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Progress of (FRP) Combined

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Abstract: Emerging materials have played a critical role in subsequent years, with a deeper focus on composite materials, both polymer-based composites, which feature lightweight and high tensile strength values. The customized fiber architectures and their arrangement in the polymer matrix play a crucial role in tailoring the properties of the resulting composite. This review paper systematically scrutiniszes the various features of Fiber-Reinforced Polymer (FRP) composites from its manufacturing processes to mechanical properties and fields of applications. This article describes the contribution of natural and artificial fibers in the development of FRP composites. Moreover, it has been reported that novel investigations are being focused onto the evolution of QDs to advance some characteristics of FRP composites. Special emphasis is given to the effect of fiber weave and orienta- tion on the performance and utility of FRP components. This paper aggregates data and analysis of the current research in order to explain the FRP composites complexities as well as predict the development and application trend of FRP composites. Additionally, the last section provides a survey of the role of additive manufacturing in the elaboration of FRP composites.

Keywords: *Composites · Quantum Dots · Fiber-Reinforced Polymer · FRP · Fiber Structures.*

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I. INTRODUCTION

In summary, composites are materials made up of two distinct structural components. One component, known as the matrix, maintains a continuous structure across all geometrical dimensions [1–3]. The other component is referred to as reinforcement; while it lacks the continuity characteristic of the matrix phase, its purpose is to enhance the properties and characteristics of the composite [4, 5]. Generally speaking, the matrix provides overall shape to the composite and prevents separation of the reinforcement phase—responsible for enhancing resistance against fractures and total failure. Meanwhile, this reinforcement contributes strength along with other essential attributes required by composites.

Composite materials can be primarily categorized based on their base material into three main types: polymer-based materials, ceramic-based materials, and metal-based materials. Among these categories, polymers are predominantly employed in constructing fiber-reinforced composites due to their lightweight nature combined with favorable strength properties. They also offer advantages such as widespread availability and ease of manufacturing at relatively low costs—a crucial consideration within transport industries.

Polymers can be broadly divided into two groups: thermosets and thermoplastics [6]. Table 1 summarizes some key properties associated with various polymers.

- *Thermosets:*

These consist of long-chain molecules that covalently bond together forming networks in three-dimensional structures. They transition from liquid to solid via chemical reactions during curing or standard solidification processes. Thermoset polymers often incorporate secondary substances like cross-linking agents or hardeners activated through heat or additional chemical reactions affecting hardening states; they do not melt under heat but rather degrade directly instead. Composites utilizing thermosets may be produced under conditions involving low temperature and pressure since these compounds exhibit lower viscosity before polymerization occurs—this quality allows them to absorb moisture which could diminish compressive strength among certain characteristics unless modified through adjustments in resin composition or blending with thermoplastics/ rubbers.

The significance of using thermoset polymers lies in their provision for stability over extended periods alongside easy access to raw resources coupled with cost efficiency; common examples include polyesters, epoxy resins, styrene resins, phenolic resins, and polyurethanes.

Conversely, **thermoplastics** refer specifically to those polymers capable of being melted down for reshaping purposes. This attribute makes them particularly suitable matrices for fiber-reinforced polymer composites. A notable example prevalent within aerospace applications includes Polyether Ether Ketone (PEEK), characterized by an operational temperature range around 160 degrees Celsius although challenges persist regarding high melting viscosities versus benefits such increased elongation at breakpoints plus impact resilience[7-10] .

II. INVESTIGATION OF THE MATRIX PHASE IN FRP COMPOSITES

The water absorption rates of thermoplastics are minimal. These materials exhibit enhanced durability against environmental

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factors and elevated temperatures while also providing desirable stiffness. However, they tend to be more expensive than thermosetting plastics. The manufacturing process for thermoplastics involves melting them into a liquid state, which contributes to higher production costs [11, 12]. In contrast, thermosets are a category of polymeric substances that can melt and flow upon heating; their softening occurs at temperatures exceeding their melting point. This property allows them to undergo various processes [13], making the melting and shaping techniques applicable in component fabrication.

Most polymers within this category feature high molecular weights with elongated chains. Thermoplastic materials generally possess considerable stiffness and demonstrate good resistance to crack propagation. They usually exhibit lower brittleness compared to thermosets and show resilience against chemicals as well; additionally, many types can be repaired or recycled effectively. Examples of common thermoplastic polymers include acrylics, polyolefins, acrylonitrile-butadiene-styrene (ABS). A comparative analysis of the characteristics between thermoplastics and thermosets is presented in Table 2 [21].

