made during the AHP analysis were consistent and valid.

The sensitivity analysis shows that kenaf fibre is the best alternative as it scored the highest priority vector in four out of six criteria (tensile strength, density, cellulose, and availability). This further validates the fibre selection process using AHP.

Hence, kenaf is chosen as the plant fibre reinforcement for the development of plant/glass fibre reinforced hybrid composites in this research. The combination of these materials in composites are analysed for its mechanical, physical, and structural performance to identify and validate its integrity in practical engineering structural applications.

4.2 Selection of woven kenaf/glass roving hybrid composites

The second objective is to fabricate and study potential stacking sequences and combinations of woven kenaf/glass roving hybrid composites. Woven kenaf is used as the alternative plant fibre reinforcement for conventional woven E-glass fibres in structural profiles. These composites were subjected to multiple tests, including tensile, compression, bending, and interlaminar shear stress (ILSS) tests, and the results were thoroughly assessed and analysed.

Conducting basic mechanical tests on hybrid composites for structural profiles with open and closed wall sections remains crucial despite available research due to several reasons. Firstly, it allows for the verification and validation of existing data, ensuring the accuracy and reliability of reported properties. Notably, variations in stacking sequences and thicknesses of structural profiles can significantly influence mechanical properties and overall performance, necessitating thorough testing to understand and optimize these parameters effectively. Since there exists a gap in research on application of plant fibres in open and closed wall structural profiles, conducting these tests becomes even more crucial for addressing this gap and advancing the

understanding of hybrid composite materials in structural applications. Lastly, conducting these tests ensures standardization and quality assurance, vital for meeting industry standards and ensuring the reliability and safety of structural profiles across various sectors.

4.2.1 Tensile properties

Parameters such as fibre strength, modulus, adhesion between fibre and matrix, fibre geometry, and weave type all have a significant impact on the tensile properties of laminated composites. Figure 4.5 shows the tensile strength and modulus of different laminated composites. Pure fibreglass reinforced laminates have shown the highest tensile strength (440 MPa) and modulus (28 GPa) among the four different laminates. Almost similar values at about 404 MPa of tensile strength have been recorded for hybrid WK/UG alternate and 2WK/3UG/2WK laminates. The hybrid laminates recorded slightly lower tensile strength and tensile modulus compared to pure fibreglass composites. This is due to the higher tensile properties of individual glass fibres compared to the kenaf single fibre. However, hybrid specimen 3WK/UG/3WK has recorded the lowest tensile strength and tensile modulus at 177 MPa and 14 GPa respectively.

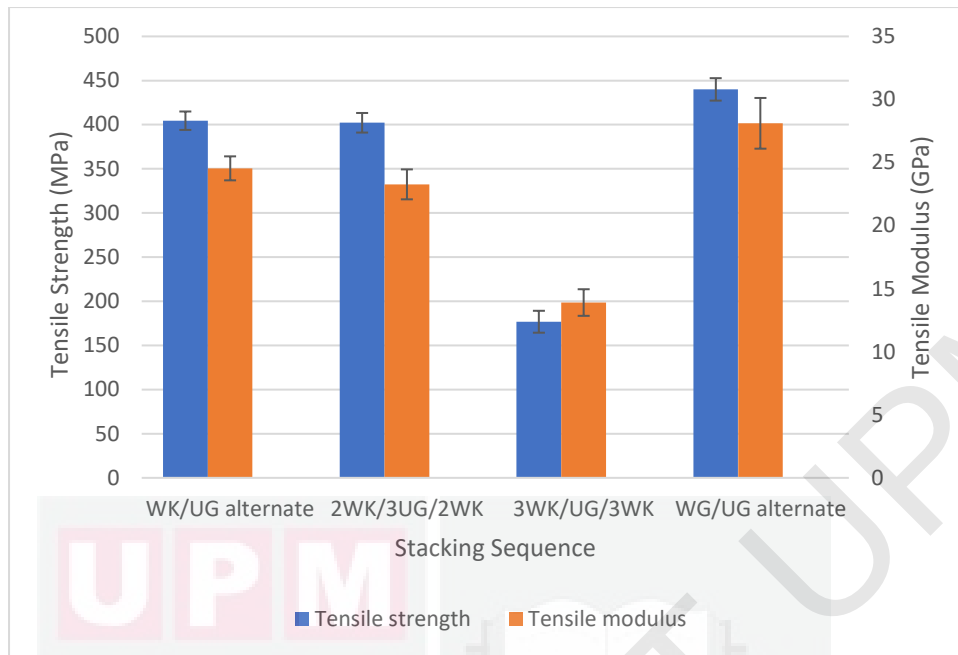


Figure 4.5: Tensile properties

As shown in Figure 4.6, comparable curvature of stress-strain profiles is observed of tensile behaviour. The graph shows linear increment up to failure. Brittle behaviour of the composites is explained when the plot suddenly dropped once the samples achieves ultimate tensile strength. All the samples' fractured in a brittle behaviour when the peak load is achieved. The plot also identifies that pure fibreglass composite attained the highest stiffness compared to the hybrid specimens. However, among the hybrid samples, WK/UG alternate laminates showed better stiffness than 2WK/3UG/2WK and 3WK/UG/3WK laminates.

The load is applied in the direction of fibres and the properties of single fibres determines the tensile strength and modulus of the composites. The experimental results clearly indicate the trend of decrease in tensile strength and tensile modulus as the volume percentage of glass fibres is decreased and replaced with kenaf fibres. However, satisfactory values of tensile

properties have been recorded by WK/UG alternate and 2WK/3UG/2WK laminates at around 404 MPa and 25 GPa respectively. The results indicate that the fibre volume fractions assigned for kenaf and glass rovings for the laminates are adequate for tensile applications with only 8.2% of strength degradation when compared to pure fibreglass composites. Tensile modulus determines the ability of samples to resist deformation with respect to the load applied.

Besides that, tensile modulus is also used to evaluate the stiffness of the composites. From the results, hybrid specimens (WK/UG alternate) recorded a slight decrease in tensile modulus at 10.7% from fibreglass specimens. Hence, the kenaf and glass composition at 45% and 55% respectively is suitable for moderate load bearing structural profile application with satisfactory mechanical strength and stiffness. The outcome has proven that woven glass fibres can be effectively replaced with woven kenaf fibres in the conventional pultrusion setup intended for low load and moderate load bearing applications.

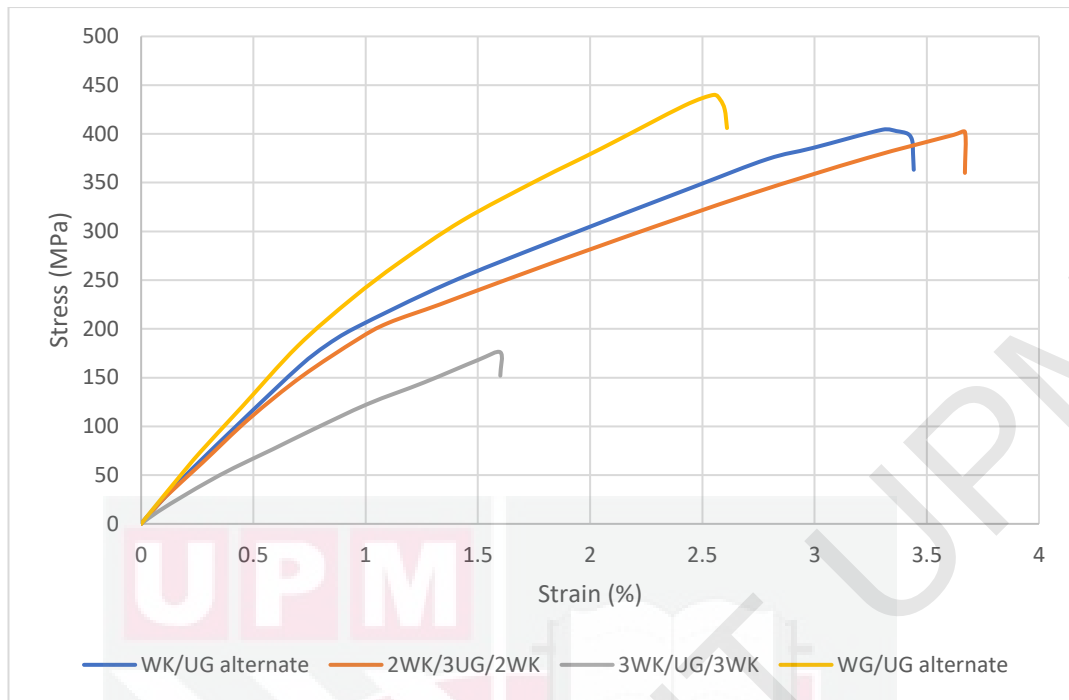


Figure 4.6: Tensile stress-strain profile

The failure modes for tensile specimens are evaluated through visual inspection. All the samples resulted in fibre breakage and delamination upon failures. However, all the samples did not break into two pieces during the tensile test. The WK/UG alternate and WG/UG alternate samples have shown similar failure modes. The kenaf mats and glass mats used in the samples respectively have gone through fibre breakage. However, transverse cracking has only happened to the mats as the glass roving plies have resisted the crack growth through the composites. This is due to higher strength properties of the unidirectional glass roving against transverse loading when compared to bidirectional fibre mats. The direct roving plies which prevent the crack from growing from one end to the other ensures that the stress is well distributed in the alternating sequences in both WK/UG and WG/UG samples.

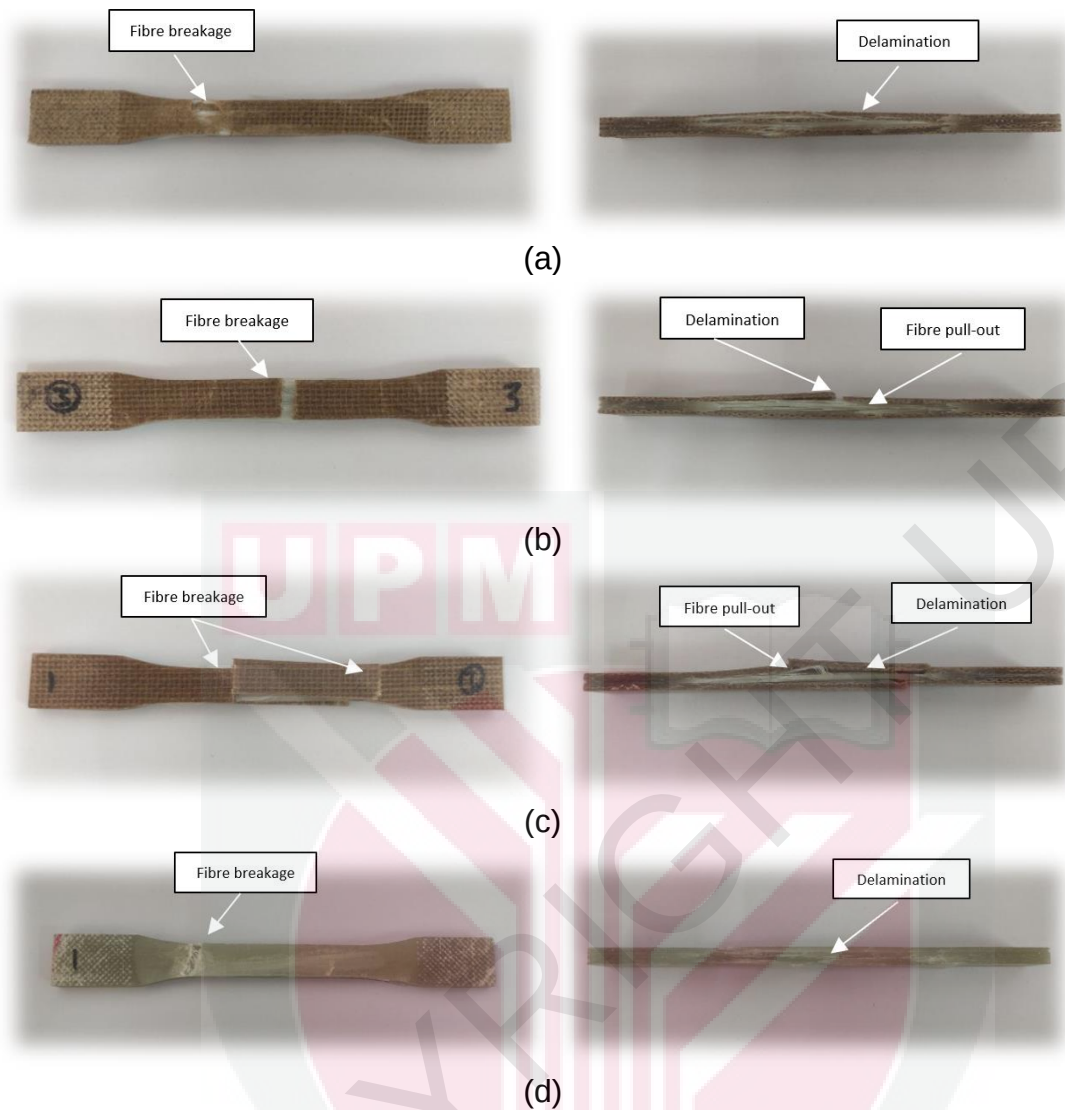


Figure 4.7: (a) WK/UG alternate tensile coupon; (b) 2WK/3UG/2WK tensile coupon; (c) 3WK/UG/3WK tensile coupon; (d) WG/UG alternate tensile coupon

Fibre breaking, fibre pull-outs and transverse cracking were clearly observed in kenaf mats in 2WK/3UG/2WK samples and 3WK/UG/3WK samples. However, there is no severe delamination observed between the kenaf-kenaf interface. In all the samples, delamination took place between the kenaf-glass interface. This might be due to the different tensile properties of the kenaf and glass fibres which caused difference in elongation during tensile loading, hence resulting in delamination between them.

