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Hybridizing Kenaf and Glass Fibres as Reinforcement in ABS Composites: Current Trends, Properties and Potential Application in Aircraft Radome

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ABSTRACT

The advancement of thermoplastic composites reinforced with hybrid kenaf/glass fibres has rapidly progressed, positioning them as viable structural materials for diverse industries. The incorporation of hybrid kenaf/glass fibres in these composites aims to introduce new dimensions of sustainability. This is driven by the superior strength, stiffness, and lightweight properties exhibited by the hybrid composites, making them well-suited for high-end structural applications. Furthermore, the hybrid kenaf/glass fibres composites offer economic advantages and various benefits, including recyclability, cost-effectiveness, biodegradability, and wide availability. Currently, these emerging composites are gaining attention in industries such as automotive, defence, aerospace, marine, construction, and naval sectors. Despite their increasing popularity, there is a notable gap in the literature, as comprehensive focus on the recent progress of hybrid kenaf/glass fibres reinforced ABS composites for structural applications is lacking. Therefore, this review paper critically discusses recent findings related to the physical, mechanical, and energy absorption properties, as well as processing techniques, of kenaf fibres and their hybrids with ABS matrix materials for aircraft radome. The article also aims to underscore the significance of hybrid kenaf/glass reinforced ABS composites in enhancing mechanical performance for applications requiring radome structures. This review also found out that the composites with quasi-isotropic sequence which combine with ±45-degree fibre orientation provide superior mechanical properties. The ±45-degree stacking is expected to enhance the mechanical properties because it offers balanced in-plane stiffness and strength as well as, improved shear properties. This orientation distributes the stresses more evenly throughout the composite material, leading to improved damage tolerance and impact resistance, which are critical for the structural integrity and durability of aircraft radomes.

Keywords: Kenaf fibres; Glass fibre; Hybrid Composites; Mechanical Properties; Structural Applications

INTRODUCTION

Aerospace industry has seen a surge in demand for lightweight materials that offer high strength and good energy absorption properties. The use of composites has provided a promising avenue for the manufacture of lightweight aircraft components such as radomes. These components need to be designed to withstand harsh conditions during flight, including exposure to wind, rain, hail, and lightning strikes. The ability of a material to absorb energy during impact and damage tolerance is crucial for radome design in aircraft. Generally, mechanical properties of natural fibres such as kenaf, which reinforce in thermoplastic composites are comparable glass fibre reinforced polymer (GFRP) composite, which makes it an attractive choice for use in aircraft radome component.

The combination of renewable lignocellulosic and synthetic materials stands out as an excellent choice for structural applications, especially in engineering sectors. Combination of natural and synthetic fibres in hybrid composites can offer superior mechanical properties suitable for aircraft radome applications. Kenaf fibre is a sustainable natural fibre that has gained attention for its high strength and lightweight properties. Typically, indoor structural composites employing lignocellulosic materials are crafted with low-cost adhesives that lack stability in moisture, while exterior-grade composites utilize higher-cost thermosetting resins that are moisture-resistant. To enhance the performance of lignocellulosic fibre composites, chemical modification techniques are are suggested to be employed (Nurazzi et al. 2021; Sandeep Singh et al. 2022; Asyraf et al. 2020).

Recent literature reflects a growing focus on the hybridization of lignocellulosic fibres—both within the same category and in combination with synthetic fibres—in polymer matrices (Alias et al. 2021; Nurazzi et al. 2022). The utilization of lignocellulosic materials from agriculture, wood, and waste as fillers and reinforcements in hybrid composites has yielded encouraging results, particularly in improving the mechanical properties of final composites. However, hybrid composites face a limitation in fibre loading, capped at a maximum of 50%. For example, Hanifawati et al. (2011) evaluated the mechanical properties of a hybrid banana/glass fibre-reinforced polyester composite, revealing improved flexural and tensile properties through the combination of these two fibres with fibre-matrix ratio below than 50%.

Kenaf is a significant commodity crop in Malaysia, cultivated for various applications. Kenaf fibres, sourced from its bast stem, are considered globally important due to their high mechanical properties (Bajuri et al. 2016). In recent decades, kenaf fibres have been utilized as co-reinforcement materials with synthetic fibres in polymer matrices such as polypropylene (PP), polylactic acid (PLA), and thermoplastic natural rubber (TPNR) to create hybrid composites (Zakaria et al. 2013; Mohd Nurazzi et al. 2017). The abundance of kenaf fibre in Malaysia makes hybrid lignocellulosic/synthetic fibres competitively priced, enabling practical manufacturing for a wide range of applications, primarily in structural contexts. However, a major challenge associated with lignocellulosic fibres like kenaf is their high moisture absorption, leading to compatibility issues with the matrix (Ahmad et al. 2020). This problem can be addressed by treating the fibres using mercerization (Nurazzi et al. 2021; Ahmad et al. 2022), which enhances adhesion between the fibre and the matrix. Additionally, the stacking sequence of fibres (Alhayek et al. 2022) and fabrication technique of composites also influence the final properties of hybrid kenaf/glass composites. In this instance, quasi-isotropic stacking mechanism method is a manufacturing technique that involves the symmetric placement of reinforcement materials in composite fabrication. The aim is to reduce directional dependencies in the material to improve isotropic properties and mechanical performance.

The hybridization of kenaf fibres with glass fibres has proven to be a promising technique for enhancing the mechanical performance and moisture resistance of natural fibre composites (Atiqah et al. 2018, 2014; Nazim et al. 2019). Davoodi et al. (2010) conducted research on hybrid kenaf/glass-reinforced epoxy composites for passenger car bumper beams, revealing an overall improvement in mechanical performance compared to the glass composites. Existing literature indicates a focus on mechanical investigations of hybrid kenaf/glass fibre composites, but a comprehensive review on this specific topic is lacking. Therefore, this review paper aims to compile the recent literatures on hybrid kenaf/glass fibre composites, focusing on their mechanical properties, fabrication processes, and stacking sequences. The article is expected to provide insights and knowledge for material engineers and designers involved in the development of lightweight and high-strength materials suitable for the mechanical properties of final composites. Such materials can offer improved damage tolerance and energy-absorbing properties under harsh flight conditions.

BIO-COMPOSITE IN AEROSPACE INDUSTRY

Currently, a significant upsurge in the global trend of utilizing crop biomass in everyday products over the past few decades due to its cost-effectiveness and its promotion of enhanced product functionality. Biomass by-products, such as natural fibres, have found application in various engineering sectors, serving as additives and structural components to reduce material costs and enhance sustainability. Bio-composites are increasingly employed in industrial applications, owing to their numerous advantages such as being lightweight, flexible, cost-effective, and recyclable.