Table 1 Investigation of the Freezing Properties of the Polymers used in the FRP Process [7–10, 37]

Polymer matrix	Young's modulus	Tensile strength	Density (g/cm^3)
	(GPa)	(MPa)	
Polyether ether ketone (PEEK)	3.5–4.4	150–170	1.3–1.35
High-density polyethylene (HDPE) [38]	0.4–1.5	14.5–38	0.9–1.0
Low-density polyethylene (LDPE) [38]	0.055–0.38	40–78	0.94–0.96
Polystyrene (PS)	2.3	25–69	0.96–1.06
Polyethylene terephthalate (PET)	2.3–9	55–159	1.38–1.5
Polypropylene (PP)	1.6	35.8	0.89–0.92
Polyvinyl chloride (PVC)	3–4	52–90	1.3–1.5
Epoxy (EP)	2.5–5	50–110	1.2–1.4
Polyester	1.6–4.1	35–95	1.1–1.4

Table 2 A Comparison of the Table 2 A Comparison of the Properties of thermoset and Thermoplastic Matrices [11, 13, 38]

	Thermoset	Thermoplastic
Advantages	• Low resin viscosity • Good fiber wetting • Strong durable chemical bond • Resistance to chemical and environmental conditions	• Fast processing • Recyclable • Re-process able • Post-formable • Tough • Resistance to humidity and harsh environment • No curing required
Disadvantages	• Brittle • No recyclable • Not post-formable • Curing required	• Poor melt flow • Weak adhesive bond
Construction method	• Resin transfer molding • Filament winding • Pultrusion	• Injection • Compression • Extrusion

III. REINFORCEMENTS

Many researchers categorize different types of composites using reinforcement classification. This method involves grouping reinforcement materials based on their dimensions along three axes that outline their general orientation: longitudinal, transverse, and vertical. Consequently, composites can be categorized into the following classes according to their reinforcements:

- **Zero-dimensional (0-D) class**: Reinforcements in this category are dimensionless across all axes—longitudinally, transversely, and vertically.
- **One-dimensional (1-D) class**: This type features a significant extent in one specific direction.
- **Two-dimensional (2-D) class**: In this classification, the reinforcements exist as planes that are parallel and extend over two dimensions.
- **Three-dimensional (3-D) class**: Comprising volumetric structures capable of being nested within each other, these have length, width, and height while spanning multiple directions simultaneously.

Fibers, whiskers, and nanotubes fall under one-dimensional structures; further details regarding these classifications have been provided elsewhere [15, 16].

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- *Types of Fibers on the Basis of their Structure*

Whiskers are elongated structures characterized as single crystals, with diameters ranging from 1 to 0.1 µm and an aspect ratio (length to diameter) exceeding 10,000. Utilizing manufacturing techniques such as chemical vapor deposition (CVD), their hardness has approached theoretical strength levels due to the high strength derived from a crystalline structure that is both free of defects and minimizes contributing factors. Various materials can be used to create whiskers, including aluminum oxide, boron carbide, and silicon carbide. It is important to note that whiskers tend not to be inexpensive, which complicates their integration into high-performance composites; consequently, industrial applications in this area remain limited. Nevertheless, the appealing mechanical properties combined with lower costs could stimulate considerable research and development focused on whisker-based materials. A cost-effective approach for producing composite materials utilizing these substances may facilitate further advancements.

Nanotubes represent another category of one-dimensional reinforcement material—most notably carbon nanotubes—which emerged in the early 1990s as a novel form of carbon. These structures comprise hexagonal sheets of carbon arranged into tubular configurations through various methods and can feature either single or multi-walled designs. Carbon nanotubes are distinguished by their exceptional strength and hardness; however, accurately measuring these attributes poses challenges due primarily to the small dimensions typically associated with tube walls.

Fibers constitute a fundamental type of one-dimensional reinforcement known for having approximate diameters between 1–10 µm while varying significantly in length—from about 50 up to 5000 µm. In addition to being utilized within polymer composite frameworks, they serve additional functions such as blankets or tapes when produced continuously into longer fibers usually measuring around 100-150 microns in diameter.