4.2.2 Compressive properties

Compressive test was carried out to study the effect of stacking sequences on the compressive properties of the hybrid composites, and the results are presented as shown in Figure 4.8. Compressive property is attributed to the presence of fibres in the composites, which provided greater load-bearing capability and resistance to the applied compression load. Besides fibre strength, the compressive properties of composites are also influenced by the matrix strength, the fibre–matrix interface and stacking sequences.

Woven kenaf/unidirectional glass alternate samples have recorded the highest compressive strength (417.15 MPa) among other hybrid specimens. The alternating sandwich specimen recorded a slight decrease in strength value at 6.09% when compared to control, WG/UG specimen (444.21 MPa). The high values of the non-hybrid composites are supported by a study conducted by Rajpurohit et al. (Rajpurohit et al., 2020) where the glass fibre samples acquiring a thickness of 1.2 mm recorded compressive strength of 316 MPa.

According to Batu et al. (Batu & Lemu, 2020), among the hybrid false banana/glass fibre reinforced epoxy composites, ones with alternate stacking sequence recorded higher compressive strength when compared to 2 glass/3 banana/1 glass stacking sequence. This is possibly due to the good interfacial adhesion and mechanical interlocking between the plant and glass fibres in the hybrid composites.

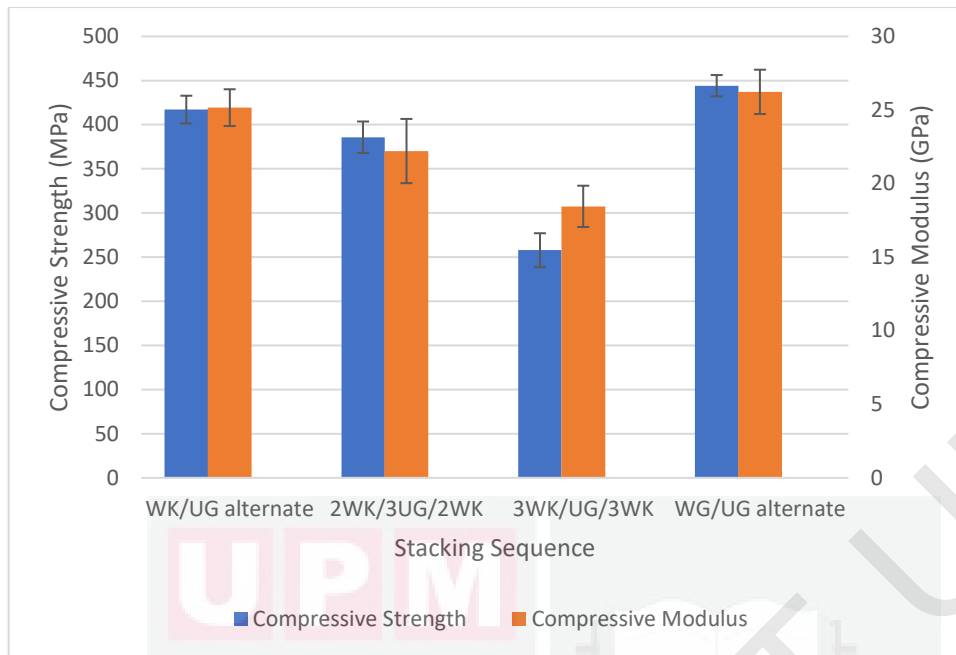


Figure 4.8: Compressive properties

On the other hand, highest compressive modulus is achieved by WG/UG alternate at about 27 GPa, followed by WK/UG alternate and 3WK/UG/3WK hybrid specimens at about 25 GPa. Whereby, lowest compressive modulus is recorded by 3WK/UG/3WK alternates at 18.45 GPa. As the kenaf to glass fibre ratio is increased in the composites, the compressive strength and modulus is reduced. Kenaf fibres have a less ordered and less densely packed atomic structure compared to glass fibres, leading to lower stiffness and strength. However, when kenaf fibres are hybridized with a high-stiffness material glass fibres, the resulting composite exhibited improved mechanical properties compared to kenaf fibres alone.

Based on the visual inspection the damage induced in WG/UG alternate samples less severe when compared to other samples. This is explained by the highest compressive modulus recorded by the samples as shown in Figure 4.8. Hence, the samples are better at resisting deformation at high

compressive loads. However, failure modes such as fibre cracking, fibre micro buckling, local fibre micro buckling with an elastic matrix, and shear failure is observed in 2WK/3UG/2WK and WG/UG alternate samples (Figure 4.9). The failure modes are correlated with the fibre/matrix adhesion in the composites (Safiee et al., 2011).

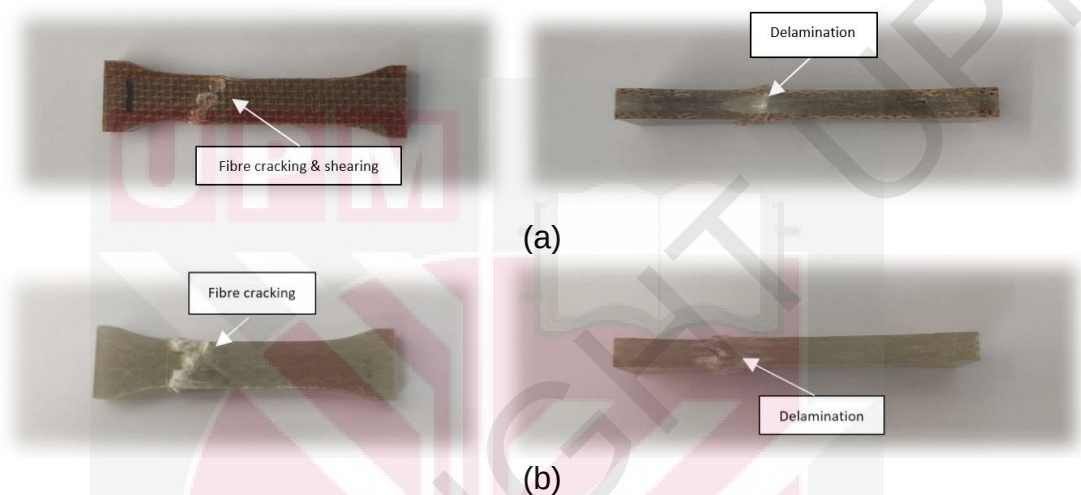


Figure 4.9: (a) 2WK/3UG/2WK compressive coupon; (b) WG/UG alternate compressive coupon

4.2.3 Bending properties

Bending properties are vital in designing structural profiles. Structural profiles are subjected to bending force which induces a combination of compressive and tensile stresses. The laminated hybrid composites' bending properties are heavily influenced by the stacking sequence, which typically involves the positioning of woven kenaf mats and direct roving glass fibres.

Figure 4.10 depicts the modulus of rupture and modulus of elasticity of various stacking sequences. Pure fibreglass non-hybrid laminates (control) recorded the highest modulus of rupture (476 MPa) and modulus of elasticity (14.77

GPa) compared to other specimens. The hybrid sample WK/UG alternate yielded the highest modulus of rupture (456.33 MPa) and modulus of elasticity (14.49 GPa) among other hybrid laminates. The alternate specimens varied with only a 4.13% of modulus of rupture and 1.9% of modulus of elasticity reduction with respect to pure fibreglass composite. The woven kenaf mats' dense, tight fibre architecture and lignin content improved composites' bending strength and resistance. The hybrid laminate, 3WK/UG/3WK recorded the lowest modulus of rupture and modulus of elasticity among all the laminated composites.

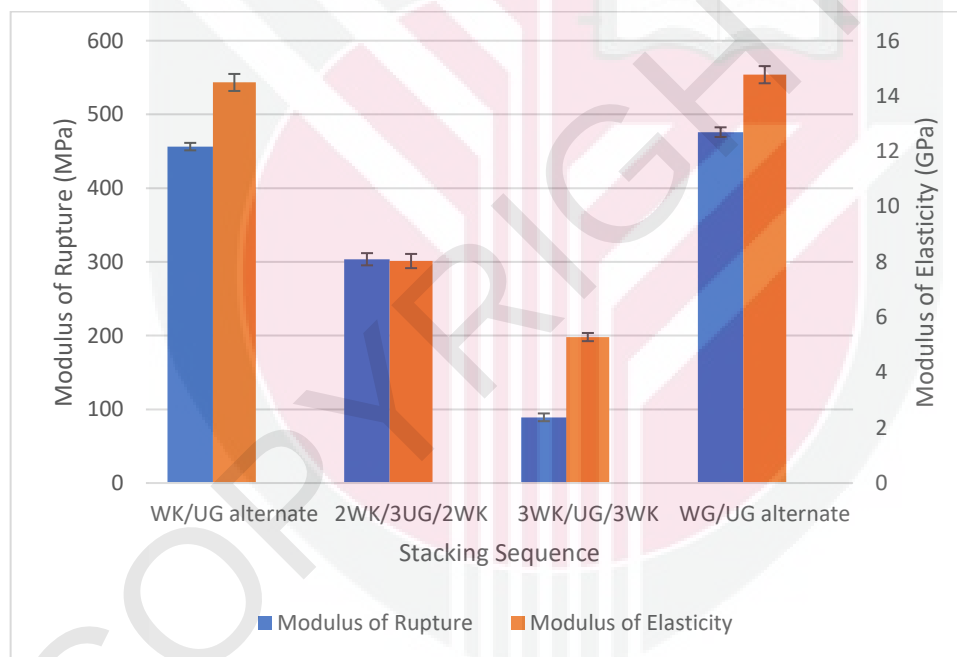


Figure 4.10: Bending properties

The experimental results clearly indicate that the stacking sequence plays an important role in determining the bending properties of hybrid laminates. Hence, alternate woven kenaf/ unidirectional glass laminates will be a potential candidate for bending applications by effectively replacing conventional pure fibreglass laminates in structural profile application.

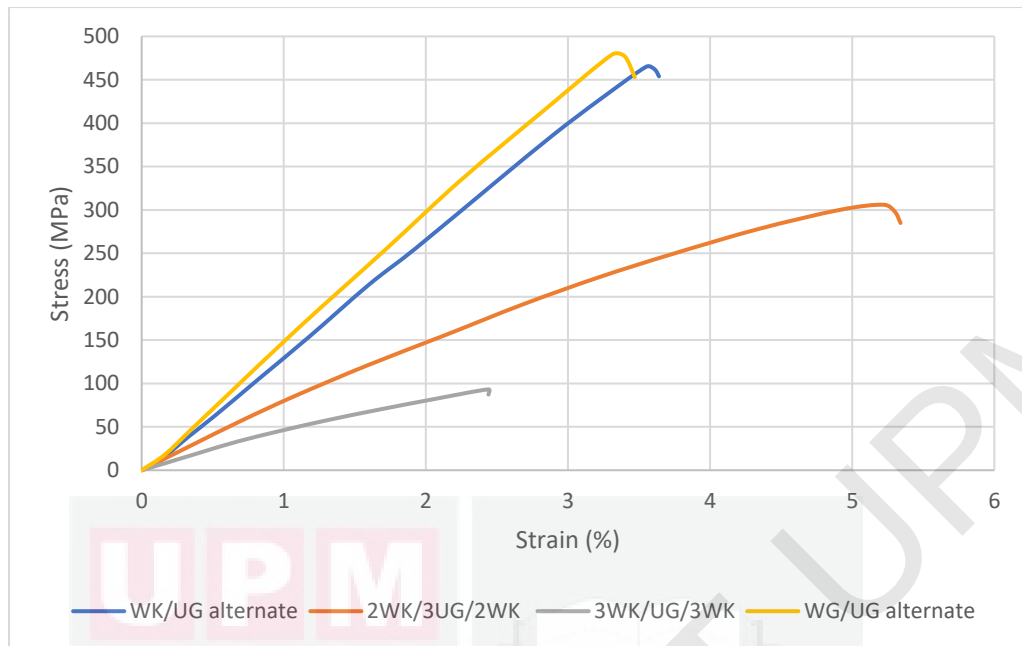


Figure 4.11: Bending stress-strain profile

The failure modes observed in the composite samples are fibre breakage and delamination. All the samples demonstrated failure at the tensile region. This is due to the higher compressive modulus of hybrid composites (Figure 4.8) have reduced deformation at the compressive region. Similar damage modes are observed in WK/UG alternate and WG/UG alternates where fibre breakage happens in the first ply at the tensile region of the composite samples. Delamination was observed in WG/UG alternate between the first ply (woven glass mat) and second ply (unidirectional glass rovings). In 2WK/3UG/2WK hybrid samples, fibre breakage was displayed by the first 2 plies of woven kenaf mats at the tensile region. Similarly, the first 3 plies of kenaf mats experienced fibre breakage in 3WK/UG/3WK samples. The samples also experienced delamination in the woven kenaf-unidirectional glass rovings interface, at the tensile region.