A notable increase has been observed in the utilization of bio-composites or hybrid bio-composites. The aerospace industry has embraced bio-composites, particularly in non-load bearing applications such as stowage bin, aircraft tray and cabin panels, over the past decade to achieve weight reduction. According to a report published by ASD Reports Premium Market in July 2020, the Global Aerospace Composites Market was valued at approximately USD 22.21 billion in 2019 and is expected to experience a healthy growth rate of more than 11.6% during the forecast period 2020-2027 (ASD report 2020). The aerospace industry's growing demand for composite materials is a significant driver of market expansion, driven by the continuous procurement of aircraft, which results in an increased need for composite materials used in various applications for both exterior and interior components.

Theoretically, polymer-based composite materials can offer a significantly superior strength-to-weight ratio compared to metals. In aerospace, hybrid composite materials provide a higher strength-to-weight ratio than metals, leading to the manufacturing of aircraft components using these materials. The design of aircraft parts is tailored to meet various safety and power criteria. The reduced weight contributes to lower fuel consumption and emissions. Additionally, the use of plastic structures requires fewer riveted joints, leading to improved aerodynamic efficiencies and reduced manufacturing costs.

The aviation industry was naturally drawn to these advantages when composites first emerged. However, it was the manufacturers of military aircraft who initially seized the opportunity to exploit their use, aiming to enhance the speed and manoeuvrability of their products (Edwards 2008). Examples of parts in the aerospace industry include the vertical tailplane, elevators, rear pressure bulkhead, nacelles fan-cowls, spoiler, and radome. Various hybrid composites find applications in the aerospace industry, such as spoiler parts, glare parts, tailplanes, and aircraft radome (Raheem & Subbaya 2021).

AIRCRAFT RADOME CHARACTERISTIC AND MATERIAL REQUIREMENTS

The primary purpose of utilizing a radome is to safeguard an antenna from its surrounding environment. It needs to withstand various environmental factors such as wind, hail, snow, ice, sand, lightning, and, in the case of high-speed airborne applications, thermal erosion and aerodynamic effects (Davis et al. 2015). The aircraft radome, as illustrated in Figure 1, functions to shield the radar antenna from weather conditions, aerodynamic loads, and bird strikes. This crucial function has the potential to be fulfilled by hybrid natural fibre composites.

Currently, synthetic fibre-based composites are predominantly used to ensure radio-frequency transparency. Radio-frequency transparent materials are those in which radio-frequency fields can penetrate without causing heating. Additionally, light aircraft radomes must be composed of high-toughness composites and have a low dielectric constant.

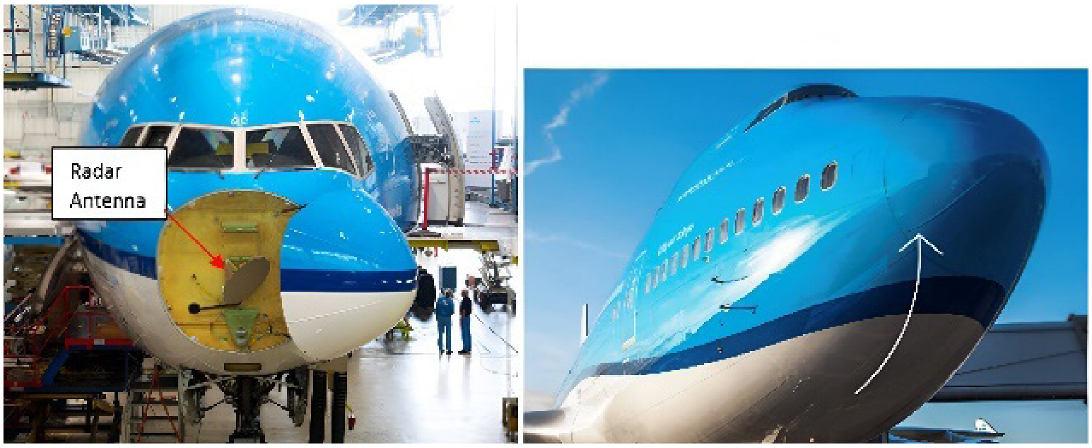


FIGURE 1. The opened radome and radar antenna for an Airbus A330 (Zeeuw, n.d.).

A radome is a protective structure designed to shield microwave equipment from environmental factors. It must provide defence against rain, hail, snow, bird impacts, and, in certain scenarios, bullets. The primary requirement for a radome is transparency to microwaves, with mechanical properties typically considered of secondary importance for most radome types.

In this instance, PE (polyethylene) fibre composites boast several advantages, including a low dielectric constant, minimal absorption of radar energy, resistance to water absorption (as water has a high dielectric constant and absorbs microwaves), and high impact and penetration resistance (Beaumont 2018). In essence, aircraft radomes are characterised by two main aspects: general characteristics (see Table 1) and mechanical performance (see Table 2).

TABLE 1. Characteristics for aircraft radome (Davis et al. 2015).

Characteristics of aircraft radome
Transmission Loss: Energy loss due to reflection and absorption because of transmission of the signal through the radome.
Beam Deflection: Beam deflection, also known as bore sight error, is the shift of the main-lobe electrical axis due to the presence of the radome.
Pattern Distortion: Pattern distortion due to the presence of an incorrectly repaired radome can cause changes in the main lobe beam widths, null depths and the structure of the side lobes.
Reflected Power: Reflected power can cause degradation of the pattern and raise side lobe levels. It can also cause frequency pulling of a magnetron.

TABLE 2. Electrical characteristics for aircraft radome (Davis et al. 2015).

Mechanical characteristics
Strength: To sustain the aerodynamic and handling loads. Based on industry standards and guidelines for aerospace engineers, radome design is a structure load of around 49 Kg/m² or 488(Pa). This load includes both aerodynamic and inertial forces
Stiffness: To provide elastic stability
Temperature resistance: Materials for aircraft should be considered for high-speed conditions that affect temperature and pressure. Depending on the application, the average temperature for aircraft in high magnitude is -54°C and pressure for outside is around 3 psi
Resistance to moisture absorption: To keep the material property constant. In high magnitude, aircraft will be exposed to a moisture environment for a long time. Moisture resistance materials should be used for aircraft parts.
Abrasion and Erosion resistance: To reduce the effects of rain, hailstorms, dust, stone etc.

RELATION KENAF FIBRE CHARACTERISTIC WITH AIRCRAFT RADOME REQUIREMENT

Kenaf, scientifically known as *Hibiscus cannabinus*, is a commercially available plant widely found in subtropical and tropical regions of Africa and Asia. The bast fibres derived from kenaf exhibit excellent mechanical performance, making them suitable substitutes for glass fibres in polymer composites as reinforcing elements (Edwards 2008). Kenaf, being a natural fibre abundant in cellulose, exhibits hydrophilic properties, meaning it has a tendency to absorb water due to its inherent composition (Noor et al. 2023). Kenaf is a composite fibre with high toughness and a low dielectric constant, making it well-suited for aircraft radome design. Typically, materials such as fibreglass, quartz, graphite, and Kevlar, along with resins like polyester, vinyl ester, cyanate ester, and epoxies, are used in radome design (Yusoff et al. 2011).