Table 3 Special characteristics of high-performance ordinary fibers [19]

Fiber	Density (g/cm^3)	Elongation (%)	Tensile strength (GPa)	Young's modulus (GPa)
Electronic	2.5	2.5	2.5–3	70
Glass-s	2.5	2.8	57.4	86
Carbon	1.4	1–4,1.8	4	230–40
Kevlar (aramid)	1.4	3.3–3.7	3–3.15	63–67
Sikh	2.3	—	2.8	190
Nylon 6 (dry)	1.14	28–45	2.7–4.5	18–40
Polyethylene	0.94–0.96	8–35	4.7–4.9	

Table 4 Types of Natural Fibers in FRP Composites [72–74]

Type of fiber	Density (g/cm3)	Young's modulus (MPa)	Tensile strength (MPa)
Pineapple fiber	1.56	6200	170
Fermented spinach	2.3	76000	3445
Babul wood	0.41	373	981
Hardener (HY951)	1 at 25 °C	—	—
Epoxy resin	1.2	20	75

Instead of utilizing single fibers, aligned bundles of fibers can be employed. These bundles are treated with a precursor material and subsequently transformed into an uninterrupted one-dimensional structure. This topic will be elaborated on in subsequent sections.

- *Types of Fibers based on Material*

Different kinds of fibers are recognized for their use as reinforcement in polymer matrix composites. These include carbon fibers, various types of glass fibers (such as E-glass and S-glass), aramid fibers (like Kevlar and Twaron), and boron fibers [18]. Recently, natural fibers have garnered significant attention in composite preparation due to their advantageous mechanical properties, low density, environmental friendliness, renewability, and cost-effectiveness. Natural fibers are defined primarily by the fact that they are not synthetic but instead originate from nature; they can be derived from mineral sources or come from animal or plant origins. Some data regarding these fiber types is presented in Table 3 [19].

- *Natural Fibers*

Currently, there is a significant emphasis on researching natural fibers in fiber-reinforced polymer (FRP) composites. In recent years, these materials have gained widespread industrial use due to their beneficial properties such as affordability, environmental sustainability, and recyclability. A key aspect of interest regarding natural fibers is their non-carbon endings; however, one notable limitation they face is hydrophilicity, which can restrict some applications [20]. Bamboo fiber serves as an example of a cellulose fiber that is favored for its availability. It's essential for researchers to consider surface damage—this presents challenges associated with natural fiber reinforced composites [21]. Notably, these fibers exhibit corrosion resistance—a distinct advantage over synthetic alternatives [22]. Additionally, charcoal filler has been identified as another form of natural fiber used to improve composite characteristics [23]. Weathering poses another challenge in the advancement of FRP composites made from natural fibers. Researchers have observed that certain composites incorporating natural fibers might show greater resistance than the polymer matrix itself ([24]). Nonetheless, weathering remains a concern that requires further exploration moving forward. The qualities needed for developing FRP composites using natural fibers are summarized in Table 4. Many of these fibers possess low density levels below those found in practical metals like aluminum (as indicated in Table 4). This suggests it is possible to produce lightweight materials without sacrificing strength by incorporating light virgin materials.

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IV. FIBER PROCESSING

➢ *Processing and Chemical Modification*

One of the major challenges encountered by both natural and synthetic reinforcements is inadequate wettability within the matrix phase. This issue is particularly prevalent with natural fibers used as reinforcements. Consequently, these materials often fail to provide adequate interfacial bonding, which affects their connection with both particles and reinforcing fibers in the polymeric composite matrix. To address this limitation, surface modification and processing of these reinforcements are necessary. Such measures ensure optimal adhesion between the fibers and the polymer matrix [25, 26]. Various techniques for physical modification include corona treatment, cold plasma application, and electrostatic discharge methods [27]. Among these approaches, plasma treatment stands out as a widely utilized industrial method; specifically, cold plasma treatment has proven effective for surface modifications without altering other properties of the fibers. This technique significantly improves mechanical bonding between reinforcement fibers and polymers while maintaining their chemical characteristics through physical alterations that modify surface morphology. As a result of such treatments, fiber surfaces become rougher—leading to an increased contact area between them and the matrix—which considerably enhances mechanical interlocking capabilities [28].

➢ *Types of Fiber and Fabrics made from them*

Different types of multi-filament fibers are manufactured, including carbon fibers, aramid fibers, and glass fibers [29]. Over the past few decades, advancements in textile technology have facilitated the creation of fabrics or textiles used as reinforcements. These reinforced materials can incorporate continuous strands of glass, carbon, or aramid fibers among others. Small diameter fiber classes or bundles can be woven together to produce a diverse range of textiles such as satin garments, plain weaves, and patterned fabrics. A notable characteristic of these textiles is their compatibility with various composite substrates chosen by users (the techniques for fabricating composite fibers will be elaborated upon later). One method available is film pre-impregnation with resin or injecting liquid resin into composites. This process necessitates specific types of produced and utilized fibers like tapes, fabrics, yarns, and wovens tailored for these applications. Following this section will be an exploration into particular textile types that serve to reinforce fiber composites [28, 29].