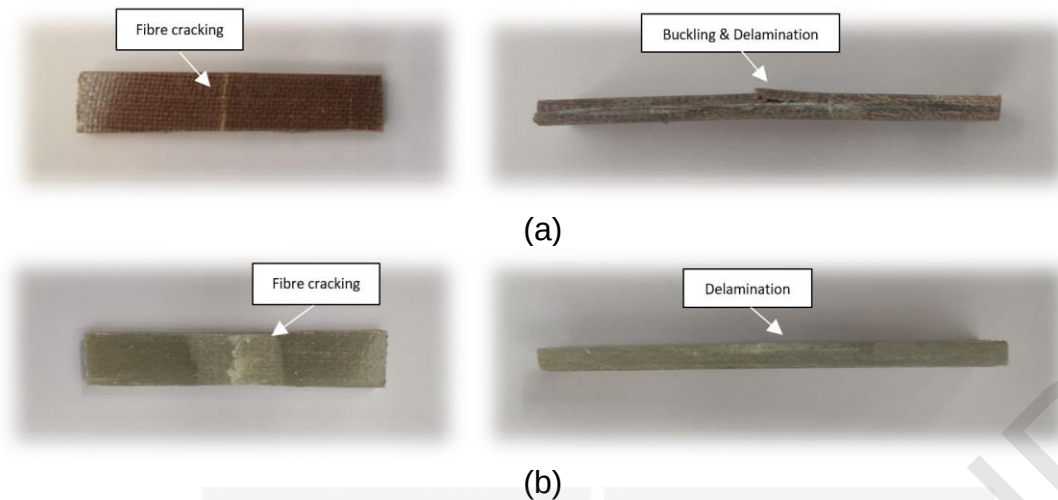


Figure 4.12: (a) 3WK/UG/3WK bending sample; (b) WG/UG alternate bending sample

4.2.4 Interlaminar shear strength

Interlaminar shear strength analysis is essential for assessing the bond strength between layers in composite materials, particularly in applications where structural integrity and safety are paramount. A high interlaminar shear strength ensures that composite layers remain bonded together under various loading conditions, such as bending, torsion, and impact, maintaining the structural stability and preventing delamination. This is crucial for ensuring the safety of users, as weak interlaminar bonds can lead to structural failure and potential accidents. By prioritizing robust interlaminar shear strength, the risk of failure due to delamination or layer separation is significantly mitigated, enhancing overall safety in structural applications including ladder applications.

The short beam bending test was used to determine the hybrid and control samples' interlaminar shear strength (ILSS). The short beam is subjected to both bending and shear stress during the three-point bending test when a load

is applied in the thickness direction. Another important mechanical test that provides information about the quality of the resin-fibre bond is the interlaminar shear strength (ILSS). Yahaya et al. (Yahaya, Sapuan, Jawaid, et al., 2014) claim that interlaminar shear cracking, micro buckling, fibre rupture, and a combination of the failure modes lead to ILSS.

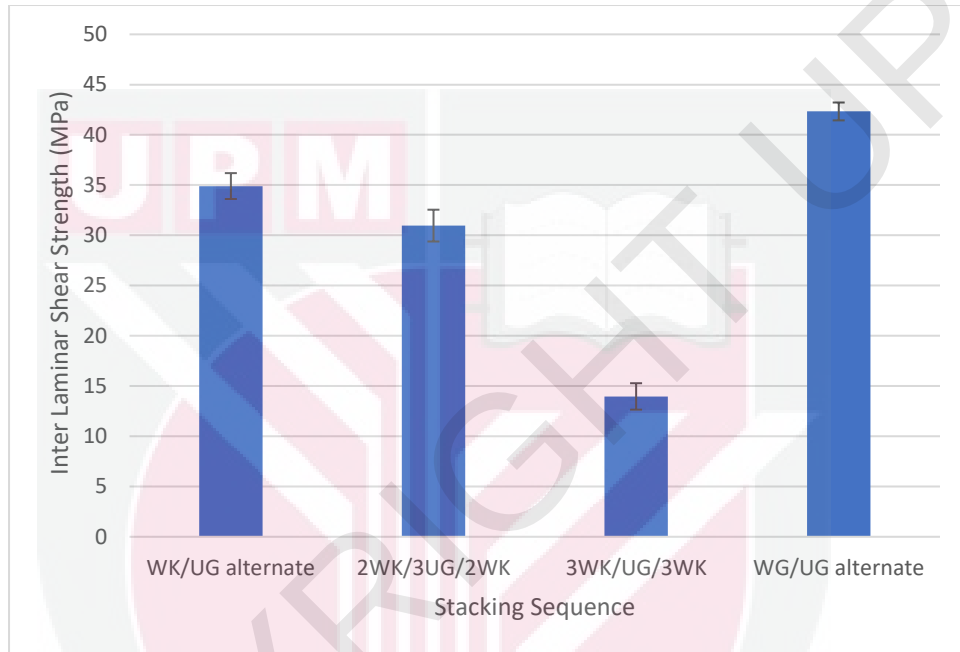


Figure 4.13: ILSS properties

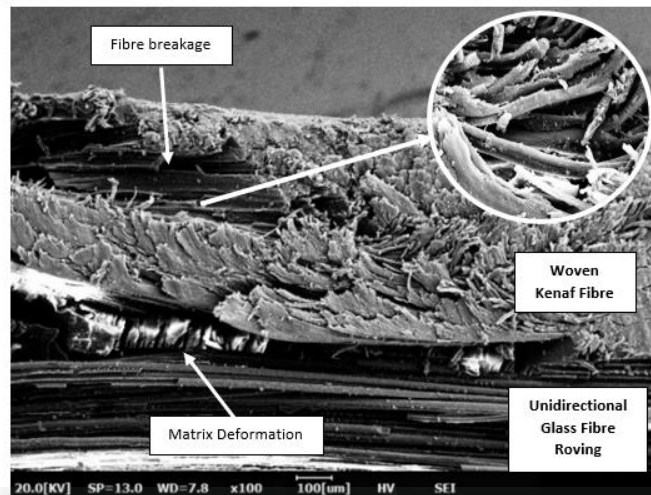
Highest ILSS is recorded in the non-hybrid control sample which is the alternate WG/UG (42.33 MPa). The higher ILSS of the composite with higher glass fibre content is attributed to the better wetting of the glass fibres by the polyester matrix, which leads to better fibre/matrix adhesion in the composites compared to hybrid samples. However, among the hybrid samples, WK/UG alternate (34.9 MPa) scored the highest ILSS followed by 2WK/3UG/2WK samples (30.97 MPa) with a minor difference in values. However, the ILSS is significantly reduced for hybrid 3WK/UG/3WK (13.97 MPa) composites. The results obtained demonstrate comparable range of values when compared to

ILSS results of other types of plant fibre composites in the most recent studies. For instance, bamboo reinforced epoxy (20.4 MPa) recorded by Rajabipour et al. (Rajabipour et al., 2022); jute/glass reinforced epoxy (26 MPa) recorded by Alves et al. (Alves et al., 2019); and jute/banana reinforced phenol formaldehyde (5.21 MPa) by Prashanth et al. (M. Prashanth et al., 2021). From the previous investigations, plant/glass fibre reinforced hybrid composites show higher ILSS values when compared to plant fibre and plant-plant hybrid composites.

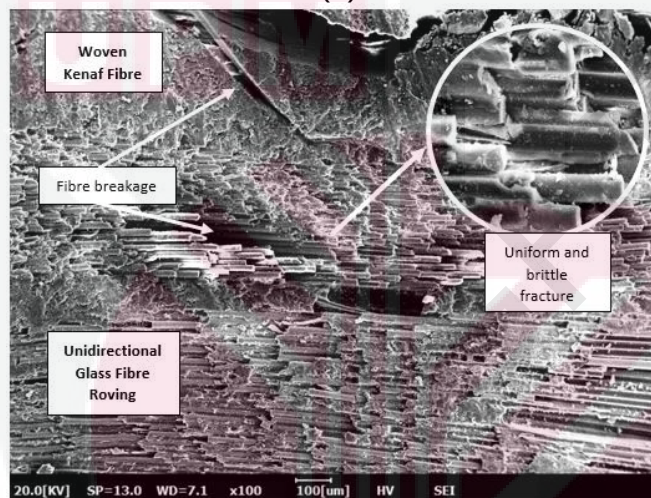
It is notable that ILSS is significantly reduced as the volume fraction of kenaf increased in 3WK/UG/3WK. This is probably due to the lower strength and poor mechanical interlocking between kenaf-kenaf region with more than 1 ply thickness in the composites. Hence, separating the kenaf mats and direct roving with a single layer of kenaf mats improved the interlaminar shear properties in WK/UG alternate. The mechanical interlocking between woven kenaf and glass rovings are stronger which resulted in higher ILSS among the hybrid specimens. Similar work has been reported by Alves et al. (Alves et al., 2019) where they studied ILSS of jute/glass reinforced hybrid epoxy composites. The researchers reported that fracture occurred between jute layers, due to the lower shear strength between jute-jute interface.

4.2.5 SEM analysis

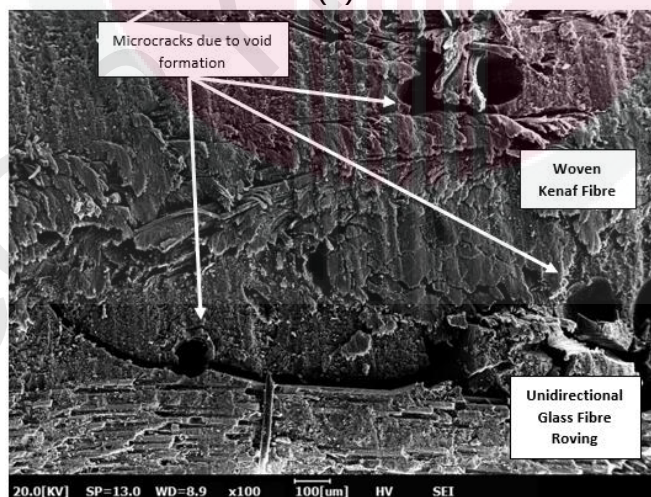
Microstructural analysis of the tensile fractured specimens was studied. The specimen's morphology and fibre-matrix interfacial adhesion were examined using scanning electron microscopy (SEM). Under tensile load, the most common failure modes for woven kenaf/unidirectional glass roving reinforced hybrid composites are matrix deformation, fibre breakage, microcracks, voids, and fibre pull-out. From WK/UG alternate samples (Figure 4.14 a & b), it is highlighted that the fracture in glass fibre rovings was relatively uniform and belonged to brittle failure (Guo et al., 2019). However, kenaf fibres were seen disoriented while demonstrating a ductile fracture. The kenaf mats demonstrates a dense and tight fibre architecture which resulted in comparable tensile properties with conventional pure fibreglass composites. Besides that, the chemically treated kenaf fibres also demonstrate a rougher surface texture ensures good fibre-matrix adherence (Madhu et al., 2020; Moshi et al., 2020). According to Nayak et al, (Nayak & Khuntia, 2019) the application of chemical treatment serves to eliminate undesirable substances such as lignin and waxy materials in plant fibres. This process contributes to the enhancement of fibre texture and quality which subsequently leads to improved bonding between the fibre and matrix within treated composites.