For aircraft radomes, the material should possess radar transparency, a low dielectric constant surface, and high toughness to withstand potential high-impact situations. For instance, Davoodi et al. (2010) revealed the use of kenaf fibre in designing car bumpers, revealing its good energy absorption properties (Davoodi et al. 2010). Hybridizing natural fibres with glass fibres, as seen in the research focused on a kenaf/glass fibre hybrid for car bumper beams, allows for improved mechanical properties over natural fibres alone.

Kenaf fibre is commonly chosen as an alternative reinforcement for composite products due to its low cost, reduced environmental impact, and favourable mechanical properties. Material engineers and scientists are drawn to kenaf fibre due to its improved and attractive flexural properties in polymer composites as reinforcement materials compared to other natural fibres. This has the potential to replace synthetic fibres like glass and carbon as primary components for both structural and non-structural applications (Saba et al. 2019).

In the context this research focuses on using kenaf fibre for aircraft radomes with the quasi-isotropic pattern method to improve their strength for aircraft applications (Alaseel et al. 2022).

In the automotive industry, natural fibre reinforcement, including kenaf fibre, has proven to be viable for various automotive parts. Several compositions of kenaf fibre with matrices and additives meet automotive requirements for non-structural and semi-structural applications in both interior and exterior parts. For instance, kenaf fibre has been used for package trays and door panel inserts in Saturn L300s, European-market Opel Vectras, and Lexus package shelves (Hassan et al. 2017). The lightweight nature of kenaf fibre composites contributes to improved fuel consumption and reduced emissions, particularly in the automotive industry.

Theoretically, kenaf fibre is considered a traditional crop in the third world, following wood and bamboo, with origins in Asia and Africa. The kenaf plant exhibits rapid growth, reaching a height of over 3 meters with a base diameter of 3 to 5 cm approximately four to five months after sowing the seeds (Dulina et al. 2019). Studies reported that about 35% dry weight of the kenaf stalk consists of the bast fibre which is often used to produce paper, textiles, and rope. Meanwhile, 65% of the kenaf fibre consists of its core which suitable for animal bedding and potting media (Tholibon et al. 2019).

In Malaysia, kenaf has become a commodity through initiatives by the Kenaf and National Tobacco Board (LKTN), expected to diversify into various engineering applications. The various parts of the kenaf plant, including the long stem that provides the long fibre, are utilized. Different forms of kenaf fibres are commonly used, such as long fibres in continuous and discontinuous yarn and woven or non-woven mats. The mechanical and physical properties of these kenaf fibres are detailed in Table 3 (Tholibon et al. 2016).

TABLE 3. Typical properties of kenaf fibre (Tholibon et al. 2016).

Properties	Details
Young’s modulus (MPa)	4300
Tensile strength (MPa)	250
Density (g/cm^3)	1.4
Fibre diameter (µm)	81
Fibre length (mm)	60

Untreated kenaf fibre presents some drawbacks, including low moisture resistance, poor thermal stability, and limited durability. Consequently, chemical treatment is necessary to enhance the properties of kenaf fibre. Chemical retting, a high-cost process utilizing chemicals to dissolve pectin and separate components, ensures more efficient production of clean, consistent, long, and smooth bast fibre surfaces (Dulina et al. 2019). Chemical treatment for kenaf fibre falls into two categories: surface modification and matrix modification.

Surface modification entails treating the fibre surface with chemicals to enhance adhesion between the fibre and matrix. Common treatments include alkali treatment, silane treatment, and acetylation treatment. Alkali treatment involves immersing kenaf fibre in a sodium hydroxide or potassium hydroxide solution, known as mercerization, which strengthens the interfacial bonding between fibres and thermoset resins by reducing fibre diameter and removing impurities. Silane treatment coats the fibre surface with a silane coupling agent, enhancing adhesion. Acetylation treatment modifies surface properties such as polarity and hydrophilicity by treating the fibre with acetic anhydride.

Research from the Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, reveals that immersion of kenaf fibre in 6 wt% NaOH for 24 h successfully cleans the fibre surface, removing impurities, and alkali treatment influences the increase in thermal stability during degradation (Ismail et al. 2021). A comparison between untreated and treated kenaf shows that alkali treatment influences the fibre’s surface, resulting in a smoother structure without irregularities caused by impurities (Ismail et al. 2021).

Matrix modification involves treating the matrix material with a chemical modifier to improve its compatibility with kenaf fibre. Common matrix modification treatments include maleic anhydride grafting, peroxide reatment, and isocyanate treatment. Maleic anhydride grafting creates functional groups in the matrix polymer that react with the kenaf fibre. Peroxide treatment generates free radicals in the matrix polymer that react with the fibre surface. Isocyanate treatment forms urethane bonds between the matrix and fibre.

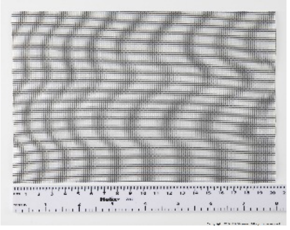
A study by Isuwa Suleiman Aji at the Faculty of Engineering, University of Maiduguri, focuses on the effect of fibre/matrix modification on tensile properties and water absorption behaviour of hybridized kenaf/PALF Reinforced HDPE Composite. The results indicate improvements in tensile properties before and after water immersion (Aji et al. 2014), serving as a reference for considering water absorption in this research, particularly for aircraft radome applications.

Chemical treatment offers several advantages, enhancing mechanical and thermal properties, increasing moisture resistance, and improving matrix compatibility. However, it also presents drawbacks such as environmental concerns, high costs, and complex processing requirements. Hence, chemical treatment is crucial for optimizing kenaf fibre properties for diverse applications. Surface and matrix modifications, with their specific advantages and limitations, are common chemical treatment methods. The choice of the appropriate method depends on application requirements and the availability of processing infrastructure.

FIBREGLASS WIRE MESH

Fibreglass mesh is a material crafted from interwoven glass fibre strands, forming a robust and pliable mesh. Widely employed in construction and renovation projects, it serves to reinforce surfaces and prevent cracking or damage. The decision to utilize fibreglass mesh in this project stems from its remarkable strengtht-to-weight ratio, characterized by both lightweight properties and high strength. Known for its substantial tensile strength, fibreglass mesh is particularly suitable for reinforcing various surfaces, including walls, ceilings, and floors. Its capability to distribute stress across a broader area enhances overall strength and stability. Additionally fibreglass mesh exhibits flexibility durability and ease of use in the fabrication process. Research by Jain et al. (2020) explored different fibreglass mesh sizes, with Table 4 indicating that the highest tensile strength. Overall, fibreglass mesh stands out as a versatile and durable material offering numerous advantages in building and construction applications. Its strength, flexibility, and ease of use make it a favoured choice for reinforcing surfaces and ensuring long-lasting perfomance.

TABLE 4. Examples of basic properties of fibreglass meshes (Fauzi et al. 2023).

