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Review

Advancements in fiber-reinforced polymer (FRP) composites: an extensive review

Shahram mahboubizadeh[1] · Abdellatif Sadeq[2] · Zahra Arzaqi[1] · Omid Ashkani[1] · Mobin Samadoghli[3]

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Abstract
Recent advancements in material sciences have underscored the increasing utilization of composite materials, notably polymer-based composites, renowned for their exceptional tensile strength and lightweight characteristics. The tailored fiber structures within these composites, and their strategic placement within the polymer matrix, are pivotal in modifying the resultant composite's properties. This review article systematically examines the diverse attributes of Fiber-Reinforced Polymer (FRP) composites, including their manufacturing techniques, mechanical properties, and application domains. In this article, the role of natural and artificial fibers in the development of FRP composites is discussed. It has also been observed that new research is being done in the direction of quantum dots (QDs) in order to improve some features of FRP composites. A particular focus is placed on how different fiber weaves and orientations impact the overall performance and utility of FRP components. By aggregating and analyzing current research, this paper aims to elucidate the complexities of FRP composites and forecast trends in their development and use. Also, in the final part, a review of the importance of additive manufacturing in the development of FRP composites has been done.

Keywords Composites · Quantum dots · Fiber-reinforced polymer · FRP · Fiber structures

1 Introduction

Basically, composites are materials that are structurally made up of two different parts, one of which is called the matrix, which, as its name suggests, has a continuous structure in all the geometrical directions [1–3]. However, there is another part of the composite, called the reinforcement, which lacks the continuity of the matrix phase, but whose role is to enhance the properties and characteristics of the composite [4, 5]. In general, the background phase creates the overall shape of the composite and holds the reinforcing phase in place, just as the reinforcing particles are responsible for increasing strength, resistance to crack growth and component failure. The strength and other required properties of the composite are provided by the reinforcement phase. Composite materials are usually classified according to the base material and there are three types of composite materials: plastic based materials, ceramic based materials and metal based materials. Generally speaking, the most commonly used materials to construct fiber reinforced composites are polymers. This is due to their light weight and desirable strength, as well as their affordability, availability, ease of manufacture and low cost. This requires a general overview of the polymers

✉ Omid Ashkani, o.ashkani.14@gmail.com | [1]Department of Materials Science and Engineering, Faculty of Engineering, Science and Research Branch, Islamic Azad University, Tehran 1477893855, Iran. [2]Mechanical and Industrial Engineering Department, College of Engineering, Qatar University, P O Box 2713, Doha, Qatar. [3]Department of Polymer Engineering, Science and Research Branch, Islamic Azad University, Tehran 1477893855, Iran.

most commonly used in the transport industry. Polymers are generally divided into two categories: thermoset and thermoplastic [6]. Table 1 provides an overview of the properties of some of these polymers. Thermosets are long-chain molecules that form three-dimensional structures through the formation of interconnected networks. They change from a liquid to a solid state through a chemical reaction, curing or normal solidification process. Thermoset polymers are formed by the addition of secondary materials such as cross-linking agents, hardeners, catalysts, either in the presence of heat or by other influencing activities that can initiate a chemical reaction or hardening. Thermoset polymers do not melt or change shape under heat. They degrade directly. At low temperatures and pressures, these materials have the ability to form composites. Thermosets have a low viscosity prior to polymerization and cross-linking. As a result, they often act as moisture absorbers, which reduces their properties, including compressive strength. Their properties and characteristics can therefore be improved by introducing modifications to the resin or by alloying with thermoplastics and rubbers. Thermoset polymers are desirable because of their long term stability, easy availability of raw materials and cost effectiveness. Polyesters, epoxy resins, styrene resins, phenolic resins and polyurethanes are examples of thermoset polymers. In contrast, thermoplastics are polymers that can melt and be shaped into different shapes. This makes them ideal as matrices for fiber-reinforced polymer composites. Polyetheretherketone (PEEK), which has a working temperature range of around 160 degrees Celsius, is one of the polymer commonly used in the aerospace industry. Thermoplastics have challenges such as high melt viscosity, but they also offer advantages such as higher elongation at break and impact resistance [7–10].