(a)



(b)



(c)

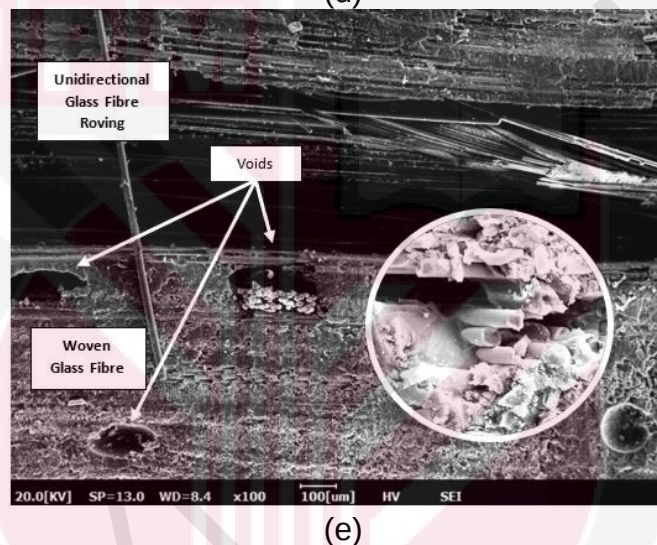
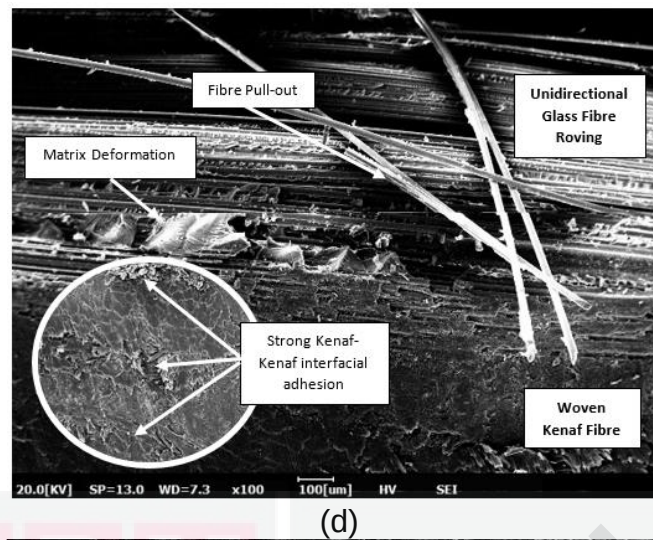


Figure 4.14: (a & b) WK/UG alternate specimen; (c) 2WK/3UG/2WK specimen; (d) 3WK/UG/3WK specimen; (e) WG/UG alternate specimen

In every hybrid variant, the kenaf-matrix, kenaf-glass, and kenaf-kenaf interfacial adhesion is good. However, the experimental results show that kenaf/glass interphase in WK/UG alternate perform better than kenaf-kenaf interphase in 2WK/UG/2WK although the kenaf to glass ratio is controlled in both specimens. Limited debonding and fibre pull-outs can be observed in the kenaf/glass hybrid specimens. This ensures a good fibre-matrix interface in the composites. Due to the failure occurring within the fibre such as fibre pull-outs, failure at the interface between the matrix and the fibre can be avoided

(Laksono et al., 2021). Besides that, matrix deformation in the composites also indicated the strong bonding between the fibre and matrix. Similar damage modes were observed by Cavalcanti et al. (Cavalcanti et al., 2019), where breakage of fibres and fewer voids present due to fibre pull-out indicated a good fibre-matrix adhesion. The reinforcement transfers stress uniformly throughout the matrix in the composites (Sekar et al., 2020).

4.2.6 Summary

Overall, for the application in open and closed wall structural profiles, the mechanical properties of kenaf/glass hybrid composites were investigated. Pure fibreglass specimens have recorded highest mechanical properties in tensile, compressive, bending and ILSS tests. However, the kenaf/glass hybrid composites have also proven their capabilities by showing good agreement with the conventionally used fibreglass samples.

Some specific conclusions have been made from the study conducted. Good tensile results were obtained from WK/UG alternate samples and 2WK/3UG/2WK samples with a decrease of about 8.2% of tensile strength and 10.7% of tensile modulus when compared to conventional fibreglass samples. Alternating sandwich WK/UG samples recorded higher compressive strength when compared to other hybrid specimens and recorded a slight decrease in strength value at 6.09% compared to pure fibreglass composites. However, higher compressive modulus is recorded by 3WK/UG/3WK and WK/UG alternate samples have resulted in reduction of deformation in compressive loads.

Highest modulus of rupture and modulus of elasticity were observed in hybrid alternate WK/UG samples than other hybrid laminates and recorded satisfactory bending properties with only a decrement of 4.13% in rupture modulus and 1.9% in elasticity modulus when compared to the control specimen. The ILSS of hybrid composites 2WK/3UG/2WK and alternate WK/UG showed good agreement with the pure fibreglass composites.

SEM analysis revealed failure modes such as matrix deformation, fibre breakage, microcracks, voids, and fibre pull-outs in tensile fractured woven kenaf/unidirectional glass roving reinforced hybrid composites.

From the results, it can be concluded that alternate WK/UG can be a potential alternative to replace pure fibreglass composites in moderate load bearing structural profiles in various industries such as aerospace, civil, marine, automotive, and sporting goods. For instance, bicycle frames, seat frames, ladders, stairs, gratings, flooring beams and mezzanine floors are some examples of moderate load bearing structural applications in which kenaf-glass structural profiles can be potentially applied. Moreover, the hybrid composite 3WK/UG/3WK shows promise for low load bearing applications, especially when incorporating a higher ratio of kenaf to glass fibres. As a result, both the hybrid WK/UG alternate and 3WK/UG/3WK composites are selected for more comprehensive analyses of their durability properties through fatigue and Izod impact testing in the following objective.

4.3 Testing of kenaf/glass roving hybrid pultruded composites

In pursuit of the third objective, pultruded profiles were fabricated using the chosen stacking sequence to assess their durability. Closed and open-walled pultruded profiles were fabricated by collaborating with industrial experts and investigated for their resilience, thereby addressing a significant gap in the literature regarding the performance of these profiles. This addition broadens the scope of the research, providing insights into the durability of kenaf/glass reinforced pultruded profiles under different structural configurations and contributing to a more comprehensive understanding of their suitability for practical applications. Within this section, the fatigue and Izod impact characteristics of both Pultruded WK/UG alternate and Pultruded 3WK/UG/3WK hybrid composites were investigated and compared with conventional fibreglass pultruded composites. Additionally, the density, weight, and cost analysis were also done to compare the hybrid profiles with conventionally manufactured fibreglass profiles.

4.3.1 Static analysis

Tensile properties of the specimens were investigated to find the average ultimate tensile strength (UTS) for fatigue analysis. Figure 4.15 shows the tensile strength and modulus of hybrid and non-hybrid pultruded composites. The non-hybrid, pultruded WG/UG alternate specimens have shown the highest tensile strength (458.28 MPa) and modulus (32 GPa) among the three pultruded laminates. This is due to the higher tensile properties of individual glass fibres compared to the kenaf single fibre. However, interesting results

have been exhibited when the lower tensile strength kenaf fibres are replaced with woven glass fibres and hybridised with unidirectional fibreglass rovings. The hybrid pultruded WK/UG alternate specimens recorded a tensile strength of 410.6 MPa and a tensile modulus of 26 GPa. The samples recorded a strength reduction of 10.4% and a modulus reduction of 18.75% compared to pultruded WK/UG composites. However, hybrid specimen 3WK/UG/3WK has recorded the lowest tensile strength and tensile modulus at 185 MPa and 15 GPa, respectively. The higher kenaf to glass fibre ratio resulted in significant strength reduction at about 59.6% and modulus reduction at about 53.13% compared to the conventional fibreglass specimen.

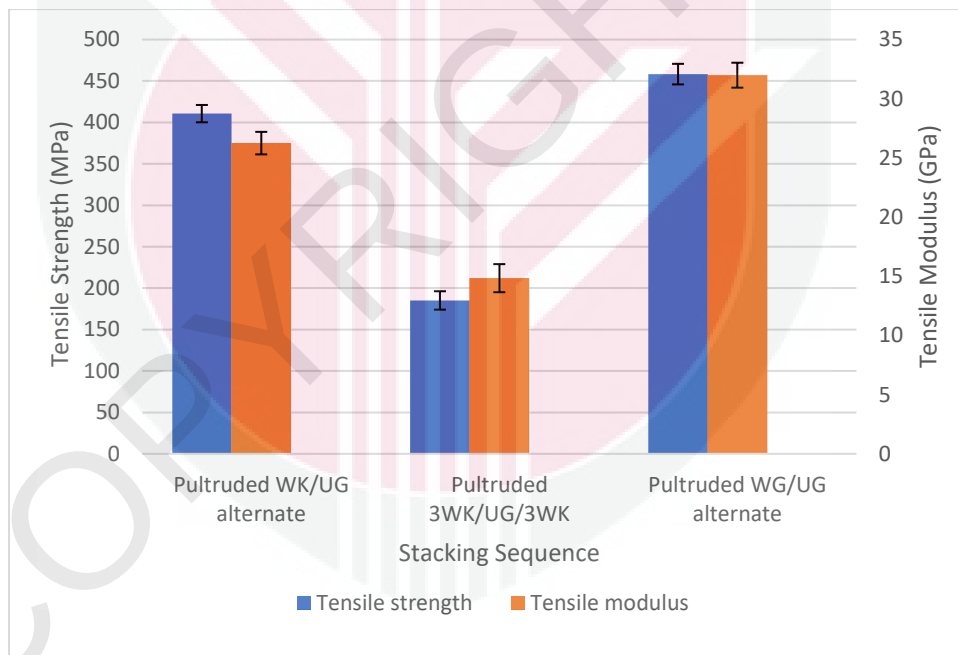


Figure 4.15: Tensile properties of pultruded composites

According to Figure 4.16, stress-strain profiles show the tensile properties of the hybrid and non-hybrid (control) specimens. The graph shows a linear increment up to failure. The brittle behaviour of the composites is explained when the plot suddenly drops once the samples achieve ultimate tensile

strength. When the peak load is achieved, all the samples fractured in a brittle behaviour. However, the maximum displacement of the specimens shows that pultruded WK/UG alternate is slightly more ductile in its plastic region when compared to pultruded WG/UG alternate specimens. The tensile modulus explains that pure fibreglass composite attained the highest stiffness compared to the hybrid specimens. However, among the hybrid samples, WK/UG alternate laminates showed better stiffness than 3WK/UG/3WK laminates. Overall, the load is applied in the direction of fibres, and the properties of single fibres determine the tensile strength and modulus of the composites. The experimental results indicate a decrease in tensile strength and tensile modulus as the volume percentage of glass fibres is decreased and replaced with kenaf fibres.

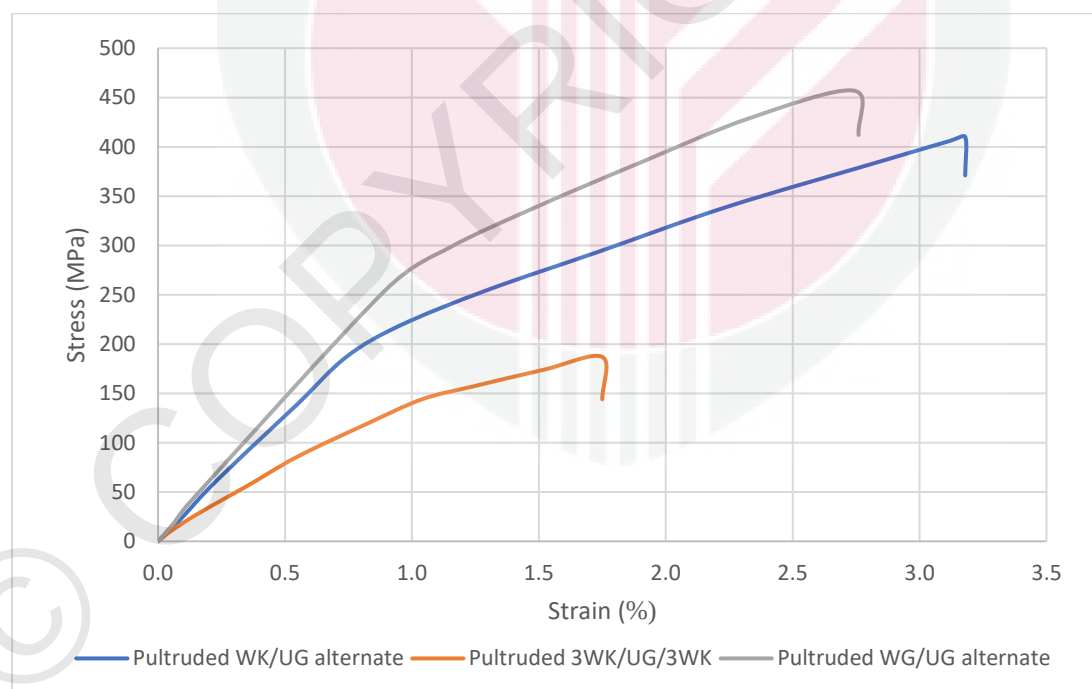


Figure 4.16: Tensile stress-strain curves of pultruded composites

4.3.2 Fatigue analysis

Repeated tension-tension loading was applied to the composite specimens until fracture occurred. The stress on the specimens was systematically decreased in 10% increments, starting from 80% of the ultimate tensile strength (UTS) and ending at 50% of the UTS. The force values corresponding to stress amplitude and mean stress were calculated and imposed on the specimens. A plot of stress (S) versus the number of cycles to failure (N), known as an S-N curve or Wöhler Curve, was generated to illustrate the test results. This curve represents the relationship between cyclic stress amplitude and the number of cycles required for failure to occur.