Weight (g)		±75	±53
Grid size (mm)		3.0 x 2.5	4.4 x 4.2
Tensile strength (N/5cm)	Warp	350	850
	Weft	760	1000
			

ACRYLONITRILE BUTADIENE STYRENE (ABS)

Thermoplastic Acrylonitrile Butadiene Styrene (ABS) is a polymer material widely employed in various applications due to its distinctive properties. ABS has high impact resistance and toughness, making it potentially suitable for radome applications requiring durability and resistance to mechanical stress. ABS polymer is widely employed in various industries its ability to withstand impacts, exhibit high tensile strength, enhance durability at low temperatures, resist physical aging, and sensitivity to thickness and notch radius, along with its notably advantageous processability (Mohamed et al. 2024). Additionally, ABS has excellent electrical insulation properties, rendering it suitable for radome surfaces that demand a dielectric material. Being a thermoplastic material, ABS can be melted and reshaped multiple times without significant degradation, making it extremely versatile and commonly utilized for automotive parts due to its ability to be moulded into various shapes.

The key properties of ABS lie in its impact resistance and toughness. The three constituents provide a balance of properties, with butadiene units contributing to good impact strength, acrylonitrile units imparting heat resistance, and styrene units providing the copolymer with rigidity. Properties like hardness, ductility, and heat resistance can be modified by incorporating different materials in varying proportions. Notably, impact resistance remains robust even at low temperatures. Research demonstrates ABS's commendable mechanical properties, as outlined in Table 5 (Shaik et al. 2023).

TABLE 5. Examples of basic properties of fibreglass meshes (Fauzi et al. 2023

Property	Value
Young's Modulus [GPa]	2.28
Tensile strength [MPa]	43
Flexural modulus [GPa	2.48
[MPa] Flexural modulus [GPa Flexural	77
strength [MPa Notched Izod [KJ/m]	0.203
Heat deflection temperature [˚C]	81

ABS consists of acrylonitrile, butadiene, and styrene as its three primary monomers, with industrially significant ABS polymers adopting a two-phase structure. This structure comprises dispersed polybutadiene rubber particles grafted with styrene and acrylonitrile within a matrix of styrene acrylonitrile copolymer. (Hashim 2020). Adjusting the monomer proportions influences material properties, with increased acrylonitrile enhancing rigidity and heightened butadiene content improving impact strength.

ABS's high impact resistance makes it a preferred choice for applications subject to physical stress or vibration. Its resistance to weathering, chemicals, and heat makes it suitable for outdoor and chemically challenging applications. Moreover, ABS's lightweight nature facilitates easy handling and transportation. Common applications include automotive components, household appliances, toys, and consumer electronics. Its aesthetic appeal, ease of colouring, polishing, and finishing for a glossy appearance also contribute to its popularity. In aerospace industries, ABS thermoplastics find use in interior design parts due to their mechanical strength, durability, lightweight nature, cost-effectiveness, easy installation, and aesthetic appeal, contributing to weight reduction and increased fuel efficiency (Ranjan 2020).

The final properties of ABS are influenced by processing conditions. Moulding at high temperatures improves gloss and heat resistance, while moulding at low temperatures yields optimal impact resistance and strength. Incorporating fibres (typically glass fibres) and additives in resin pellets enhances the strength and extends the operating temperature range to as high as 80 °C (176 °F). Pigments can be added to modify the original translucent ivory to white colour. The hot press process involves melting ABS, with previous studies recommending a 1:1 ratio of ABS to fibre mass for optimal results (Budrun et al. 2020).

Despite its numerous advantages, ABS is not without drawbacks. Warping, a deformation caused by temperature fluctuations during manufacturing, leading to shrinkage and contraction, is a notable issue. Correct handling is crucial to mitigate warping risks. Additionally, ABS exhibits lower temperature resistance compared to some other thermoplastics, limiting its suitability for high-demand applications. Overall, ABS stands out as an excellent material with diverse applications and features that make it a preferred choice in various industries.

COMPOSITE LAMINATE

Composite laminates consist of multiple layers of different materials bonded together using adhesive or resin, finding applications in various engineering fields due to their favourable combination of qualities like robustness, rigidity, and endurance. Designing and analysing composite laminates is crucial for developing advanced materials in engineering solutions. Kenaf fibre stands out as an economically viable option among natural fibres for manufacturing composites (Suriani et al. 2021).

Kenaf bast fibres exhibit excellent mechanical performance, making them suitable substitutes for glass fibres in polymer composites as reinforcing elements (Alaseel et al. 2022). Specifically, fibre configurations such as orientation, length, and content significantly influence the physical and mechanical properties of kenaf fibre composites (Bonnia et al. 2012). Optimizing the stacking sequence of these fibres in polymer composites to achieve quasi-isotropy grants them high strength, enabling effective use in composite structures. As mentioned earlier, the optimal composite strength is achieved by balancing fibre orientations such as ±45°, 0°, and 90°, commonly known as the quasi-isotropic pattern. Figure 2 illustrates the quasi-isotropic pattern.

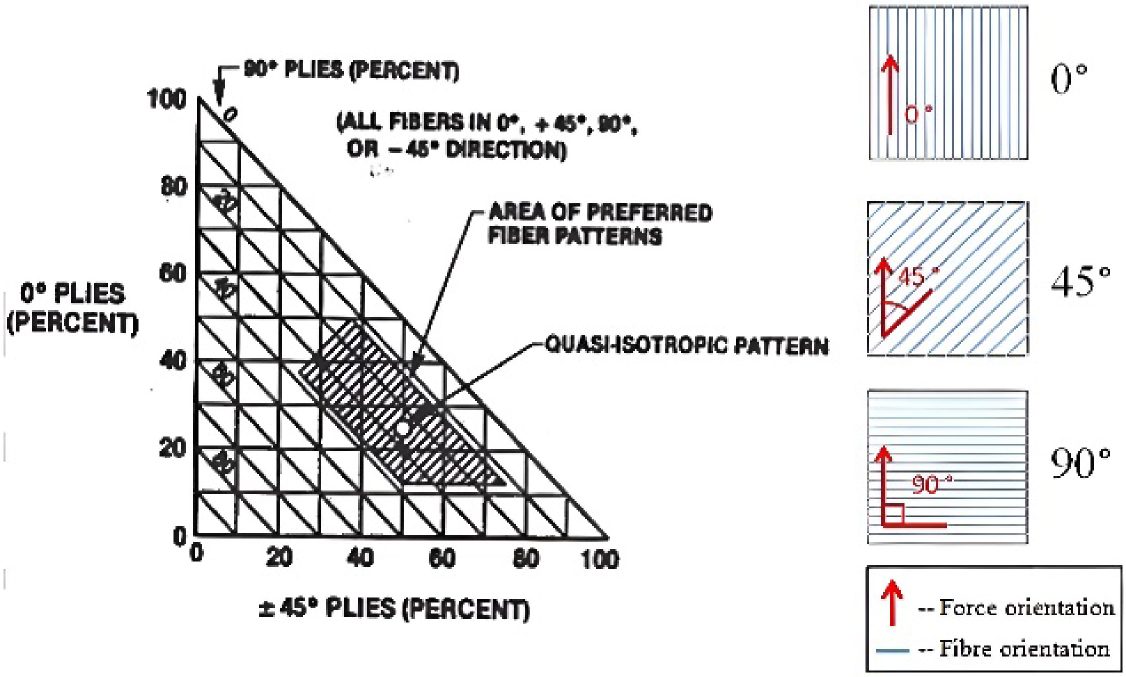


FIGURE 2. Recommended composite fibre laminate patterns for structural use (Fitri et al. 2024).