➢ *Tows or Roving*

Roving typically pertains to glass fibers, which are produced as untwisted units encompassing continuous strands of glass. In the context of carbon materials, a collection of carbon fibers is referred to as a tow, derived directly from PAN precursor material. A single carbon tow consists of between 1,000 and 48,000 filaments; however, it should be noted that this film operates separately.

- *Tow & Roving*

Achieving uniform tension during the alignment of yarns in both tow and roving is essential since inconsistent tension can lead to various developmental problems. The behavior of these fibers under tension significantly influences the effectiveness of reinforcement in final components.

Yarns tend to consist of fewer filaments or strands compared to those found in roving and are formed through spinning processes while being subjected to tension around an edge. The twist and ply are gauged by turns per centimeter; this process secures the position of the fibers while maintaining any applied tensions for subsequent procedures such as weaving or filament winding.

When stronger threads are necessary, multiple stands may be twisted together. To create twists and plies effectively, some interwoven strands must be rewound counter-directionally relative to their original twist direction. S twisting denotes one direction while Z twisting signifies another; several threads—typically two or more—are balanced with both S and Z twists accordingly [11].

➢ *Fabric*

Fabrics can be classified as either woven or non-woven and come in various types. In certain cases, they may incorporate two or more different fiber types during the weaving process. For example, a fabric might consist of carbon fibers arranged in the longitudinal direction (the warp) alongside glass or aramid fibers positioned perpendicularly (in the weft). To prevent curling or crimping that leads to wrinkles and creases [11], specific textile techniques can be utilized. This approach ensures a wrinkle-resistant design by maintaining the alignment of fibers through the weaving yarns. The resultant fabric may feature fibers aligned at multiple angles—0, 90, or even 45 degrees—with any ratio being feasible. By flattening out waves formed during fabrication, this method significantly enhances both compressive strength and hardness when compared to other traditional woven fiber options (such as wrinkle-free fiber-reinforced polymer composites). Various methods exist for preparing precursor fibers for integration into matrix systems; among these are weaving, braiding, and knitting techniques. Both three-dimensional woven fabrics and braiding technologies play crucial roles in producing three-dimensional reinforcement preforms used particularly in aerospace composite manufacturing—especially those involving carbon-carbon composites—which will be discussed further in the next section [11]. Refer also to Table 5 for details on corresponding resins employed in composite production [6, 30].

➢ *Nonwoven Fabrics*

Nonwovens are materials composed of continuous strands and fine fibers, exhibiting isotropic properties. The filaments utilized in their production are typically made from glass fiber that is bonded with a polymeric binder. These fibers can reach lengths of up to 50 mm. An alternative category within nonwoven fabrics is known as felt, which represents the second type; it employs needle-punching techniques for various applications [11].

➢ *Woven Fabrics*

Woven textiles encompass a wide variety of materials. The method of weaving affects their flexibility, pliability, and the coefficient for fiber reinforcement. In these fabrics, the warp threads run parallel to the machine's direction while the weft threads intersect them at right angles to create the fabric structure. Two common types of woven fabrics are satin twill and basket weave, distinguished by how their warp and weft threads alternate above and below each other. An additional advantage of woven fabrics is their capacity to incorporate two or more different reinforcing fibers simultaneously from various materials. This allows manufacturers to combine carbon fibers in the warp with glass or aramid fibers in the weft configuration. Occasionally, thermoplastic fibers are also integrated alongside essential primary fibers; during production,

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these thermoplastics melt down sufficiently enough to bind together and support those main fibers.

Research indicates that fiber architecture plays a crucial role in fiber-reinforced polymer composites [35]. It has been observed that when fibrous components exhibit waviness or twisting within layered composites, there is a reduction in compressive strength. Furthermore, increasing layers of fiber within such composites contributes positively towards enhancing overall material strength [11].