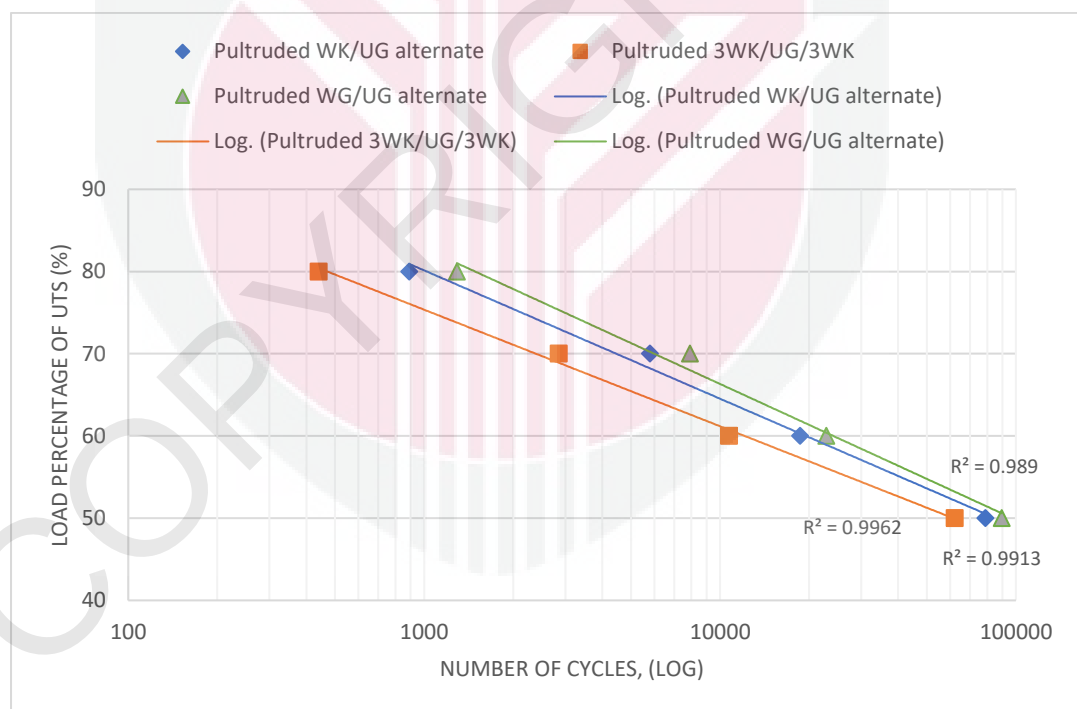


Figure 4.17: Fatigue test

By analyzing the S-N curve, it becomes evident that decreasing the applied stress leads to an increase in the number of life cycles, indicating improved fatigue resistance. The hybridization of kenaf and glass fibres, as well as the

varying ratio of kenaf to glass fibres in the hybridized pultruded composites, significantly affected the fatigue life. This indicates that there were notable differences in the fatigue properties between the hybridized pultruded composites and conventional pultruded composites made entirely of fibreglass.

Fatigue strength is compared between the materials using the Wöhler's curve by analyzing the stress amplitudes at a specific number of cycles to failure. The material with the higher stress amplitude at a given number of cycles is considered to have a higher fatigue strength. The data indicates that the highest fatigue strength is achieved by Pultruded WG/UG alternate followed by Pultruded WK/UG alternate and Pultruded 3WK/UG/3WK specimen. Kenaf/glass fibre reinforced hybrid pultruded composites achieved slightly lower fatigue strength than non-hybrid specimens. Compared to glass fibres, kenaf fibres typically have lower tensile strength and fatigue resistance. Hence, increasing the proportion of kenaf fibres in the hybrid composite lower the overall fatigue strength of the material.

On the other hand, fatigue sensitivity between materials is analysed from the slope of the S-N curves. A steeper slope indicates a higher rate of fatigue strength degradation, implying greater fatigue sensitivity. Materials with steeper slopes have a more rapid reduction in fatigue life as the stress amplitude increases. From the data, highest fatigue sensitivity is achieved by Pultruded WG/UG alternate followed by Pultruded WK/UG alternate and Pultruded 3WK/UG/3WK specimen. It is notable that, increase in the kenaf to glass ratio have resulted in decreased fatigue sensitivity. Sharba et al.

(Sharba, Leman, Sultan, Ishak, & Hanim, 2016) stated that an increase in kenaf to glass ratio in its hybrid composites resulted in a decrease in fatigue sensitivity, which is a desirable property of materials at low load applications.

A study on plant fibre composites by Liang et al. (Liang et al., 2012) resulted similar properties where flax fibre reinforced composites show decreased fatigue sensitivity and fatigue strength compared to glass fibre composites. Kenaf fibres, being of plant origin, possess inherent damping characteristics. The introduction of kenaf fibres in the hybrid composite contribute to enhanced damping properties (Asyraf et al., 2021; Hassan et al., 2017). Damping refers to the ability of a material to dissipate energy during cyclic loading, reducing the magnitude of stress fluctuations. This damping effect helps to absorb and dissipate energy, mitigating stress concentrations and reducing fatigue sensitivity. Therefore, the presence of kenaf fibres in hybrid composite exhibit lower sensitivity to fatigue-induced failure compared to non-hybrid fibreglass composites. Due to its lower elastic modulus and excellent damping properties, kenaf fibres exhibit improved damage tolerance compared to brittle glass fibres (Sivakumar et al., 2018). Hajer et al. (Hadiji et al., 2020) stated that natural fibre composites such as flax-PP, hemp-PP, kenaf-PP demonstrated improved damping properties compared to glass fibre composites. Similarly, findings from Diharjo et al. (Diharjo et al., 2018) show that an increase in kenaf to glass fibre ratio led to improved vibration-damping factor and a decrease in elastic modulus of the hybrid composite. The increased kenaf content in the hybrid composite introduce additional mechanisms for energy absorption and crack deflection, enhancing the

composite's resistance to fatigue crack initiation and propagation (Ramraji et al., 2022). The findings are supported by Sharba et al. (Sharba et al., 2015) when kenaf fibre composites demonstrated a slower stiffness degradation when compared to glass fibre composites. Researchers have also recorded that woven kenaf fibres offer good balance in static and fatigue strengths with low fatigue sensitivity in bidirectional planes compared to glass fibres which make them attractive in structural applications (Sharba, Leman, Sultan, Ishak, & Azmah Hanim, 2016).

Fatigue is typically be categorized into two distinct regions known as high cycle fatigue and low cycle fatigue. High cycle fatigue manifests failure signs after exceeding 10,000 cycles under relatively low stress levels. Conversely, low cycle fatigue occurs at fewer cycles, usually below 10,000, accompanied by increased plastic deformation (Shahar et al., 2022). Upon examining the S-N curve, it is observed that when the stress level reaches 60% of the ultimate tensile strength (UTS), all the data points are situated within the high cycle fatigue region. Hence, both hybrid WK/UG alternate and 3WK/UG/3WK specimens demonstrates good fatigue resistance and durability, particularly in high cycle fatigue conditions. The materials withstand many cycles, exceeding 10,000, at relatively low stress levels without signs of failure. This indicates that the material has the potential for long-term reliability in structural applications involving cyclic loading (Gao et al., 2022; Noël, 2019).

Table 4.2: Damage on samples after fatigue testing

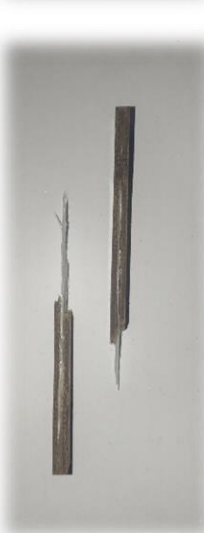
Stress intensity	50%	60%	70%	80%
Pultruded WK/UG alternate				
Pultruded 3WK/UG/3 WK				
Pultruded WG/UG alternate				

Table 4.2 depicts the results of fatigue testing, specifically focusing on failure modes at 60% of the fatigue life. Notably, all tested samples experienced failure due to a combination of fibre pull-out, fibre breakage, delamination, debonding, and matrix cracking. The observation suggests that the applied stress was efficiently distributed along the specimens, leading to significant delamination within the material. The kenaf/glass hybrid specimens exhibited unique failure modes that provide valuable insights into the interfacial adhesion between the kenaf fibres and the direct roving of glass fibres. The presence of sufficient interfacial adhesion indicates good bonding and interaction between the kenaf fibres and the direct roving. Proper wetting, which is the process of the resin impregnating the fibres during composite manufacturing, likely contributed to this enhanced interfacial adhesion (Hashim et al., 2021). The improved interfacial adhesion between the kenaf fibres and the direct roving is significant for composite performance.

Overall, different ratios resulted in varied fatigue performances, emphasizing the importance of fibre composition in achieving desired durability. The hybridization of kenaf and glass fibres introduced a new dynamic in the material's fatigue behavior. These hybrid composites demonstrated altered fatigue characteristics due to the combined properties of kenaf and glass fibres, resulting in different fatigue life cycles.

4.3.3 Impact analysis

Izod impact testing is a type of mechanical test used to evaluate the impact strength or toughness of a material. It measures the energy required to break a specimen under a single, high-velocity blow. This test is particularly relevant for assessing a material's ability to withstand sudden impact or shock loading, which is a critical aspect of its durability in various applications (Asumani & Paskaramoorthy, 2020). It involves striking a standardized notched specimen with a pendulum hammer and measuring the energy absorbed during the fracture. Structural applications often involve materials that need to withstand impact or sudden loading conditions. The Izod impact test provides valuable information about a material's ability to resist and absorb energy during impact events. This data is crucial for assessing the safety and reliability of structural components, as it helps identify materials that can withstand unexpected or dynamic loading conditions without catastrophic failure.

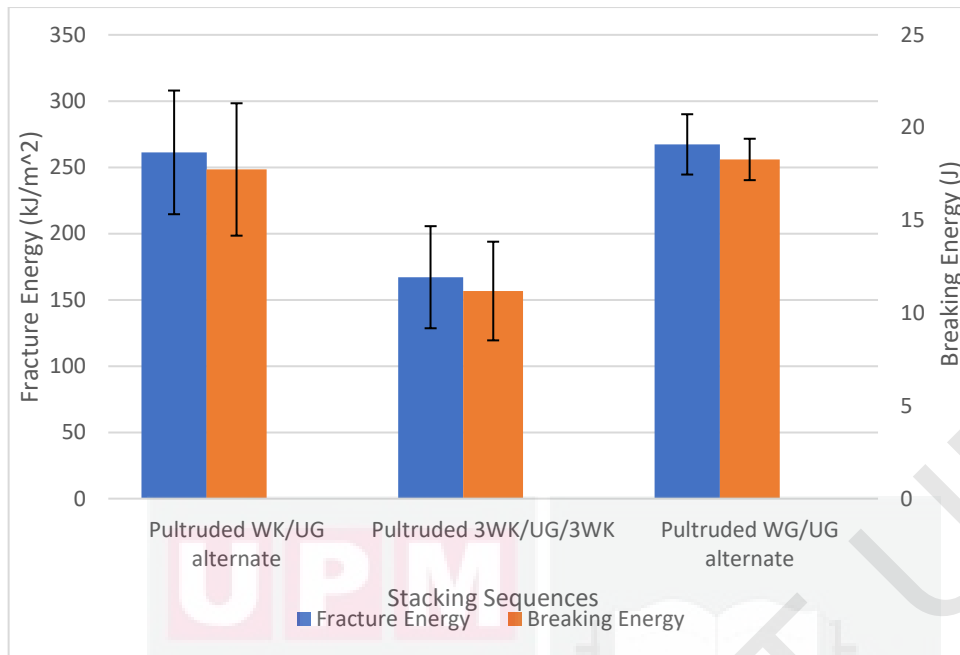


Figure 4.18: Izod impact testing

The pultruded WK/UG alternate hybrid composites show similar impact strength with pultruded WG/UG alternate non-hybrid composites at about 260 kJ/m². Kenaf fibres and glass fibres possess different mechanical properties. While glass fibres are known for their high stiffness and strength, kenaf fibres offer good impact resistance and toughness (Ahmad Nadzri et al., 2020). The combination of these two fibre types in hybrid composites can result in a complementary blend of properties. Singh et al. (Singh et al., 2020) recorded that hybridized kenaf/glass composites demonstrate significantly higher impact strength compared to pure kenaf composites. Hence, the inherent impact resistance of kenaf fibres, when combined with the strength of glass fibres, can contribute to a similar overall impact strength compared to non-hybrid fibreglass composites. However, further increasing the kenaf to glass ratio resulted in a slight reduction in impact strength. Similar discussions have been made on plant/glass fibre hybrid composites by Saroj et al. (Saroj &

Nayak, 2021) and Ghani et al. (Ghani et al., 2022), where the impact strength reduced with significant increase in kenaf to glass ratio and jute to glass ratio respectively. The impact strength of Pultruded 3WK/UG/3WK is 37.5% lower than Pultruded WK/UG alternate. Hence, pultruded WK/UG alternate is found to have the optimum kenaf to glass ratio and stacking sequence as the composites demonstrate almost similar impact properties compared to conventional non-hybrid fibreglass.