2 Investigation of the matrix phase in FRP composites

Thermoplastics have low water absorption. They are more resistant to environmental and elevated temperature conditions and have desirable stiffness. However, they are more expensive than thermosets. The manufacturing process for thermoplastics, which requires a melting process to convert them to a liquid state, is costly [11, 12].

Thermosets, as opposed to thermoplastics, are polymeric materials that have the ability to melt and deform when exposed to heat. When exposed to temperatures above their melting point, they either melt or soften. This allows various processes to be carried out on them [13]. Consequently, melting and forming in these materials is used to construct and shape various components. The majority of these polymers have long chains and a high molecular weight. Thermoplastic materials have a reasonable degree of stiffness and a high resistance to crack propagation. They tend to be less brittle than thermoset materials and tend to resist chemicals. In addition, they can be repaired and recycled. Examples of thermoplastic polymers are acrylics, polyolefin, acrylonitrile butadiene and styrene. The Table 2 presents the characteristics of thermosets and thermoplastics.

Table 1 Investigation of the freezing properties of the polymers used in the FRP process [7–10, 37]

Polymer matrix	Young's modulus (GPa)	Tensile strength (MPa)	Density (g/cm^3)
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 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

3 Reinforcements

The classification of reinforcements is used by many researchers to classify different types of composites. In other words, the reinforcement materials are categorized by their dimensions in the longitudinal, transverse and vertical axes. Based on this, composites can be classified according to how they're reinforced as follows [14].

1. Zero dimensional (0-D) class: it includes reinforcements that do not have any significant dimensions along the longitudinal axis, the transverse axis and the vertical axis.
2. One dimensional (1-D) class: this is the type of reinforcement that has a significant dimension in a particular direction.
3. Two-dimensional (2-D) class: this type of reinforcement has a flat and two dimensional structure.
4. Three-dimensional (3-D) class: it includes volumetric and nested structures. It extends in different directions of length, width and height. One-dimensional structures include fibers, whiskers and nanotubes. These will be further investigated [15, 16].

3.1 Types of fibers on the basis of their structure

Whiskers are referred to as one-dimensional structures and are often found as single crystals with a diameter in the range of 1–0.1 µm. Their length to diameter ratio is greater than 10,000. Not only can their strength be increased to close to theoretical strength, but their hardness can also be increased by appropriate manufacturing methods such as chemical vapor deposition (CVD). The desired crystalline structure, free of defects and contributing factors, is responsible for the high strength achieved. Whiskers can be made from a variety of materials. These include aluminum oxide, boron carbide and silicon carbide. In general, whiskers are expensive. Their use in high performance composites is challenging. As a result, their use in composite materials is limited. However, there is potential for significant research and development of whisker-based materials due to their desirable mechanical properties and relatively inexpensive production. To make the production of composites based on these materials practical and economical, further advances in manufacturing methods are required. Another type of one-dimensional reinforcement is nanotubes. Carbon nanotubes are the most important of these [17]. This category of materials emerged in the early 1990s. It is a novel form of carbon. Carbon nanotubes are made up of sheets of carbon with a hexagonal structure that can be formed into tube-like structures using a variety of techniques. The walls of these nanotubes can be single or multiple walls. As expected, carbon nanotubes have a high degree of strength and hardness. However, these parameters are difficult to measure due to the small dimensions and geometry of the tube walls.

The most important category of one-dimensional reinforcements is that of fibers. They have a diameter of approximately 1–10 µm and a length of 50–5000 µm, if considered as individual fibers of short length. They can be used as blankets or tapes in addition to their direct use in polymer composite structures. However, when they are produced as continuous and long fibers, they are often made to measure between 100 and 150 microns. Fiber bundles can sometimes

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 ºC	–	–
Epoxy resin	1.2	20	75

be used instead of individual fibers. Such fibers consist of aligned groups of fibers which are impregnated with a precursor material and finally converted into a continuous one-dimensional structure. This will be discussed later.