Obtaining a comprehensive understanding of the behaviour of each layer and the interaction between them is crucial in the analysis of composite laminates. Various factors, including fibre orientation and the volume fraction of each material within the laminate, significantly impact the mechanical properties of the composite laminates. Therefore, considering these factors is essential during the analysis of composite laminates.

THEORY AND ANALYSIS: COMPOSITE LAMINATE

Composites are often composed of layers (plies) bonded together to create a laminate. A layer may consist of short fibres, unidirectional continuous fibres, or woven/braided fibres embedded in a matrix. A layer with woven or braided fibres is termed fabric (Kollár & Springer 2003). Unidirectional composites exhibit the highest strength when loaded along the fibres; however, their strength decreases considerably in other directions, depending on the matrix material (Alhashmy & Aramco 2016). Since properties and orientations are consistent within the ply group, it can be treated as a single layer.

One essential aspect of composite laminates analysis is calculating the elastic constants of each layer. These constants provide information about the stiffness and strength of the composite laminate. The elastic constants for each layer are determined using the mechanical properties of the individual composite materials and an appropriate mathematical model that relates the physical properties to the mechanical behaviour.

Another critical aspect of composite laminate analysis involves determining the stress and strain distribution throughout the composite laminate. Numerical methods such as Finite Element Analysis are used for this purpose, involving the discretization of the composite material into small elements to calculate stresses and strains within each element. The resulting stress and strain distribution help determine the strength and stiffness of the composite laminate under various loading conditions (Alhijazi et al. 2020).

In summary, the theory and analysis of composite laminates involve understanding the mechanical behaviours of the composite material, calculating elastic constants for each layer, and determining stress and strain distribution throughout the composite laminate. This analysis process is crucial for designing composite laminates capable of withstanding intended loads without failure. The use of numerical methods like Finite Element Analysis allows accurate and efficient analysis of composite laminates. Composite laminates are continually advancing, and their properties and potential applications are expected to expand over time.

COMPOSITE STIFFNESS PREDICTIONS

The accurate prediction of composite stiffness is a crucial aspect of the design and analysis of composite laminates. Several factors, including the material properties of individual layers, the volume fraction of each layer, and the orientation of layers relative to a global coordinate system, collectively influence the stiffness of a composite laminate. Achieving precise stiffness predictions is essential for modelling the behaviour of composite laminates under various loading conditions.

The stiffness of the composite can be described by the elastic modulus, which is subdivided into two models. The first model follows the linear upper bound reinforcement, defined by the simple rule of the mixture as shown in the composite material Equation (1). This expression is applied for continuous fibre (Alhashmy & Aramco 2016).

$$E_c = E_f V_f + E_m V_m \tag{1}$$

The second model is valid for non-linear bound and non-continuous fibre. This expression is more complex as seen in Equation (2).

$$E_c = \frac{E_m V_m + E_f (V_f + 1)}{E_f V_m + E_m (V_f + 1} \tag{2}$$

E_c = Elastic Modulus of composited
E_f= Elastic Modulus of Fibres
E_m = Elastic Modulus of matrix
V_f= Fibre Volume Fraction (Usually approx. 0.6)
V_m = Matrix Volume Fraction (Usually approx. 0.4)

It is evident from the above considerations that the incorporation of either short fibres or continuous fibres with high stiffness can significantly enhance the stiffness of aluminium matrix composites (Alhashmy & Aramco 2016). Accurate stiffness predictions empower engineers to optimize the design of composite laminates by strategically selecting materials and layer orientations, ensuring the achievement of desired levels of stiffness and strength. Overall, stiffness predictions are a crucial aspect of confidently anticipating the behaviour of composite laminates in real-world engineering applications.

STACKING SEQUENCE AND FIBRE ORIENTATION

The stacking sequence, as depicted in Figure 3 (Soami 2018), is defined by the fibre orientation of each ply concerning the first axis of the laminate coordinate system. Laminated composite materials are typically constructed from unidirectional plies of a specified thickness and with fibre orientations limited to a small set of angles, such as 0°, +45°, −45°, and 90° (Todoroki & Ishikawa 2004). The stacking sequence is read from bottom to top, and the orientation angles are generally specified in degrees. The orientation of fibres in each layer is crucial, as it determines the specific mechanical properties of the composite laminate. Consequently, the stacking sequence governs the interaction between these layers to achieve the intended structural performance. Fibre orientation refers to the specific direction in which the fibres are arranged within each layer of the composite material. The orientation of the fibres is critical to achieving the desired performance of the final structure.

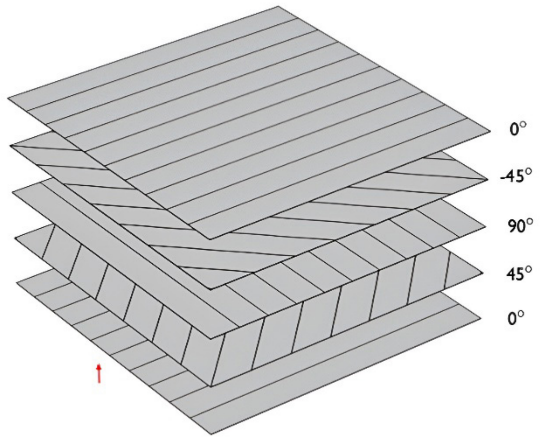


FIGURE 3. Example of a stacking sequence [0/45/90/-45/0] used in a composite laminate (Soami 2018).

The fibres can be oriented in various ways, including in a unidirectional or multidirectional pattern. The direction of the fibres affects the strength, stiffness, and other mechanical properties of the composite material. Experiments have shown that the optimal fibre orientation can increase structural stiffness, failure loading, and buckling stress over the traditional quasi-isotropic fibre distribution without increasing the weight (Gurdal 1993; Todoroki 2004). A research study demonstrates the effect of fibre orientation on the mechanical properties of kenaf fibre. The results show that the kenaf sandwich composite with kenaf fibre in an anisotropic orientation design will form a strong bridge over the crack and increase the break resistance of kenaf fibre. Polyester/kenaf composite with kenaf fibre in an anisotropic arrangement achieved the highest tensile, flexural, and impact properties. This was followed by a sandwich composite with kenaf fibre in isotropic and perpendicular orientations. It can be concluded that the strength of the polyester/kenaf sandwich composite increases with the decrease of fibre orientation (Singh & Gupta 2022). Hence, both the stacking sequence and fibre orientation are critical factors in determining the performance of composite materials. They must be carefully designed and optimized to achieve the desired level of performance for a given application.