Table 5 Characteristics of the fiber architecture [6, 30, 75]

Dimension	Fibrous architectures	Different structures
In two dimensions	Woven fabric	• Plain • Twill • Satin
	Knitted fabric	• Woof-knitted • Warp (complexity)-knitted
	Braided structures	• Diamond • Orderly • Hercules
	Non-woven	-
In three dimensions	3D solid woven fibrous structures	Orthogonal Through-thickness angle interlock Layer-to-layer angle interlock Fully interlaced
	3D hollow woven fibrous structures	Spacer structure
	3D nodal woven fibrous structures	Honeycomb-structure

➢ *Braided Fabrics*

Braided fabric production needs advanced technologies. The ways of making woven fabrics are a little less costly compared to these to make woven materials, leading to increased the price of manufacturing. But the density of braids is more than woven fabrics. The braiding machines that are necessary for braiding fabrics have limited width, so braided fabrics are narrower than woven fabrics. Therefore, they work only at small scale and are primarily used for the strengthening of some sort of parts and profiles, such as a particular type of pipe [11]

➢ *No Crimp Fabrics*

Non-crimp fabrics consist of fibers that are either sewn or knitted together with thermoplastic polymer materials, commonly using nylon or polyester, as well as high-performance fibers like aramids. These types of fabrics do not exhibit wrinkles or knots [31].

➢ *Tapes*

Tapes are basically narrow cloths created from dry fibers (a encompass of exclusive technologies devel- oped by Epson, Dry Fiber Technology converts fibrous supplies into real use [32]). They have a width of under 100 mm. Tapes which are aligned fibers can be in plain weave which is a woven tape or made up of polymeric fibers which are knotted and hold fibers into a desired arrangement.

➢ *3D Textile Preforms*

Reinforcements are built as whole units. These can be finished later by pouring in resin and curing. There are different types of weaves that can form these structures. The manufacturing methods of these textiles stand out for their formability, resin impregnation and the time-wasting, especially for complex shapes. An overview of some processing and manufacturing conditions applicable to various textiles is presented in Table 6 [28–30, 33–35].

➢ *Polymer Fiber Composites with High Performance*

Specifically, due to their advantageous characteristics such as being lightweight while maintaining high structural stiffness and strength, polymer fiber composites are widely utilized in the aerospace and aviation industries. This utilization enhances efficiency and optimization for transportation vehicles. Additionally, these materials are favored because of their favorable strength-to-weight ratio and capacity to endure various environmental conditions.

The use of these composites is influenced by factors like the type of matrix employed, the nature of reinforcement used, the ratio between matrix and reinforcement, formulation specifics, and manufacturing techniques. A critical factor affecting overall composite strength is the bond integrity between fibers and the polymer matrix. Typically characterized by significant hardness and tensile strength, fibers are encapsulated within a continuous background matrix designed to support those reinforcing elements. The polymer matrix transmits applied loads to this reinforcement; since reinforcements generally exhibit greater strength than matrices themselves, they contribute significantly to both mechanical robustness of the composite structure as well as its resistance against external forces [33, 34]. Table 7 presents an array of properties associated with fiber composites that depend on a blend of fiber attributes alongside those inherent in the selected polymer matrix [33].

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V. CONSTRUCTION AND DESIGN OF FIBER-REINFORCED POLYMER COMPOSITES REQUIREMENTS

Thus, the design methods for composites encounter a strong shift with respect to the conventional design methods for the components having isotropic and homogenous alloys. Composite materials, by their nature, are inherently anisotropic. Moreover, the effects of thickness variation must be taken into consideration in the design and analysis of composites [35]. Because composites typically have a layered structure, the bonding between layers and the shear stresses that act on them are limited. Such stresses act in the transverse directions and can be greatly amplified at free boundaries, such as open holes or unbound edges [36, 37]. This may lead to damage in the laminate. The shear and normal stresses that occur between layers can be influenced by how the plies are stacked and arranged. It is essential to reevaluate all these factors during the design phase. Consequently, designing fiber-reinforced polymer composites presents significant challenges.

Table 6 Different Textiles Processed and Manufactured [28–30, 33–35]

Textile process	Productivity/establishment	Fiber orientation	Preform style
Sewing	High productivity and short setup time	It depends on the basic preforms	Complex prefoms are possible by combining several structures
Needlework	High productivity, long setting time	Complex fiber orientations are possible	Additional fibers are embedded on the main fabric
3D texture	Average productivity, long setup time	A wide range of thicknesses is possible, but in-plane fibers are generally limited to 0.90° orientation (except in advanced knitting machines)	Flat fiber integral dimensional stiffeners, woven sandwich structure and simple profiles
Next braids	Medium productivity, short start-up time	0° fibers: It is possible to weave fibers between 0 and 80° and 90° fibers	Open and closed profiles (I. L Z. 0. U. etc.) and flat fibers
Knitting	High productivity with long setup time	Strongly looped fibers in a structure	It does flat and very complex fairies
No creases		Multi-axis orientation in plane 0°/901 ± 45°. A maximum of 8 layers is possible	Flat fibers and integrated sandwich structures