3.2 Types of fibers based on material

Various types of fibers are used as reinforcements in polymer matrix composites. These include carbon fibers, glass fibers (E-glass, S-glass, etc.), aramid fibers (Kevlar, Twaron) and boron fibers [18]. In recent times, natural fibers have received a great deal of attention in the field of composite manufacturing due to their suitable mechanical properties, their low density, their environmental benefits, their renewability and their economic feasibility. A first definition of natural fibers is that they are not synthetically produced but are found in nature. They can be of animal, plant or mineral origin. The characteristics of some of these fibers are presented in Table 3 [19].

3.3 Natural fibers

Nowadays, the development of natural fibers in FRP composites is of interest. During the recent years, these composites are used in the industry due to their special properties such as low price, environmental friendliness and recyclability. Natural fibers are generally of interest due to their elimination of the carbon cycle. Of course, one of their defects is their hydrophilicity, which limits some of their applications [20]. One of these natural fibers is bamboo fiber, which is mainly used due to its availability. Generally, surface damage is one of the limitations of composites reinforced with natural fibers [21], which needs to be considered by researchers in the future. Of course, these fibers have a high resistance to corrosion, and there is this superiority over synthetic fibers [22]. It is worth mentioning that charcoal filler is also considered as one of the natural fibers to improve the properties of composites [23]. Notably that weathering is another challenge in the development of FRP composites with natural fibers. In this field, the researchers observed that the use of composites with natural fibers can show more resistance than the polymer matrix [24]. Of course, there is still the challenge of weathering and it is necessary to conduct more research on it in the future.

Table 4 shows the characteristics of some natural fibers in the development of FRP composites. As it is clear in the Table 4, the density of most of these fibers shows a small value and the density is even lower than the lightest practical metal (aluminum). This shows that by adding a light material, the strength can be increased and at the same time, a light material can be produced.

4 Fiber processing

4.1 Processing and chemical modification

Inadequate wettability within the matrix phase is one of the major challenges faced by natural and synthetic reinforcements. This problem is more prevalent with natural fibers used as reinforcements. Therefore, these reinforcements do not provide adequate interfacial bonding and bonding between the particles and reinforcing fibers with the polymeric matrix of composites. Therefore the reinforcements need to get processed and surface modified. This process will result in the proper bonding of the fibers to the polymer matrix [25, 26].

Various techniques such as electrostatic discharge methods such as corona treatment, cold plasma and others are used for physical modification and processing of fibers [27]. Among these, plasma treatment is the most commonly used industrial method, and currently cold plasma treatment is highly effective and used to surface modify fibers without affecting their other properties. Through the use of physical processing and surface modification methods, we observe an increase in the mechanical bond between the reinforcement fibers and the polymer matrix of composite materials. In essence, the morphological properties of the surface are altered by physical processing and modification, without altering the chemical properties. After physical modification of the fibers, their surface becomes rougher. This leads to an increased contact area between the fibers and the matrix, which significantly improves their physical adhesion [28].

4.2 Types of fiber and fabrics made from them

Carbon fibers, aramid fibers, glass fibers and other multi-filament fibers are produced in a variety of forms [29]. In recent decades, textile technology has been applied to the production of fabrics or textiles as reinforcements, and these reinforced textiles can be made from continuous glass, carbon or aramid fibers, among others. A wide range of fabrics and textiles, such as satin woven garments and plain woven fabrics without patterns, can be woven using classes or bundles of small diameter fibers. An important aspect of these textiles is their ability to be incorporated into the composite substrate of choice (later we will discuss methods of composite fiber fabrication). One of these methods, for example, is the pre-impregnation of resin films or the injection of liquid resin. This requires appropriate forms of fibers for use in these composites, including various tapes, fabrics, yarns and woven fabrics. Some of the textiles used to reinforce fiber composites will now be examined [28, 29].

4.3 Tows or roving

Roving is commonly used in relation to glass fibers. These are formed as untwisted bundles containing a number of continuous glass fibers. In the case of carbon, the bundle of carbon fibers is called a tow. It is processed directly from the PAN precursor material. A carbon tow consists of 1,000–48,000 filaments, the film of which is separate. The need to apply uniform tension to the filaments as uneven tension can cause problems is an important aspect of tow and roving. The tension behavior of the fibers has a major influence on the final components and can be the cause of variations in their reinforcement effectiveness. Yarns are typically made by spinning a set of filaments or strands, often fewer than in roving. They are formed under tension when pulled over an edge. The twist and ply are approximately measured in turns per centimeter. This holds the fibers in place and retains any tension during subsequent processes such as weaving or filament winding. Two or more stands can be twisted together in cases where heavier threads are required. The twist and the ply are then achieved by rewinding a number of the intertwined strands in the opposite direction to the twist of the stand. The directions of twisting and plying are indicated by S and Z twisting. Two or more threads are created with S and Z twists in order to maintain balance [11].