Figure 4.19: WK/UG alternate; (b) 3WK/UG/3WK alternate; (c) WG/UG alternate

Figure 4.19 effectively illustrates the results of Izod impact testing, clearly depicting the failure modes of different specimens. Among the tested samples, the kenaf/glass hybridized specimen, Pultruded WK/UG alternate and the Pultruded 3WK/UG3WK specimen showed severe delamination upon impact testing. Additionally, more visible fibre pullouts were observed in the hybrid

specimen. The observed failure modes in the hybrid specimens can be attributed to the damping properties of kenaf fibres. Kenaf fibres have inherent damping characteristics, contributing to a more ductile failure behavior in the hybridized specimens. The damping property of kenaf fibres allows them to undergo greater deformation and energy absorption during impact, leading to delamination and fibre pullouts as the material redistributes stress to absorb the impact energy (Azammi et al., 2020; J. Zhang et al., 2019).

On the other hand, the pultruded fibreglass specimen demonstrated a failure mode that lacked signs of delamination. This is in line with the nature of glass fibres, known for their high tensile modulus and brittle properties. Glass fibres have excellent stiffness and strength, but they are relatively brittle and more prone to sudden fracture under impact loads. As a result, the failure observed in the fibreglass specimen was more brittle, with less delamination compared to the hybridized specimens. The absence of delamination in the fibreglass specimen can be attributed to the higher stiffness and reduced damping capacity of glass fibres. Unlike kenaf fibres, glass fibres are less deformable and have lower energy absorption capabilities. Consequently, when subjected to impact forces, glass fibres tend to experience sudden fracture and minimal deformation, leading to brittle failure with limited delamination.

It is important to find the right balance between kenaf and glass fibres in hybrid composites to achieve the desired combination of properties. Considering factors such as specific application requirements and the trade-off between weight reduction and impact performance is essential when selecting the appropriate kenaf to glass ratio for a particular composite application.

4.3.4 Density analysis

One of the key factors that plays a crucial role in defining the characteristics of a composite material is its density. The density determines whether the material can offer improved strength-to-weight or cost-to-weight ratios for designing various applications. This aspect is particularly important in pultruded profile applications due to the advantages of lighter structural products. Lighter profiles are easier to handle and transport, making them more convenient for installation, assembly, and maintenance. They are less cumbersome and pose a lower risk of injury during handling and installation. Besides that, in applications such as aerospace, automotive, and renewable energy sectors, lighter pultruded profiles contribute to lower energy consumption, leading to enhanced fuel efficiency, extended battery life, and optimized system performance.

Table 4.3: Average density of pultruded hybrid kenaf/glass and non-hybrid fibreglass composites

Material	Kenaf/Glass alternate	3WK/UG/3WK	Fibreglass
Average density (g/cm ³)	1.5101	1.3504	1.6697

Table 4.3 presents the average density values obtained from density tests. The average density values obtained from density tests from highest to lowest are Pultruded Fibreglass (1.6697 g/cm³), followed by Pultruded Kenaf/Glass alternate (1.5101 g/cm³) and Pultruded 3WK/UG/3WK (1.3504 g/cm³). It is evident from the table that as the ratio of kenaf to glass fibre loading increases,

the density of the pultruded composites decreases, resulting in lighter materials.

4.3.5 Specific strength, cost and weight analysis

The weight and cost analysis were conducted for 0.3048 m (1 ft) of kenaf/glass reinforced pultruded hollow square tubes (Figure 4.20). The weight rankings, from heavy to lightweight, were determined as follows: Pultruded WG/UG alternate ranked heaviest, followed by Pultruded WK/UG alternate, and finally, Pultruded 3WK/UG/3WK as the lightest among the three. The Pultruded WK/UG alternate recorded a weight that was 9.6% lower than the Pultruded WG/UG alternate. This reduction in weight highlights the advantage of incorporating kenaf fibre in the pultruded profile, which contributes to a more lightweight structural component. Furthermore, the Pultruded 3WK/UG/3WK profile demonstrated an even more significant weight reduction of 19.1% compared to the conventional fibreglass profile. This substantial decrease in weight signifies the significant benefits of adopting plant fibres like kenaf in

pultruded profiles, offering the potential for lightweight structural parts in various applications.

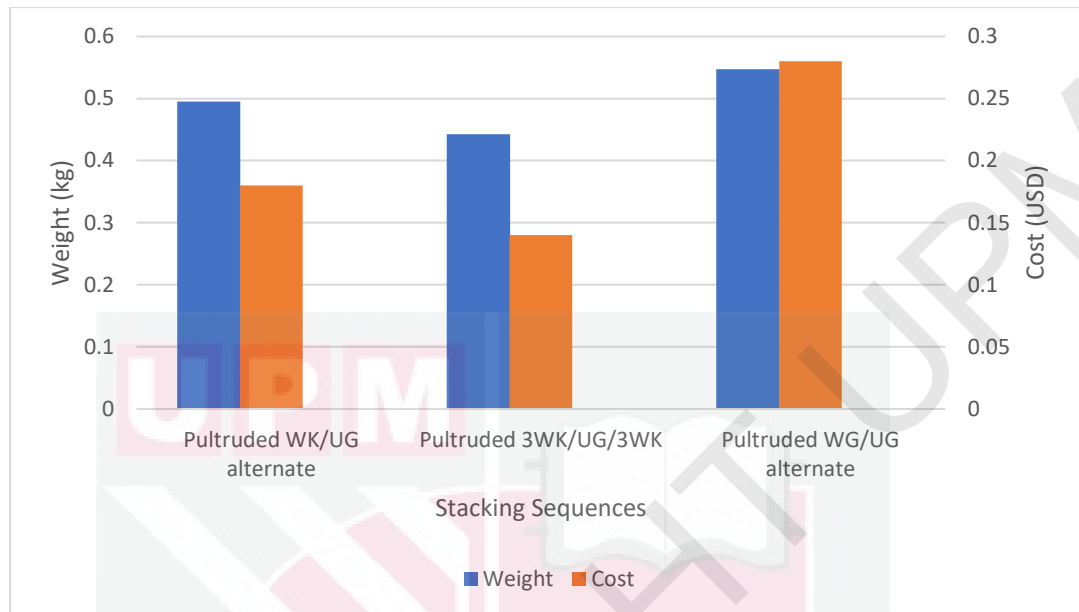


Figure 4.20: Cost of fibres and weight comparison of 0.3048 m (1 ft) pultruded hollow square tube

Similarly, the cost analysis resulted in rankings from highest to lowest cost as follows: Pultruded WG/UG alternate with the highest cost, followed by Pultruded WK/UG alternate, and finally, Pultruded 3WK/UG/3WK with the lowest cost among the three. The cost data of reinforcing fibres (per kg) in Ringgit Malaysia and US Dollar is listed in Table 4.4.

Table 4.4: Cost of reinforcing fibres in Malaysia

Reinforcing fibres	Cost per kg in Ringgit Malaysia (RM)	Cost per kg in US Dollar (USD)
Glass Fibre Direct Roving	3.50	0.75
Woven Glass Fibre Mat	5.20	1.12
Woven Kenaf Fibre Mat	2.50	0.54

* The cost data presented reflects values in USD converted from Malaysian Ringgit and is based on rates in Malaysia as of November 2023.

The pultruded WK/UG alternate exhibited a remarkable cost reduction of 35.7% compared to the Pultruded WG/UG alternate. This significant cost reduction showcases the economic advantages of utilising kenaf fibre in pultruded profiles, making it a cost-effective alternative without compromising performance. Moreover, the Pultruded 3WK/UG/3WK profile demonstrated an outstanding cost reduction of 50% compared to the conventional pure glass fibre reinforced profile. This remarkable cost-saving potential positions pultruded profiles with plant fibres like kenaf as an attractive option for various industries looking to reduce raw material costs while maintaining structural integrity. The specific strength (strength to weight ratio) of pultruded composites is compared in Figure 4.21. Pultruded WK/UG alternate recorded a specific strength of 2.719×10^5 Nm/kg, while Pultruded WG/UG alternate recorded 2.745×10^5 Nm/kg, showing only a slight decrease of about 0.95%. Additionally, the specific strength of Pultruded 3WK/UG/3WK is about 1.371×10^5 Nm/kg, which is approximately 50.05% lower than that of Pultruded WK/UG alternate.

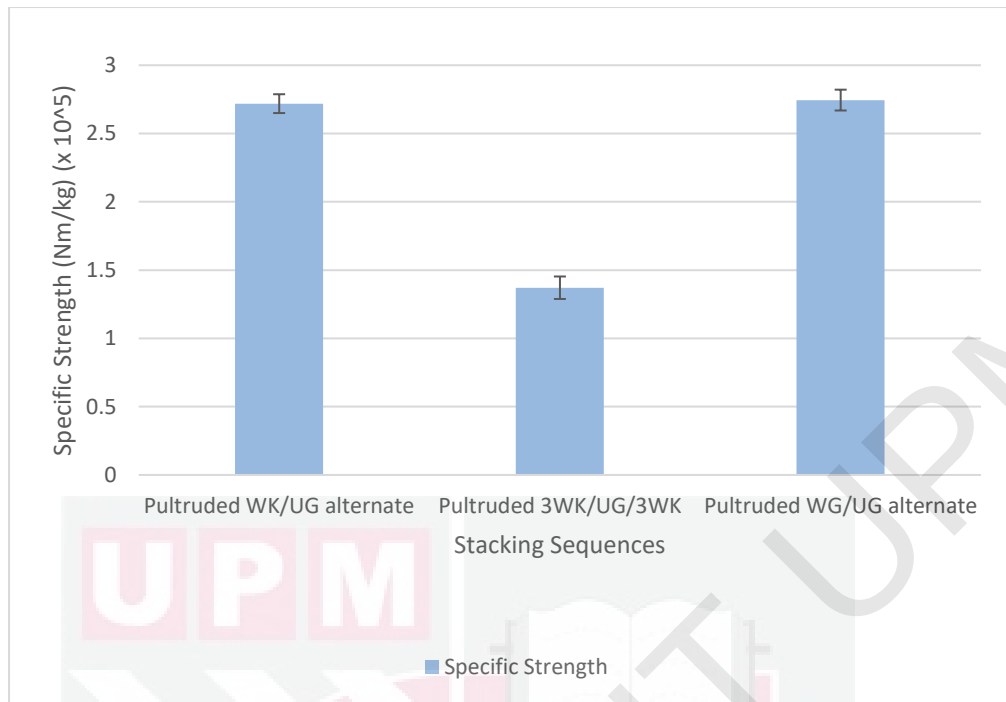


Figure 4.21: Specific strength comparison

The specific strength, weight and cost analysis demonstrates the positive implications of incorporating plant fibres, such as kenaf, into pultruded profiles. Using kenaf contributes to lightweight structural parts, offering potential benefits in weight reduction and enhanced strength performance. Additionally, it significantly lowers the raw material cost, making it a cost-effective and environmentally friendly alternative to traditional fibreglass reinforcement (Rasheed et al., 2023; Sathish et al., 2021). Lighter profiles reduce transportation costs since less energy is needed to move them. This is particularly beneficial when transporting large quantities of profiles or shipping over long distances. They also contribute to environmental sustainability by reducing the consumption of raw materials and energy during manufacturing and transportation. These findings highlight the promising prospects of plant fibre-reinforced pultruded profiles as a viable solution for various industries seeking lightweight and economical structural components.

4.3.6 Summary

From the fatigue analysis, highest fatigue strength is achieved by Pultruded WG/UG alternate followed by Pultruded WK/UG alternate and Pultruded 3WK/UG/3WK composites. However, highest fatigue sensitivity is achieved by Pultruded WG/UG alternate followed by Pultruded WK/UG alternate and Pultruded 3WK/UG/3WK specimen. It is notable that, increase in the kenaf to glass ratio have resulted in decreased fatigue strength and decreased sensitivity.