Table 7 Characteristics of Reinforcing Fibers and Polymers used in FRP Composites [33, 34]

Fibers	Polymer matrix	Composite
Hard, brittle, strong, low density	Rigidity and strength are less malleable or brittle	Hardness through synergistic action (like wood)
High temperature capability	It can be polymer, metal or ceramic	High rigidity and stiffness in the fiber direction, but weak in the angle to the fiber axis
Able to carry bulk loads as reinforcement	It transfers the load to and from the fiber	To optimize fiber properties
Usually continuous	It shapes and protects the fiber	
Orientation for principal stresses		

➢ *Methods of Composite Fabrication*

In addition, the fibre properties are unidirectional and therefore a fibre reinforced polymer composite specimen is shaped to achieve the desired strength not only in one direction but across all others. This forms a 2 or 3 dimensional strength field. Besides the shape and dimensions which are of great importance, many other aspects are crucial in terms of the design and manufacturing of fiber-reinforced polymer composites. These are the matrix–fiber interaction, no fiber damage during processing and complete fiber distribution in the matrix. The impregnation and infiltration method is one of the important methods for preparing and manufacturing such a composite. Before being able to form the desired composite, a resin liquid is placed on the fiber bed and hardened. Using autoclaves for curing is common to most manufacturing methods for homogeneous composite production, resulting in relatively high production costs. To overcome this problem, cost-effective alternatives not involving autoclaves have been suggested. This includes non-autoclave molding, resin transfer molding, vacuum assisted resin transfer molding, resin sheet infusion, etc. [38]. The manufacturing of a thermoset composite is different from that of a thermoplastic composite. For example, the curing and solidification processes differ. The above processes can be done in the following: Thermosetting polymers rely on a chemical reaction. Thermoplastic polymers use solidification of the polymer melt. Several methods can be used to melt and solidify polymers; Depending on the positioning of the fibers in composite structures, it varies. The layered fabrics or aligned fiber sheets are aligned for every plane and layer in the desired directions, which is the main method for producing aircraft components [29]. In the below sections we will discuss about methods of manufacturing thermoset and thermoplastic fiber composites. Section 2 describes the manufacturing process for thermoset base materials backgrounds polymer composites. 5 and includes:

- Resin transfer: Impregnation [35] of fibrous preforms [32] with a low viscosity liquid resin that can be cured and formed.
- Liquid or melted resin injection into the fiber preform under pressure and polymerization by resin impregnation and resin layer diffusion.
- Fibrous sheet or fabric structures. These are impregnated with a particular resin in a process, and then are piled on top of one another.

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- These are then cured with subject to, pressure and temperature.
- Mechanical Properties of Epoxy Resins These enclose adequate and suitable adhesion to the fibers and low shrinkage. Resin transfer molding (RTM) process for epoxy resins is possible due to their tendency for low viscosity during molding.

Typically, epoxy systems are cured between 120 degrees centigrade and 180 degrees centigrade. These are not useful above 100 degrees centigrade &130 to 150 degrees centigrade. Polyamides are thermoplastics with good high temperature properties. They have a working temperature under 300 degrees Celsius and cure at 270 degrees Celsius. But they are expensive so their use are restricted. Accordingly, multi-layer composites do not develop thickness-related stresses and mechanical impact damage cracks through delamination as thermoplastics have a lower elongation at break [39]. Polyamides are also called high temperature thermoplastics. Their operating temperature is below 300°C and they cure at 270°C. But their use is limited by their expense. Thermoplastic materials have a low elongation at break, resulting in limited thickness-related stresses and mechanical impact damage resistance [40]. Due to the high melt viscosity of thermoplastics, resin transfer infusion (RTI) systems are used for thermoplastic composites manufacturing. The impregnation and creation of this resin layer over the fibers is a crucial step in this process. The entire system is then strengthened at high temperature and pressure to form the desired shape. Another principle of composite manufacturing with thermoplastics is to insert fibre fabrics or fibre bundles between thermoplastic foils. Then hot pressing (heat and pressure) to get the desired final composite. Lastly, it should be mentioned that long-fiber composites

The laminate processes are commonly used in the aerospace industry to manufacture composite materials. During this process, sheets of reinforcing fibers are introduced with polymers according to these methods [12]:

- They are infused with the desired resin and
- The conditions of pressure, temperature and time are critical because this is when the resin is applied to the mold. The advantages as well disadvantages of FRP composites manufacturing are summarized in Tab.8 [41–43].