COMPOSITE MANUFACTURING PROCESS OF BIO COMPOSITE AIRCRAFT RADOME

The composite manufacturing process encompasses designing the geometry of the product, fibre orientation process, composite laminate, lay-up of the composites, fabrication, post-processing, and curing. A key aspect of this process is studying and understanding the fibre laminate patterns used for fabrication. This not only provides superior strength, durability, and weight reduction for the product but also ensures user-friendliness and environmental friendliness.

COMPRESSION MOULDING

Compression moulding is a widely used process in various industries, including aerospace, automotive, and construction (Mitschgang 2012). It involves pressing or squeezing a deformable material charge between two halves of a heated mould and transforming it into a moulded part after cooling or curing. The equipment typically includes a large tonnage press, usually around 150 tons to 2500 tons, and heated dies (Greene 2021).

This process can produce various composite materials, such as thermosetting polymers, thermoplastic composites, and advanced composites. Key advantages of compression moulding include its ability to produce large, complex parts with a high degree of accuracy and repeatability, as well as parts with diverse mechanical, electrical, and thermal properties (Mitschgang 2012).

Compression moulding is employed to produce composite parts and components using high-strength and lightweight composite materials, such as thermosets and thermoplastic resins, carbon fibres, or synthetic polymers. The process utilizes a mould filled with composite material, which is then compressed under high pressure to achieve the desired shape.

VACUUM INFUSION PROCESS

The vacuum infusion process (VIP) is a practical method for producing high-quality composite parts with benefits such as higher quality, better consistency, increased glass content (resulting in enhanced specific strength and stiffness), good interior finish, quicker cycle time, and reduced cost. In VIP, resin is infused into the laminate using a vacuum. The fabric fibres and core materials are loaded into the mould initially, and ribs, inserts, and other components can be added without resin. The dry material is sealed shut using a counter mould or a vacuum bag. A high vacuum pump removes all air in the cavity, consolidating the fibre and core components. Resin is then fed into the mould cavity while still under vacuum to wet out the fabric fibres and core (Sanjeevi & Shanmugam 2018).

Vacuum infusion is utilized for producing large and complex composite structures requiring strength and durability. The vacuum pressure ensures complete resin impregnation of the fibres, resulting in a high strength-to-weight ratio. Infusion rates depend on factors such as resin viscosity, resin flow distance, media permeability, and vacuum amount. Material choices, flow media, resin flow layout, and vacuum port locations are critical for producing high-quality parts (Sanjeevi & Shanmugam 2018). Widely used in the marine, automotive, and aerospace industries, vacuum infusion is suitable for parts requiring accuracy, repeatability, corrosion resistance, and fatigue resistance.

This process is appealing due to its automation capabilities, enabling the production of complex geometries without waste, enhancing the stiffness of structures like ribs. Moulding cycle times typically range from 60 to 300 seconds, depending on part thickness, making it one of the fastest moulding processes for thermoset materials (Pierre et al. 2023)

PHYSICAL PROPERTIES OF FIBRE REINFORCED THERMOPLASTIC COMPOSITES

Physical properties are a crucial set of criteria to be considered in the evaluation of hybrid thermoplastic composites. These properties encompass key factors such as lightweight construction, exceptional toughness, thermal stability, design flexibility, water absorption, and density. In this research, specific attention will be given to studying pertinent physical properties related to the final product—namely, the aircraft radome. Two focal aspects under consideration are the water absorption characteristics and the density of the product.

WATER ABSORPTION

The water absorption test for polymer composites was conducted following the ASTM D570-40 protocol, involving soaking the specimens in distilled water at room temperature for 10 days. Subsequently, to ensure the absence of any remaining moisture, the hybrid composites were heated at 60 °C for 24 hours and then weighed using a precision scale. The composites were immersed in water immediately after being weighed. At intervals of 24 hours, the composite specimens were removed from the water bath, and any water on the specimen surface was removed using tissue paper. Following this, the composite specimens were reweighed to determine the mass of water they absorbed. The percentage of water absorption was calculated using the formula:

$$W_A\,(\%) = \frac{W_1 - W_0}{W_0} \times 100 \tag{3}$$

where WA is the water absorption, $W1$ is the weight of the composite after water immersion, and $W0$ is the weight of the composite before water immersion (Sanjeevi & Shanmugam 2018).

Hybrid thermoplastic composites typically exhibit low water absorption, a desirable characteristic in many applications. The inherent water resistance of the thermoplastic resin matrix and the presence of reinforcing fibres like carbon or glass contribute to this low water absorption. These fibres act as barriers, hindering water ingress and preserving the mechanical and electrical properties of the composite. Low water absorption is crucial in applications where materials are exposed to water or other liquids. To evaluate the durability of composites based on their field of application, it is essential to study the moisture absorption behaviour of natural fibre composites, considering mechanisms such as diffusion, capillary transport, and flaws in the interfaces between fibres and the matrix (Sreekala et al. 2002).

VOID CONTENT PROPERTIES

Void content analysis is a crucial consideration in composite fabrication, as voids can significantly impact mechanical properties, strength, and overall quality. Voids, also known as porosity, are defects that occur during the manufacturing process and can play a significant role in the mechanical performance of composites (Zuhairah et al. 2021). Excessive voids can weaken the composite, reduce its load-bearing capacity, and increase the risk of delamination or failure. Figure 4 illustrates the extensive research conducted by various scholars from 2015 to 2020, studying the presence of void content in their composites fabricated through various processing methods (Zuhairah et al. 2021).

Void content is influenced by manufacturing processing circumstances, which can affect the composite's performance. Uneven shrinkage caused by temperature gradients during solidification or compounding can lead to void formation. Minimizing void content is essential for achieving optimal performance and structural integrity in composite fabrication. Various techniques are employed to reduce or eliminate voids, including proper mixing of composite components, vacuum process, pressure moulding, vacuum infusion setup, autoclaving, and the use of specialized equipment like vacuum pumps or resin injectors (Table 6).