The Izod impact analysis show that pultruded WK/UG alternate hybrid composites having similar impact strength with pultruded WG/UG alternate non-hybrid composites. However further increasing the kenaf to glass fibre ratio in Pultruded WK/UG alternate resulted in a decrease of impact strength. The specific strength, weight and cost analysis evidently shows that implication of plant fibres in pultruded profile application contribute to lightweight structural parts with lower raw material cost.

4.4 Case study

As the fourth objective, a case study was conducted to evaluate the structural performance of kenaf/glass reinforced hybrid pultruded profiles. A working prototype ladder is developed and tested for its structural integrity. Pultruded WK/UG alternate is chosen as suitable stacking sequence to fabricate square hollow tubes to serve as the side rail of the prototype ladder.

4.1 Testing of ladder

The experiments conducted on the ladder made up of kenaf/glass reinforced hybrid pultruded profiles were performed in accordance with the ANSI 14.5 ladder standard. Four different tests were carried out to evaluate the ladder's structural performance under various loading conditions: horizontal bending test, side sway test, static side rail cantilever bending test, and inclined load test. The deflection of the ladder was recorded for each test while applying increasing loads and permanent deformation was recorded after removing the loads.

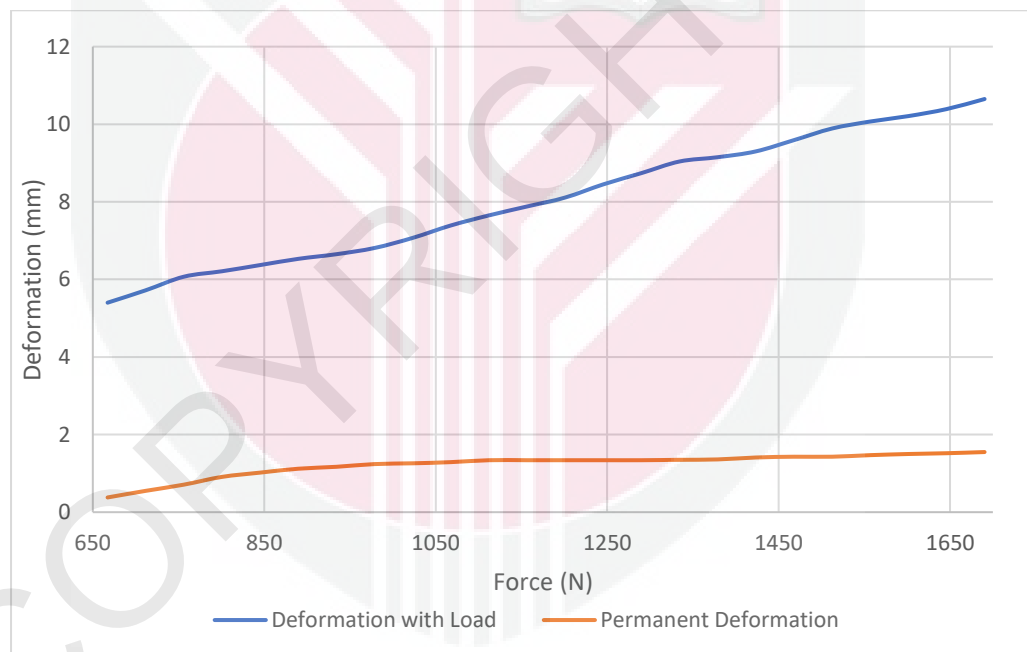


Figure 4.22: Horizontal bending test

In horizontal bending test, the ladder is placed horizontally and subjected to a bending load applied horizontally. The deflection of the ladder is measured as a function of the applied load. This test evaluates the ladder's resistance to bending forces when used horizontally, simulating real-world scenarios where

the ladder might be used as a platform or walkway. According to Figure 4.22, the horizontal bending test resulted in a linear plot of deformation with load. The ladder's deflection showed a consistent and proportional increase with the increase in applied load. This linear relationship between deformation (y-axis) and test load (x-axis) suggests that the ladder exhibited elastic behavior throughout the test. In the elastic range, the ladder can withstand bending forces and return to its original shape once the load is removed, ensuring its structural integrity and safety.

Moreover, the plot of permanent deformation also revealed interesting findings. It exhibited a very minimal amount of permanent deflection, which means that the ladder experienced only a slight residual deformation even after the load was removed. The short linear phase at the start of the permanent deflection plot suggests that, initially, the ladder experienced some plastic deformation or minor structural adjustments due to the bending loads. However, as the test load continued to increase, the permanent deflection reached a stable state, where the ladder's deformation remained constant even under higher loads.

The maximum average deflection observed during testing was 10.65 mm at a test load of 375 lbs. This deflection value is considerably lower than the maximum allowable average deflection set by the standard, which mandates that the ladder shall not exceed 91 mm. Notably, the ladder exhibited remarkable strength and structural integrity, successfully sustaining the ultimate test load of 470 lbs without experiencing any ultimate failure. This outcome highlights the ladder's robust design and its ability to withstand

significant loads without compromising safety. The small and stable amount of permanent deflection is a favorable outcome, as it indicates that the ladder is not prone to accumulating excessive permanent deformation or structural damage. It ensures that the ladder remains safe and retains its intended shape, even after repeated use and exposure to bending forces. The ladder demonstrated exceptional performance, achieving super-duty classification by the standard.

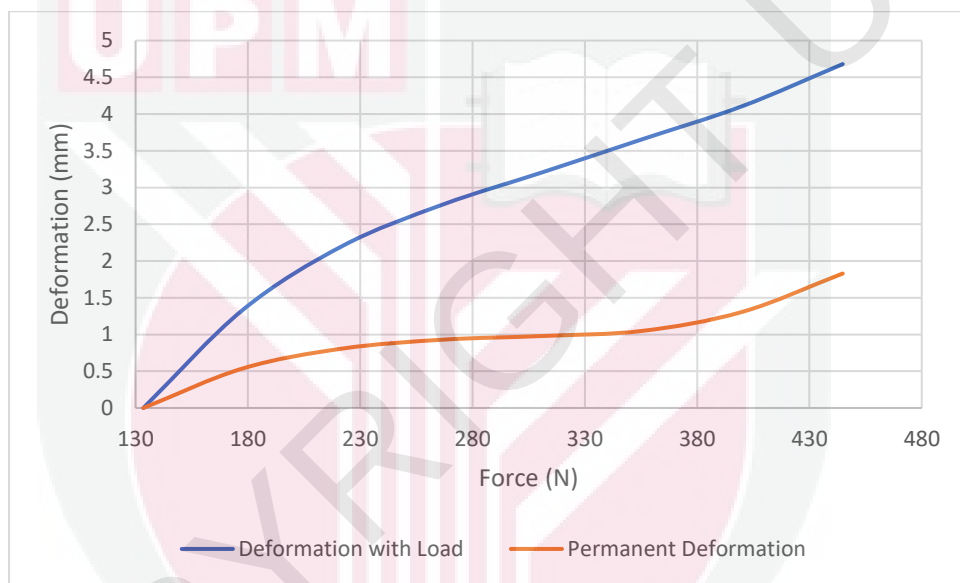


Figure 4.23: Side sway test

The side sway test assesses the ladder's ability to resist lateral forces when used in a leaning or inclined position. The ladder is secured at the top and allowed to sway laterally under a controlled load. The deflection and stability of the ladder are monitored during the test, ensuring that the ladder can withstand side forces without tipping or failing. According to Figure 4.23, the deformation curves exhibited a characteristic behavior, starting with a logarithmic curve at the initial loading stage, followed by a transition to linear growth as the test load increased. This observation suggests that the ladder's

response to small loads was nonlinear and more sensitive at lower loading levels, represented by the logarithmic segment. As the load magnitude increased, the ladder's behavior became more linear, indicating that it behaved in a more predictable and stable manner under higher loads.

Furthermore, the permanent deformation plot as a function of the test load also showed an interesting trend. Similar to the deformation curve, the plot of permanent deformation started with a logarithmic segment, indicating that permanent deformation accumulated more rapidly at lower lateral loads. This behavior suggests that at lower forces, the ladder experienced some degree of plastic deformation or localized yielding. However, as the lateral test load increased beyond a certain threshold, the permanent deformation curve transitioned into an exponential phase. This exponential behavior signifies that the ladder's permanent deformation increased at an accelerating rate with further lateral force increments. The exponential segment is attributed to the onset of more significant structural damage or plastic deformation mechanisms that became dominant under higher lateral forces.

Overall, the deformation with load applied and permanent deformation only occurred at minimal displacement which indicated that the ladder could perform at higher load up to 100 lbs with a maximum of 4.68 mm of deformation with test load and 1.83 mm of permanent deformation. Hence, according to ANSI 14.5 for side-sway test, the ladder is rated at high-duty performance which allows deformation up to 24 mm at 85 lbs.

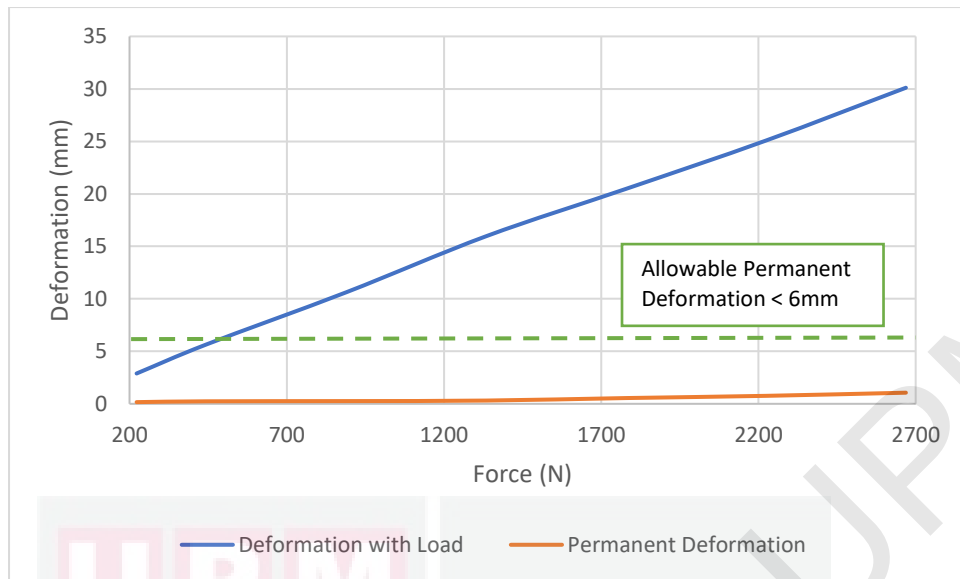


Figure 4.24: Static side rail cantilever bending test

In Static Side Rail Cantilever Bending Test, one side rail of the ladder is supported while the other side is cantilevered outward. A load is applied at the end of the cantilevered side rail, and the deflection is measured. This test evaluates the strength and stiffness of the ladder's side rails, which are crucial for supporting the weight of a person or equipment while climbing. According to the plot of the side rail cantilever bending test (Figure 4.24), the deformation with load curve exhibited a linear relationship. As the load was incrementally applied, the ladder's deflection increased proportionally, indicating an elastic response within its linear range. This linear behavior is favorable as it demonstrates the ladder's ability to deform elastically under bending forces and return to its original shape once the load is removed.

However, the plot of permanent deformation showed an interesting and contrasting observation. The gradient of the permanent deformation curve is almost zero, indicating that the ladder experienced negligible permanent

deflection even after the load was removed. In other words, the ladder almost fully recovered its original shape once the load was taken off.

The ladder was able to withstand a maximum load of 600 lbs indicating its performance up to super-duty applications according to the standard. The ladder's material composition, which is kenaf/glass reinforced hybrid pultruded profiles, possess high elasticity and strength, allowing it to respond elastically under bending loads without incurring permanent deformation. This outcome suggests that the ladder's material and design effectively resisted any plastic deformation or structural damage during the side rail cantilever bending test. It exhibited excellent resilience, with minimal permanent deflection, signifying that it can withstand bending loads without suffering any significant permanent deformation.

The inclined load test involves applying a load to the ladder while it is placed at an inclined angle. The ladder's deflection and stability are monitored during the test. This test is designed to mimic real-world scenarios where the ladder might be used on uneven surfaces or placed at an angle against a structure. According to the test conducted, the ladder was able to sustain a load of 1200 lbs without any signs of ultimate failure.

4.2 Summary

In conclusion, the tests on the kenaf/glass reinforced hybrid pultruded profile ladder have provided valuable insights into its structural behavior under load. Understanding these behaviors is essential for ensuring the ladder's safety, reliability, and long-term performance in real-world applications.