VI. FRP COMPOSITE AND QUANTUM DOTS

One of the key methods for enhancing frameworks currently involves quantum dots, which have garnered significant interest from researchers [44]. Conversely, graphene quantum dots have emerged as a novel material [45]. Graphene quantum dots (GQDs), similar to nanotubes, are frequently utilized in fiber-reinforced polymer (FRP) composites. The incorporation of graphene substantially improves various mechanical properties of the composite, including surface shear strength, tensile strength, bending strength, and fatigue resistance [46]. Many materials highlight the function of quantum dots in bolstering and improving the mechanical attributes of composites due to their optoelectronic characteristics.

However, when present during FRP development, these quantum dots can modify piezoelectric properties [47]. In addition to graphene quantum dots, another category worth noting is carbon quantum dots. Research has been conducted on carbon-polypropylene nanocomposites incorporating these carbon-based structures. Overall findings suggest that adding carbon quantum dots enhances the fluorescence capabilities of polypropylene materials [48]. At the nanoscale level, there is considerable attention towards carbon nanotubes (CNTs). Utilizing CNTs as an additive within polymers enables enhanced strength while maintaining low weight. Furthermore, these materials exhibit exceptional thermal and electrical properties [49][50].

Notably challenging is their susceptibility to non-destructive testing methods (NDT), which complicates production processes【49】. Carbon nanotube-based composites necessitate NDT approaches to mitigate potential damage incurred during inspections by researchers.

The application of CdSe quantum dots has attracted some notice in advancing nano-polymers related to this field【51】. It would be prudent for researchers also to explore other types such as gold and ZnS quantum dots regarding their significance in developing FRP composites.

VII. APPLICATIONS OF FRP

FRP is recognized as a crucial material across various industrial sectors. This type of material finds extensive application in the transportation sector and the construction of highway bridges. Numerous advancements have been made related to this area, prompting recommendations for researchers to continue their efforts toward its further enhancement. It is important to highlight that significant focus has also been directed towards this remarkable fabric within the realm of construction of wind turbine blades [53]. For instance, figure 1 illustrates a three-dimensional model of a turbine blade that employs fiber-reinforced polymer (FRP) materials. Currently, wind turbines are recognized as one of the cleanest and most environmentally friendly energy production methods, leading to increased focus on the manufacturing processes for FRP-based turbine blades [53, 54]. A significant advantage of using these materials in turbine blades is their potential for reuse and recyclability.

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Table 8 Advantages and Disadvantages of Methods used to Produce FRP Composite [41–43]

Method	Disadvantages	Advantages
Manual layout	Calcareous unconformity slippery quality Easy formation of air bubbles	Low-cost,wide-spectrum tool
Molding under pressure	The high cost of using expensive templates	Ink parts—wide range—stability
A vacuum	Low pressure, low speed inconsistency	Stick design Type of fiber composition Better quality for the price
Resin transfer molding	Long curing time Hard for complex tile port Waste rate High gearing rate High cost Lack of repeatability	Low minimum cavity- relatively low tooling, Uniform thickness and liter loading, Molding close to the shape, Automatic process, Using low advance injection

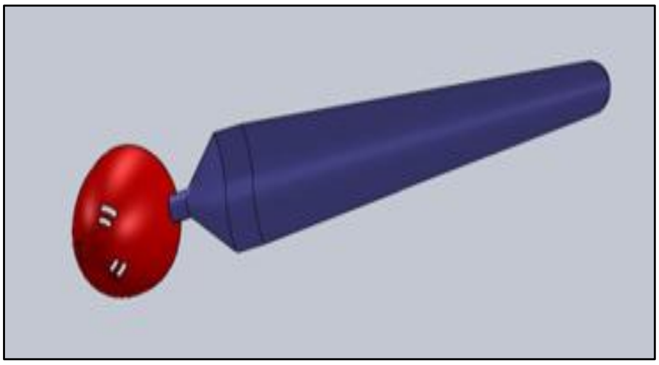

Fig 1 One of the Wind Turbine Blades and its Structure in 3D model (Design by Authors)

In the construction sector, recycled materials are increasingly utilized [55], with FRP composites serving as a straightforward application within sound barrier systems. An example includes natural fiber composites created from reinforced rice husk-polyurethane (PU), which were used to construct this type of sound barrier system [56]. The use of FRP composite walls in sound barriers offers benefits such as ease of handling during installation and exceptional corrosion resistance [57].