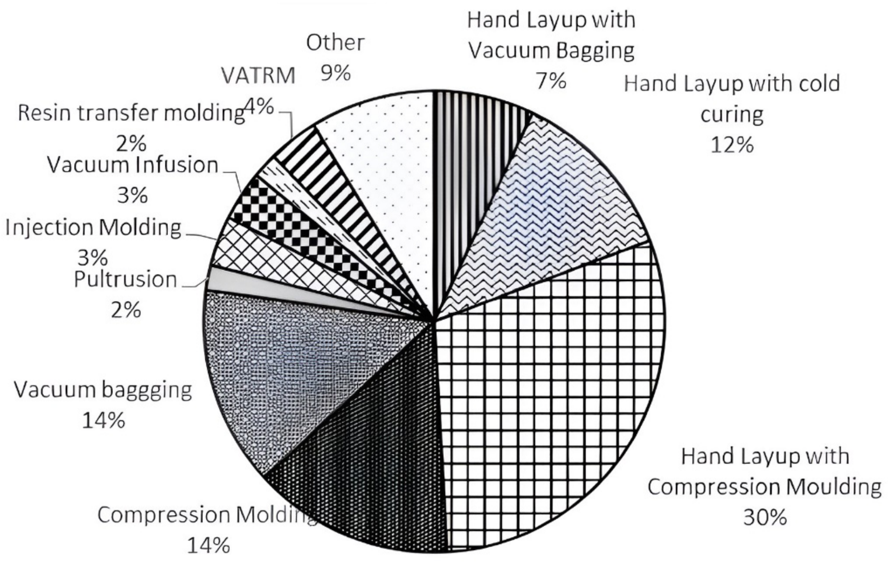


FIGURE 4. Percentages of void content of composites fabricated using various methods (Zuhairah et al. 2021).

TABLE 6. A few techniques and measurable for void studies (Zuhairah et al. 2021).

Techniques	Measurable parameter
Density determination	Void content
Microscopy	Void content Size 2D shape Location/Distribution
Ultrasonic testing	Void content Planar size Planar location/distribution
Micro- CT	Void content Size 3D shape Location /distribution

MECHANICAL PROPERTIES OF FIBRE REINFORCED THERMOPLASTIC COMPOSITES

The mechanical properties of hybrid thermoplastic composites are typically evaluated using tensile, flexural, and scanning electron microscopy tests. Tensile test measures the maximum stress a material can endure while being stretched or pulled before breaking, while flexural test indicates the maximum stress a material can withstand under bending without breaking. Additionally, SEM analysis is employed to examine the surface morphology and microstructure of the composite material (Agnivesh et al. 2020).

As a result of the synergy between different thermoplastic polymers used in the composite, hybrid thermoplastic composites exhibit superior mechanical properties, including elevated tensile and flexural strength and stiffness. SEM analysis is a crucial tool for understanding the microstructure and surface morphology of the composite, aiding in the identification of any defects that could impact its mechanical performance.

TENSILE PROPERTIES

Hybrid thermoplastic composites demonstrate elevated tensile strength, thanks to the synergistic effects of different thermoplastic polymers used in the composite. Tensile tests are conducted to understand the behaviour of samples under tension load, wherein the samples are pulled to their breaking point to determine the ultimate tensile strength (UTS) of the material (Hafizin et al. 2021). For instance, composites made from a combination of polypropylene and polyamide exhibit higher tensile strength than those composed of either of these polymers alone. A significant portion of the existing research on fibre hybrid composites focuses on analysing the mechanical characteristics of these composites. In their study, Davoodi et al. (2010) examined the mechanical properties of a composite material made from a combination of kenaf and glass fibres reinforced with epoxy. The purpose of the study was to evaluate the suitability of this composite for use in automotive bumper beams. The tensile strength and modulus of the bumper beams made from ordinary glass mat thermoplastic (GMT) were found to be lower than those of the tested bumper beams. The hybrid composites exhibited a tensile strength of 155 MPa and a modulus of 7.3 GPa. The superior tensile qualities of the hybrid composites mostly stem from the epoxy's greater maximum yield strength and modulus, in contrast to the polypropylene used in GMT production.

A separate study conducted by Sapiai et al. (2020) examined the mechanical properties of silica nanoparticles modified unidirectional kenaf and investigated the mechanical characteristics of silica nanoparticles modified unidirectional kenaf and hybrid glass/kenaf epoxy composites. The study used different fibre loadings of 5, 13, and 25 weight percent (wt %) to create hybrid composites. The acquired findings have determined that the inclusion of nano-silica in composites has enhanced the rigidity of the composites, hence improving the efficiency of load transmission to the fibre. The maximum reported values for tensile strength and modulus were 62.59 MPa and 5.61 GPa, respectively, with a fibre loading of 25%.

Manap et al. (2020) have previously revealed study results on the tensile characteristics of kenaf/glass hybrid composites. The kenaf fibre was subjected to a treatment using 7% sodium hydroxide (NaOH) and then several samples were created by including varied amounts of nano silica. These samples were then crushed to form composites. The study has shown a positive correlation between the addition of nano-silica and the enhancement of both tensile strength and modulus in hybrid composites.

FLEXURAL PROPERTIES

The flexural characteristics of a polymer composite dictate the maximum capacity for bending resistance or stiffness of the composites. Sharba et al. (2016) conducted a study to examine how the orientation of kenaf fibres affects the mechanical characteristics of a kenaf/glass hybrid composite. The study used three variants of kenaf fibres, namely non-woven, woven, and unidirectional twisted yarn kenaf, to fabricate hybrid composites. The findings indicated that the hybrid composites had the maximum flexural strength and modulus, measuring 291.6 MPa and 17 GPa correspondingly. Yahaya et al. (2016) also reported the same discovery, showing that the woven kind of kenaf reinforcement had the maximum flexural strength compared to the non-woven and unidirectional yarn.

Alaseel et al. (2022) conducted research on kenaf/glass hybrid composites to investigate the impact of varying fibre loading on the water absorption and flexural characteristics of these composites. The researchers created samples by altering the proportions of kenaf and glass fibres in the hybrid composites. The findings indicated that the kenaf/glass fibre ratio of 40:60 yielded the maximum flexural strength of 190 MPa in comparison to the other ratios. The flexural strength of the hybrid composites was shown to drop by up to 40% upon immersion in water. The decline in flexural strength is likely a result of the deterioration of the chemical bonding between fibres and polymers, leading to the formation of voids that subsequently contribute to the development of microcracks on the inner and surface regions (Alaseel et al. 2022).

Moreover, Muhammad et al. (2015) discovered that the flexural strength of treated kenaf/glass hybrid composites was greater than that of the untreated sample. The kenaf and glass fibre were subjected to treatment using a 6% solution of sodium hydroxide and a silane coupling agent, respectively. The untreated hybrid sample had a flexural strength of 59.1 MPa, while the treated sample showed a flexural strength of 68.1 MPa. A further study conducted by Ramesh & Nijanthan (2016) examined how varying fibre orientations impact the mechanical characteristics of kenaf/glass hybrid composites. The researcher used two distinct fibre orientations, namely 0° and 90°, to fabricate the hybrid composites. The collected data showed that the flexural strength of the 0° fibre orientation was greater than that of the 90° fibre orientation. The findings also indicated that the orientation of the applied force on the specimen would dictate the flexural strength of the composites.

INTERLAMINAR SHEAR STRENGTH

The aircraft industry is constantly seeking materials with a strong strength-to-weight ratio and excellent mechanical qualities (Yasir et al. 2021). The benefits of composites include lightweight and a high strength-to-weight ratio (Mouritz et al. 2001). The short beam shear test is utilized in this work, providing practical information on interlaminar shear strength (ILSS), and it can also be employed in real design applications. The ILSS of fibre-reinforced composites describes the shear strength between laminate planes of composites and is determined using the short beam shear test.