4.4 Fabric

Fabrics can come in both woven and unwoven forms. They can be of different types. In some cases, they can be woven from two or more different types of fiber. For example, a fabric may be woven with carbon fibers oriented in the 0 degree direction (the warp) and with glass or aramid fibers oriented in the 90 degree direction (the weft). Textile techniques can be used to prevent fiber curling or crimping, which causes wrinkles and creases [11].

This method produces a wrinkle-free fabric by holding the fibers in place with weaving yarn. This fabric can contain fibers oriented in any direction, such as 0, 90 or 45 degrees. Any ratio is possible. Due to the elimination of the waves present in the final fabric, wrinkle-free fiber reinforced polymer composites show significant improvements in terms of compressive strength and hardness when compared to other woven fibers. Precursor fibers prepared for incorporation into the matrix can be produced by a variety of methods. These include weaving, braiding and knitting. Advanced weaving and braiding techniques are also used in the manufacture of 3D reinforcement preforms for aerospace composite applications, with 3D woven fabrics being used extensively in carbon–carbon composites. These techniques will be discussed further [11]. In Table 5 along with the resins that are used in the manufacture of the composite, the following are listed [6, 30].

4.5 Nonwoven fabrics

Nonwovens are materials composed of continuous strands and fine fibers, and have isotropic properties. The strands that are used in this process are often made of glass and are held together by a polymeric binder. They can be up to 50 mm in length. Another type of nonwoven fabric is felt, which is formed by the stitching and needle-punching of a fabric, and is used for a variety of applications [11].

4.6 Woven fabrics

A wide range of textiles are covered by woven fabrics. Their pliability, flexibility and fiber reinforcement coefficient are affected by the way they are woven. In woven fabrics, the warp thread runs in the direction of the machine, while the weft thread runs at right angles to it to form the fabric. The two main types of woven fabric are the satin twill fabric and the basket weave fabric. They differ in the way in which the warp and weft threads are laid alternately on top of and underneath each other. The ability to have two or more different types of reinforcing fibers of different materials at the same time is an advantage of woven fabrics. This allows manufacturers to use, for example, carbon fibers in the warp and glass or aramid fibers in the weft. In addition to the desired primary fibers, thermoplastic fibers can sometimes be added. In this case, the thermoplastics are melted during the manufacturing process and form a suitable package to hold and reinforce the primary fibers. In fiber-reinforced polymer composites, the structure of the fibers used is critical. If the fibers are wavy and twisted, there will be a reduction in the compressive strength of the material. It is also important to note that the strength of layered composites increases with the number of fiber layers used [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

4.7 Braided fabrics

The production of braided fabrics requires complex technologies. This increases the cost of production compared to woven fabrics. However, the weight of braids is higher than that of woven fabrics. The width of braided fabrics is narrower than that of woven fabrics due to the limitations of braiding machines. As a result, their applications are limited and they are mainly used for the reinforcement of specific components and profiles, such as certain types of tubes [11].

4.8 No crimp fabrics

Non-crimp fabrics are made from fibers that have been sewn or knitted together using thermoplastic polymer fibers, typically nylon or polyester, or high performance fibers such as aramids. These fabrics are free from wrinkling and knotting [31].

4.9 Tapes

Tapes are essentially narrow fabrics made from dry fibers (Dry Fiber Technology, a proprietary set of technologies developed by Epson, transforms fibrous materials into tangible value without using water [32]). They are less than 100 mm wide. Tapes can be either woven or made up of aligned fibers that form a plain weave pattern, or they can be made using polymeric fibers that are tied in knots to hold the desired arrangement of fibers.