Within the automotive industry, there is considerable interest in utilizing FRP composites due to their lightweight characteristics [58, 59]. Researchers have also been examining steel-FRP composite properties. This combination enhances strength across various automotive components while simultaneously reducing overall weight—a crucial factor for improving energy efficiency [60]. It has been recommended that future studies pay close attention to titanium-FRP composites; incorporating graphene could potentially enhance their properties further.

The aerospace sector has shown substantial investment in these materials due to several key attributes: lightness, high strength levels, and excellent corrosion resistance. Special emphasis is placed on carbon fiber-reinforced polymers because they exhibit superior mechanical qualities compared to other available options [61, 62]. Additionally, investigations into natural fibers within aerospace applications reveal an interest stemming from their favorable strength-to-weight ratios along with environmental friendliness and non-toxic nature [63].

Additive manufacturing technology plays an essential role across various fields—including aerospace and automotive—by facilitating diverse applications related to forming FRPs. In this context,* continuous fibers can be integrated into structures made through additive techniques* **[64]**.*

This process boasts economic advantages when producing complex parts alongside shortened production cycles.* Previous research highlighted photo-polymerization methods employed for fabricating FRP composites **[65]**.* Some notable additive manufacturing techniques along with corresponding types of fibers or matrices utilized appear in Table 9.* Among them,* selective laser melting (SLM) stands out as one prominent method noted for its precision concerning manufactured parts like dental implants **[66]**, thus paving pathways toward novel explorations.*

Fused deposition modeling (FDM)* emerges likewise among prevalent methodologies contributing significantly towards developing advanced structural forms [67–69] . Through FDM*, any variety* of reinforcing fibers can be applied including carbon, glass, aramid—with different architectures ranging from nano-scale short varieties up until continuous lengths—and ongoing exploration remains warranted regarding this subject matter[67]* . Moreover , silicon carbide nanoparticles have found utility acting upon reinforcement throughout certain3D printing operations***{70}. Furthermore , thermal &mechanical properties associated with poly carbonate nano composites warrant acknowledgment within this discussion .

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Table 9 Some Additive Manufacturing Methods in the Development of FRP Composites

Additive manufacturing process	Fibers	Matrix	Refs.
FDM	Carbon-Wood-Glass	ABS, PLA,	[76-78]
SLM	Carbon nanotubes, glass	Photo-polymer, epoxy	[79-81]
SLS	Metal, graphene oxide	Metal, PMMA	[82, 83]
Direct writing	Nylon	Soft polymer	[84]

Research has been conducted on materials that include titanium nitride. Findings indicate that additive manufacturing plays a significant role in advancing this category of materials [71].

VIII. CONCLUSION

Polymer-fiber composites, particularly fiber-reinforced polymer (FRP) composites, have emerged as essential materials in engineering due to their combination of the strength and flexibility of fibers with the adaptability of polymer matrices. Their lightweight characteristics, high durability, and resistance to degradation make them prevalent across various sectors such as aerospace, automotive, marine industries, and construction.

➢ *Additive Manufacturing:*

Research efforts have predominantly concentrated on creating FRP composites through additive manufacturing techniques. One promising avenue for research advancement is the concurrent use of quantum dots within this manufacturing process.

Incorporating graphene quantum dots (GQDs) into these composites enhances the mechanical properties of parts produced via additive methods. Moreover, integrating natural fibers alongside quantum dots can effectively improve the performance metrics of fiber-based composite materials; further investigation into this area is recommended for researchers.

Another innovative strategy involves utilizing gold quantum dot-assisted methodologies in designing FRP composites. As highlighted throughout this discussion:

- High Strength-to-Weight Ratio: FRP composites offer substantial strength without significantly increasing weight—a crucial factor in aerospace applications that aim at optimizing design efficiency and fuel consumption.
- Flexibility and Moldability: The inherent versatility allows FRPs to be molded into complex shapes necessary for advanced engineering designs.
- Corrosion Resistance: Serving as alternatives to metals, FRPs are capable of enduring corrosive environments which reduces maintenance expenditures while extending service life.
- Design Versatility and Durability: The ability to customize during production aligns well with current trends toward bespoke designs; additionally their fatigue resistance contributes to longevity even under repetitive stress conditions.

Despite being a transformative category within material science realms, many aspects concerning the performance capabilities of FRP composites continue undergoing intensive exploration. Future advancements are expected not only to yield more environmentally robust variants but also tailored solutions catering specifically to diverse industrial requirements. Ongoing studies on FRP composites will likely reinforce their significance within modern material science disciplines and engineering practices.

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