ASTM D2344 is a standard test method for the short-beam strength of polymer matrix composite materials. This test method determines the interlaminar shear strength of a composite material by subjecting a small beam specimen to a three-point bending test. After conducting the ASTM D2344 test, the results provide information about the material's ability to resist shearing forces, which is crucial for its structural integrity and performance. In conclusion, this test will include values for interlaminar shear strength, measured in either MPa or psi, allowing for a meaningful comparison of the performance of different materials for aircraft radomes.

IMPACT PROPERTIES

The energy absorption capacity of hybrid thermoplastic composites is a crucial characteristic for various industrial applications. It signifies the material's capability to dissipate energy from impacts or shocks, preventing damage to structures or components. The energy absorption mechanisms of hybrid thermoplastic composites rely on the deformation behaviour, failure modes, and microstructure of the composite.

Engineering structures are routinely exposed to impacts from foreign objects, occurring during movement, maintenance, and manufacturing. Laminated composite structures are more susceptible to impact damage than similar metallic structures. In this research, the aircraft radome has a high likelihood of impacting bird strikers at high speed. Studying the impact properties of this composite is essential to ensure that these hybrid thermoplastic composites can withstand high-impact conditions.

Impact strength denotes a material's ability to resist fracture under sudden and high-speed stress. The material's impact resistance is vital in engineering materials, in automotive applications. Material characteristics are significantly influenced by factors such as elastic modulus, orientation, and the connection between fibres and the matrix (Navaranjan & Neitzert 2017). The impact resistance of composites is defined as their ability to resist fractures under impact loads. According to the ASTM D256 standard, the impact strength of composites is measured using an Izod impact testing machine (Rout et al. 2022).

In hybrid thermoplastic composites, energy absorption occurs through various mechanisms, including matrix cracking, fibre pull-out, interfacial debonding, fibre fracture, and delamination. The specific energy absorption mechanism depends on the microstructure of the composite, especially the location, orientation, and volume fraction of the reinforcing fibres. The energy absorption mechanisms in hybrid thermoplastic composites are complex and depend on the microstructure and the deformation behaviours of the composite. The specific energy absorption mechanism varies depending on the type of impact load and the location and orientation of the reinforcing fibres. Understanding the energy absorption mechanisms is crucial for the design and optimization of hybrid thermoplastic composites for different industrial applications.

For instance, Ismail et al. (2019) examined the impact characteristics of kenaf/glass hybrid composites. The researcher investigated the impact of varying weight percentages of kenaf and glass fibres on the outcome. The hybrid composites consisting of 75% glass fibre and 25% kenaf fibre had the maximum impact strength, measuring 39.08 J. In addition, Singh et al. (2020) examined the impact of silanisation on the mechanical and tribological characteristics of kenaf/carbon and kenaf/glass hybrid composites. The S-G2K3G2 composite, consisting of treated kenaf and glass, had the maximum impact strength of 87.944 J/m2 when compared to samples containing kenaf and carbon, as well as untreated samples. The findings demonstrate that the silanised composites, which have received silane treatment, exhibit enhanced adhesion between the fibres and matrix. The mechanical characteristics of kenaf/glass hybrid composites have been evaluated by Davoodi et al. (2010). The study conducted a comparison between untreated hybrid composites and glass mat reinforced polypropylene composites (GMT). The collected data indicates that the inclusion of kenaf in hybrid composites has resulted in a nearly 50% reduction in impact strength compared to the typical GMT (Starr 2000).

QUASI-STATIC INDENTATION PROPERTIES

The quasi-static test is employed to measure the energy that composite materials can absorb when subjected to axial loads, without experiencing dynamic or rate effects. This type of test is particularly relevant for assessing impact resistance under low-velocity impact scenarios, providing valuable insights for composites (Farhood et al. 2021). Quasi-static indentation properties are critical aspects of hybrid thermoplastic composites, determining their ability to resist localized deformation and damage. Under quasi-static indentation loads, hybrid composites undergo various deformation mechanisms, including elastic deformation, plastic deformation, and failure. These properties are influenced by factors such as the volume fraction, orientation, and distribution of reinforcing fibres, the type and properties of matrix polymers, and the load rate (Mehmet 2018).

The volume fraction, orientation, and distribution of reinforcing fibres significantly impact the quasi-static indentation properties of hybrid composites. A higher fibre volume fraction enhances the composite's stiffness and indentation resistance, reducing plastic deformation (Farhood et al. 2021). Fibre orientation also influences deformation mechanisms, with longitudinal fibres offering greater indentation resistance compared to transverse fibres. Additionally, the distribution of fibres within the composite affects stress distribution and damage mechanisms. In hybrid composites, fibre distribution plays a crucial role in determining deformation behaviour and indentation damage mechanisms.

To predict the indentation process of selected fibre-reinforced polymer composites, a quasi-static indentation test was conducted. The test results were presented and analysed in terms of force-displacement curves, energy absorption (indentation energy), and damage mechanisms. The curves from the quasi-static indentation test consist of three main regimes: elastic (initial failure), damage (indentation region), and friction regions. The study focused on the indentation process, including indentation resistance, energy absorption, and damages obtained by cylindrical composite specimens. All specimens were tested using a universal testing machine (UTM) system, specifically the WDW-200E model.

CONCLUSION

In conclusion, incorporating kenaf and glass fibres into ABS composites marks a significant advancement in aerospace materials. By combining the strengths of both natural and synthetic fibres, these hybrid composites offer a unique mix of strength, durability, and lightweight properties crucial for aerospace applications. They not only meet the stringent requirements of aircraft radomes but also support the industry's goals of sustainability and cost efficiency. Moreover, ongoing research and development are expected to reveal even more potential in these hybrid materials. Advances in fibre treatments, resin formulations, and manufacturing techniques promise to further improve their mechanical properties, thermal stability, and resistance to environmental factors like moisture and UV radiation. In this case, the findings from literature underscores the significance of hybrid kenaf/glass reinforced ABS composites in enhancing mechanical performance for applications requiring radome structures.

This review also revealed that the composites with four stacking quasi-isotropic sequences with stacking with ±45-degree fibre orientation provide superior mechanical properties. The ±45-degree stacking is expected to enhance the mechanical properties because it offers balanced in-plane stiffness and strength, improved shear properties, and better resistance to torsional loads. This orientation distributes the stresses more evenly throughout the composite material, leading to improved damage tolerance and impact resistance, which are critical for the structural integrity and durability of high-performance structures.

The future of aerospace engineering is closely linked with the evolution of hybrid composites. By continually advancing material science and engineering, we are paving the way for safer, more efficient, and environmentally friendly air travel. The development of next-generation aircraft components using hybrid kenaf/glass fibre composites reflects our commitment to creating a more sustainable and resilient future.

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DECLARATION OF COMPETING INTEREST

None.

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