4.10 3D textile preforms

Reinforcements are produced as complete units. They can be completed later by adding resin and curing. These structures can be formed using various types of weaves. The manufacturing methods for these textiles are important in terms of formability, resin impregnation capabilities and reducing production time, especially for complex shapes. Table 6 gives an overview of the processing and manufacturing conditions for a number of different textiles [28–30, 33–35].

4.11 Polymer fiber composites with high performance

In general, due to their many advantages, including their strong and stable structure combined with their low weight, polymer fiber composites are widely used in aerospace and aircraft applications. The result is an increase in efficiency and optimization of fuel consumption in transport vehicles. Furthermore, their strength to weight ratio and ability to withstand environmental conditions make them desirable. Factors such as matrix type, reinforcement, matrix/reinforcement ratio, formulation and manufacturing process define the applications of these composites. A critical factor in the overall strength of the composite is the bond strength between the fibers and the polymer matrix. Fibers typically have high hardness and strength. They are embedded in the continuous matrix (background), which serves to hold and preserve the reinforcing materials. When subjected to external loads, the polymer matrix transmits the applied forces to the reinforcement, and since the strength of the reinforcement is higher than that of the matrix, most of the resistance to applied forces and the mechanical strength of the composite relies on the added reinforcements within the matrix structure [33, 34]. A combination of fiber properties and the polymer matrix used as the matrix demonstrates a set of characteristics exhibited by fiber composites which is specified in Table 7.

5 Construction and design of fiber-reinforced polymer composites requirements

Compared to the design of components made from homogeneous alloys with isotropic properties, the design methods for composites require significant changes. This is due to the inherent anisotropic nature of composite materials. In addition, the design and analysis of composites must take into account the effects of thickness variation [35]. The bonding between the layers and the influence of shear stresses on them are limited because composites often have a layered structure. The transverse stresses that are generated can be significantly increased at free boundaries, such as open holes

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 preforms 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		

or free edges [36, 37]. This can cause the laminate to become damaged. The shear and normal stresses between the layers can be affected by the stacking and arrangement of the plies. All these factors need to be reassessed and taken into account in the design process. This makes the design of fiber reinforced polymer composites challenging.

5.1 Methods of composite fabrication

Due to the unidirectional nature of fiber properties, the design of fiber-reinforced polymer composites involves shaping the specimens to ensure that the desired strength is achieved not only in a specific direction but also in other directions. This creates a two or three dimensional strength distribution. In addition to the importance of shape and dimensions, other factors are important in the design and construction of fiber-reinforced polymer composites. These include the matrix-fiber relationship, the avoidance of fiber damage during manufacture and the achievement of complete fiber distribution within the matrix. An important method for forming and constructing such composites is impregnation and infiltration. In this process, a resin liquid is applied to a fiber bed and, after the resin has solidified, the desired composite is formed. Most manufacturing methods for producing homogeneous composites use autoclaves for curing, which increases production costs. To address this issue, alternative cost-effective methods that do not require autoclaves have been proposed. These include non-autoclave molding, resin transfer molding, vacuum assisted resin transfer molding, sheet resin infusion and more [38]. Thermoset and thermoplastic composites are manufactured in different ways. The curing and solidification processes, for example, are different. These processes can be carried out in one of the following ways:

Chemical reactions are used in thermosetting polymers.

Solidification of the polymer melt is used in thermoplastic polymers.

The melting and solidification of polymers can be achieved by various techniques.

When forming composite structures, there are several methods of arranging the fibers. The primary method used to manufacture aircraft components is the use of layered fabrics or aligned fiber sheets, which are synchronized or oriented in the desired directions in each layer and plane [29]. The methods of manufacturing thermoset and thermoplastic fiber composites are discussed below. The manufacturing process for polymer composites with thermoset base materials backgrounds is described in Sect. 5 and includes:

1. Impregnating [35] fibrous preforms [32] with a liquid resin that is capable of being cured and molded by means of resin transfer.
2. Injection of liquid or molten resin into the fiber preform under pressure, followed by curing by a process of resin impregnation and diffusion of resin layers.
3. Fabric or sheet structures made from fibers. These are impregnated sequentially with a specific resin and then stacked.
4. They are subject to pressure and temperature curing.
5. Epoxy resins have favorable mechanical properties. These include sufficient and appropriate adhesion to the fibers and low shrinkage. Due to their ability to mold at low viscosity, the resin transfer molding (RTM) process is feasible for epoxy resins.