The results from the tests revealed interesting findings regarding the ladder's behavior under load and its response after the load was removed. The observation suggests that the ladder experienced some level of residual deflection even after the loads were removed. The reduced gradient indicates that the ladder did not fully return to its original state, which is attributed to plastic deformation. The ladder's material has experienced some degree of plastic deformation during the loading tests, particularly when subjected to high loads. Plastic deformation results in permanent changes to the material's shape and can contribute to the observed residual deflection. Besides that, the ladder's structural behavior is not perfectly linear, especially when exposed to higher loads. Nonlinear effects could lead to differences in the response during loading and unloading, resulting in residual deflection.

Overall, kenaf/glass reinforced hybrid pultruded profiles in the application of prototype ladder has proven its potential in structural applications. The ladder is rated as a special-duty ladder with a working load of 375 lbs (170.1 kg). To further investigate and validate these findings, it is crucial to conduct additional tests and consider different loading scenarios. It is also essential to assess the ladder's performance against the ANSI 14.5 ladder standard to ensure compliance with safety requirements.

In practical applications, the observed residual deflection could have implications for the ladder's usability and safety. If the ladder does not fully return to its original state after use, it might affect stability and structural integrity over time. Depending on the specific application, it might be

necessary to implement periodic inspections and maintenance to monitor the ladder's condition and address any potential issues.



CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

In this chapter, conclusions based on each objective are made. The novel contributions of this work are highlighted. Recommendations for future research have been also discussed.

5.1 Conclusions

A research project was conducted to develop hybrid pultruded profiles made up of plant fibres and glass fibres for structural applications. The specific focus was on using plant fibres to develop sustainable and durable composites for open and closed wall structural profile applications, marking the novelty of the research in addressing both environmental sustainability and structural integrity simultaneously. Sandwich structured hybrid composites were fabricated and tested by combining kenaf and glass fibres through hand lay-up, compression moulding and finally pultrusion techniques. In addition to pioneering the development of hybrid pultruded profiles, this research project introduced a novel contribution by conducting comprehensive durability analyses, a relatively less explored aspect in plant fibre composite research. By systematically evaluating the fatigue properties of the newly developed plant fibre-glass hybrid composites, this study addressed a significant gap in existing literature and provided essential insights into the long-term durability and performance of these materials under cyclic loading conditions. Furthermore, the research ventured into practical applications by focusing on

structural ladder development and testing, an area where plant fibre-based composites are relatively unexplored. The successful construction and testing of a single-pole structural ladder, surpassing ANSI standards, not only demonstrated the feasibility and efficacy of the developed composites but also showcased their potential for real-world structural applications.

Moreover, this research project highlighted the underexplored potential of applying plant fibres in structural applications. Despite the growing interest in sustainable materials, the utilization of plant fibres in structural profiles remained relatively limited, with most studies focusing on conventional fibreglass composites. By demonstrating the mechanical, fatigue, and impact properties of plant fibre-glass hybrid composites, this study bridged the gap between sustainable materials and structural applications, paving the way for the widespread adoption of environmentally friendly and resilient composite solutions in various industries.

5.1.1 Selection of suitable plant fibre using AHP

Based on the first objective, after conducting an AHP analysis to identify a suitable alternative, kenaf fibre was chosen, satisfying the fundamental design objectives and criteria for the intended application. To ensure the reliability of the decision-making process, a consistency analysis was carried out, resulting in an overall inconsistency ratio of 0.01, well below the maximum CR value of 0.1. This validates the consistency and validity of the judgments made during the AHP analysis. Furthermore, a sensitivity analysis reaffirms the superiority of kenaf fibre as it obtained the highest priority vector in four out of six criteria,

including tensile strength, density, cellulose content, and availability. This additional assessment further strengthens the credibility of the fibre selection process based on AHP methodology.

5.1.2 Selection of woven kenaf/glass roving hybrid composites

In accordance with the second objective, the study focused on investigating the mechanical properties of kenaf/glass hybrid composites for application in pultruded structures. Specific conclusions drawn from the study indicated that WK/UG alternate and 2WK/3UG/2WK hybrid samples showed satisfactory tensile results, with a decrease of approximately 8.2% in tensile strength and 10.7% in tensile modulus compared to the conventional fibreglass samples. The WK/UG alternate sandwich samples exhibited higher compressive strength than other hybrid specimens, with a slight decrease of 6.09% compared to pure fibreglass composites. Additionally, 3WK/UG/3WK and WK/UG alternate samples demonstrated higher compressive modulus and reduced deformation under compressive loads. Hybrid alternate WK/UG samples exhibited the highest modulus of rupture and modulus of elasticity among the hybrid laminates, showing satisfactory bending properties with only a decrement of 4.13% in rupture modulus and 1.9% in elasticity modulus compared to the control specimen. The ILSS of hybrid composites 2WK/3UG/2WK and alternate WK/UG displayed good agreement with the pure fibreglass composites. SEM analysis revealed various failure modes in tensile-fractured woven kenaf/unidirectional glass roving reinforced hybrid composites, including matrix deformation, fibre breakage, microcracks, voids, and fibre pull-outs. WK/UG alternate and 3WK/UG/3WK hybrid sequences

were chosen to fabricate pultruded profiles and further investigate their durability properties (fatigue and impact) in the third objective.

5.1.3 Testing of kenaf/glass roving hybrid pultruded composites

As per the third objective, the fatigue analysis revealed that the Pultruded WG/UG alternate composite had the highest fatigue strength, while also being the most sensitive to fatigue. On the other hand, the Pultruded WK/UG alternate and Pultruded 3WK/UG/3WK composites showed lower fatigue strength but were less sensitive to fatigue. The Izod impact analysis highlighted that the pultruded WK/UG alternate hybrid composites had comparable impact strength to the pultruded WG/UG alternate non-hybrid composites. However, further increasing the kenaf to glass fibre ratio in the Pultruded 3WK/UG/3WK composites led to decreased impact strength. Additionally, the density, weight and cost analysis emphasized the advantages of utilizing plant fibres in pultruded profiles, offering lightweight structural parts and cost savings in raw materials. These findings indicate that the use of kenaf as a reinforcing fibre in pultruded composites presents both mechanical and economic benefits for various applications.

5.1.4 Case study

According to the fourth objective, a single-pole structural ladder has been developed by installing kenaf/glass reinforced hybrid pultruded square hollow profiles as its side rails. Testing such as horizontal bending test, side sway test, static side rail cantilever bending test, and inclined load test were conducted with regards to ANSI standards, evaluating the structural

performance and integrity of the working prototype ladder. The tests recorded very minimal permanent deflection and hence surpassed the basic requirement to be applied in real life applications. The findings indicated that the ladder could be rated as a special-duty ladder with a working load of 375 lbs (170.1 kg). Overall, kenaf/glass reinforced hybrid pultruded profiles in the application of prototype ladder has proven its potential in structural applications.

5.1.5 Summary

The findings have successfully fulfilled the objectives outlined at the start of this investigation. The research findings on kenaf/glass reinforced hybrid pultruded profiles reveal promising prospects for structural applications across diverse industries. The Pultruded WK/UG alternate configuration demonstrates suitability for moderate load-bearing profile applications, making it a valuable choice for industries such as automotive components, aerospace flooring, marine boat decks, and industrial walkways. Its ability to combine impact resistance with lightweight properties enhances safety and performance. On the other hand, Pultruded 3WK/UG/3WK configuration proves well-suited for low load bearing profile applications in industries like renewable energy, sporting goods, and infrastructure. Components like interior trims in automobiles, partition walls in commercial buildings, and pedestrian bridges benefit from their lightweight nature and durability. The hybridization of kenaf and glass fibres provides an optimal blend of properties, offering innovative and sustainable structural solutions in various industrial settings.

5.2 Recommendations for future research

To further advance the field of plant/glass fibre reinforced pultruded composites, several key areas warrant future research. These recommendations aim to enhance the mechanical performance, durability, sustainability, and applicability of these composites. The following recommendations provide a roadmap for future investigations and promote the practical implementation of plant/glass fibre reinforced pultruded composites in various industries.

- i. Researchers should leverage available data on natural fibres from previous research and prioritize the development of applications in specific areas where plant/glass fibre hybrid pultruded profiles can offer unique advantages, such as aerospace and automotive components, construction materials, or sporting goods by fostering collaborations with industry partners. Conducting targeted research to evaluate their performance, durability, and economic benefits in these specific contexts is essential for advancing the field and realizing the full potential of these sustainable materials.
- ii. Explore the use of different matrix resins, such as polyester, vinyl ester, epoxy, or bio-based resins, to understand their influence on the mechanical, thermal, and chemical properties of plant/glass fibre pultruded composites. Assess the impact of resin selection on manufacturing processes, composite performance, and sustainability aspects.

- iii. Develop advanced computational models and simulations to predict the mechanical behaviour and performance of plant/glass fibre pultruded composites. Integrate multi-scale modelling approaches to capture the behaviour of fibres, matrix, and the composite structure, facilitating material optimization and design.
- iv. Conduct long-term durability studies to assess the performance of plant/glass fibre hybrid pultruded profiles under various environmental conditions, including exposure to moisture, temperature variations, UV radiation, and chemical agents. Investigate degradation mechanisms, aging effects, and the ability of the profiles to retain their mechanical properties over extended periods.
- v. Evaluate the environmental impact of plant/glass fibre hybrid pultruded profiles compared to traditional materials. Conduct life cycle assessments to quantify the carbon footprint, energy consumption, and waste generation associated with their production, use, and disposal.
- vi. Explore different coating materials, optimizing adhesion and bonding between coatings and profiles, assessing the impact of coatings on mechanical properties, evaluating durability and resistance to environmental factors, developing and investigating functional coatings.
- vii. Investigate recycling methods and assess the recyclability of plant/glass fibre pultruded composites. Explore techniques such as mechanical recycling, chemical recycling, or incorporation of bio-based or biodegradable materials to enhance the sustainability of the composite materials.

By pursuing these avenues of future research, further advancements can be made in the development and utilization of plant/glass fibre reinforced hybrid pultruded profiles, unlocking their full potential in diverse applications.



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LIST OF PUBLICATIONS

Journals

Balakrishnan, T. S., Sultan, M. T. H., Naveen, J., Shahar, F. S., Najeeb, M. I., Shah, A. U. M., Khan, T., & Sebaey, T. A. (2022). Selection of Natural Fibre for Pultruded Hybrid Synthetic/Natural Fibre Reinforced Polymer Composites Using Analytical Hierarchy Process for Structural Applications. *Polymers*, 14(15). <https://doi.org/10.3390/POLYM14153178>

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Conference Papers

Balakrishnan, T. S., Sultan, M. T. H., Shahar, F. S., Shah, A. U. M., & Najeeb, M. I. (2024). Advanced Pultrusion Techniques as Alternatives in Aerospace Composite Manufacturing- A Review. *E3S Web Conf.* 477 00036. <https://doi.org/10.1051/e3sconf/202447700036>

Book Chapters

Balakrishnan, T. S., Sultan, M. T. H., Shahar, F. S., Shah, A. U. M., Saravanakumar, Y. N., Chandran, N. K. (2024). *Aerospace Steel: Properties, Processing, and Applications*. Accepted by Elsa.

Conferences

1. 8th International Aerotech Conference Universiti Putra Malaysia - December 2022 - Speaker

Community Projects

1. SUXUS Edudrone Flight Training Program and the Importance of Green Drone Technology for Sustainable Agriculture in Tanjung Sedili, Kota Tinggi, Johor - May 2024 -Facilitator
2. Collaborative Drone Project for Dengue Prevention and Control between Universiti Putra Malaysia (UPM), Disease Control Division (BKP), and the Institute for Medical Research (IMR) - December 2023 - Facilitator
3. Program Klinik Pertanian Putra, Tanjung Sedili, Kota Tinggi, Johor - September 2023 - Facilitator

Events and Exhibitions

1. 35th International Invention, Innovation & Technology Exhibition (ITEX'24) - May 2024 - Exhibitor
2. Defence Service Asia (DSA) International Exhibition and Conference - May 2024 - Exhibitor
3. National Security Asia (NATSEC) International Exhibition and Conference - May 2024 - Exhibitor
4. Industrial Design, Technology & Manufacturing International Symposium - April 2024 - Exhibitor
5. MTE 2023 Sustainable Development Goals International Innovation Awards & Expo - October 2023 - Exhibitor
6. Selangor Aviation Show (SAS) - September 2023 - Exhibitor
7. ASIAN Sports Aviation Summit - September 2023 - Exhibitor
8. Defence, Security and Sustainability (DSS) Exhibition - May 2022 - Exhibitor

Workshops

1. "Aerospace Postgraduate Studies in Malaysia" webinar 2023 - Participant
2. "Challenges and Opportunities in Local Aviation Careers Post COVID-19 Pandemic" webinar 2022 - Participant
3. "Autodesk AutoCAD" workshop 2022 - Participant
4. "How To Survive & Thrive as A Young Engineer" webinar 2021 - Participant
5. "The Art of Writing a Research Paper" webinar 2020 - Participant