In general, epoxy systems are cured at temperatures between 120 degrees centigrade and 180 degrees centigrade. They cannot be used above 100 degrees centigrade and 130 to 150 degrees centigrade. Polyamides are known as high temperature thermoplastics. They have a working temperature of less than 300 degrees Celsius and cure at 270 degrees Celsius. However, their use is limited by their high cost. Thermoplastic materials have a lower elongation at break, which results in reduced resistance to thickness-related stresses and mechanical impact damage, leading to layer delamination in multi-layer composites [39].

Polyamides are known as high temperature thermoplastics. They have a working temperature of less than 300 degrees Celsius and cure at 270 degrees Celsius. However, their use is limited by their high cost. Thermoplastic materials have a lower elongation at break, which results in reduced resistance to thickness-related stresses and mechanical impact damage, leading to layer delamination in multi-layer composites [40]. Because thermoplastics have a high melt viscosity, resin transfer infusion (RTI) systems are suitable for the manufacture of thermoplastic composites. A critical point in this process is the impregnation and formation of a resin layer over the fibers. The entire system then gains strength under high pressure and temperature to achieve the desired shape. Another method of manufacturing composites using thermoplastics is to place fibre fabrics or bundles of fibers between thermoplastic sheets. This is followed by hot pressing (heat and pressure) to obtain the desired final composite. Finally, it should be noted that long-fiber composites commonly used in the aerospace industry are manufactured using laminating procedures. In this process, sheets made of reinforcing fibers are integrated with polymers using the following methods [12]:

1. They are impregnated with the desired resin and
2. The resin is applied to the mold under specific conditions of pressure, temperature and time. Some of the advantages and disadvantages of FRP composite manufacturing are shown in Table 8 [41–43].

6 FRP composite and quantum dots

Quantum dots are one of the main methods of strengthening various materials, which have attracted the attention of many researchers today [44]. Meanwhile, graphene quantum dots have been considered as a new material [45]. Graphene quantum dots (GQDs) in the form of nanotubes are prominent in FRP composites. Increasing graphene is highly effective in improving the surface shear strength, tensile strength, bending strength and fatigue strength of the composite [46]. Notably to the role of quantum dots on strengthening and improving the mechanical properties of composites, these materials have been considered in the development of composites due to their optoelectronic properties. Research has shown that the development of FRP composites in the presence of quantum dots can lead to changes in piezoelectric properties [47]. In addition to graphene quantum dots, attention to carbon quantum dots is also very important. In this regard, carbon-polypropylene quantum dot nanocomposite was considered. In general, the results showed that the presence of carbon quantum dots in polypropylene improves the fluorescence properties of the material [48].

Also, on the Nano scale, attention to carbon nanotubes (CNT) is of interest to researchers. Carbon nanotubes are considered as an additive in reinforced polymers to achieve a high strength-to-weight ratio. In addition, these materials have excellent thermal and electrical properties [49, 50]. One of the notable points is the vulnerability of these materials to non-destructive inspection methods (NDT), which is a challenge in the production process [49]. It is necessary for researchers to develop non-destructive inspection methods in order to prevent damage to composites containing carbon nanotubes.

It is worth mentioning that in the field of quantum dots, CdSe quantum dots has also received some attention in the development of Nano-polymers [51]. Of course, it is suggested that in order to investigate the role and importance of quantum dots, researchers should investigate the development of other quantum dots such as gold and ZnS quantum dots in the development of FRP composites.

7 Applications of FRP

FRP has been considered as an important material in various sectors of industries. One of the main uses of this group of materials is in the development of the transportation industry and the highway bridge [52]. Various results have been achieved in the development of these materials, of course, researchers are still suggested to make more efforts in the field of its development. It is noteworthy that attention has also been paid to this amazing material in the construction

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

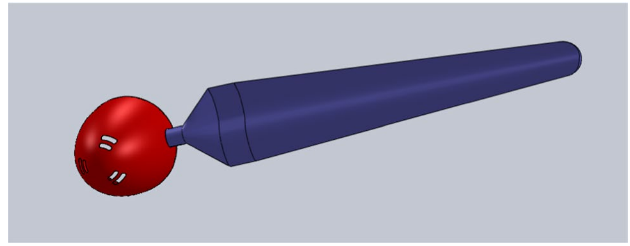

Fig. 1 One of the wind turbine blades and its structure in 3D model (Design by authors)

of wind turbine blades [53]. Figure 1 shows a turbine blade in 3D model and can use FRP for this design. Wind turbine, which are one of the environmentally friendly methods for energy production, are of interest today, and in this regard, it is customary to make wind turbine blades with FRP [53, 54]. It is worth mentioning that the reuse of these materials and their ability to be recycled can be one of the strong points in the development of wind turbine blades and waste reduction. Recycled materials can be used in the construction industry [55].

Sound barrier system is another simple and common application of FRP composites. Research has shown that natural fiber composites reinforced with rice husk-PU were used in order to create a sound barrier system [56]. The light weight of FRP composite walls and their high corrosion resistance are among the advantages of these materials in the construction of sound barrier [57].

The use of FRP composites in the automotive industry has also been highly considered. The lightness of these composites is one of the main features that lead to their development in the automotive industry [58, 59]. Also, the use of steel-FRP composites has been the focus of researchers. The use of this type of composite leads to an increase in strength in different parts of the automotive and at the same time a reduction in weight, which plays an effective role in energy conservation [60]. It is suggested that in order to complete the researches, researchers pay special attention to titanium-FRP composites. The addition of graphene may also change the properties of this composite.

Finally, special attention has been paid to these materials in the aerospace industry. Lightness, high strength and corrosion resistance are among the reasons for paying attention to these materials in the aerospace industry [× 10]. In the meantime, paying attention to carbon fiber reinforced polymers has a special place because it offers excellent mechanical properties compared to other materials [61, 62]. Research has also been done on the use of natural fibers in the aerospace industry. Along with aluminum, natural fiber composites are of interest to researchers in the aerospace industry due to their high strength-to-weight ratio, compatibility with the environment, and non-toxic nature [63].

In all mentioned applications, one of the most important issues is the use of additive manufacturing technology in forming FRP in various industries such as aerospace or automobile. In additive manufacturing technology, continuous fibers can be used [64]. The main advantage of this process is low cost for manufacturing complex parts and short production cycle. The results of previous research have reported the use of photo-polymerization to make FRP composites [65]. Table 9 shows some types of additive manufacturing methods and the fibers and matrix used in them. As can be seen in this table, the selective laser melting (SLM) method is also considered as one of the main methods of additive manufacturing. Selective laser melting has a high precision in the manufacture of some parts such as dental implants [66], and the high speed of manufacturing in this method can lead to the creation of space for new research.

Fused deposition modelling (FDM) is also among other significant methods in the development of FRP composites [67–69]. In this method, it is possible to use all kinds of reinforcing fibers such as carbon, glass, and aramid with different fiber length architectures, including Nano, short fibers, and continuous fibers, and it is necessary for researchers to focus more on this issue [67]. It should be mentioned that silicon carbide nanoparticles have also been used as a reinforcing agent in the 3D printing process [70]. Also, the thermal and mechanical properties of polycarbonate nanocomposites

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]

containing titanium nitride have been investigated. The results have shown that additive manufacturing is an important method for the development of this group of materials [71].

8 Conclusion

Polymer-fiber composites, notably fiber-reinforced polymer (FRP) composites, have emerged as a cornerstone in engineering materials, combining fiber strength and flexibility with polymer matrix versatility. Their applicability spans aerospace, automotive, marine, and construction industries, favored for their exceptional lightweight properties, high strength, and resistance to degradation. It is worth mentioning that the development of FRP composites with the additive manufacturing method has been the focus of researchers. The simultaneous use of quantum dots in additive manufacturing can be one of the important methods for further research development. Adding graphene quantum dots to these composites, especially with the additive manufacturing method, will play an effective role in the development of manufactured parts.

Also, the use of natural fibers along with quantum dots can play a very effective role in increasing the mechanical properties of these materials. It is suggested that researchers pay special attention to this issue in the future. Also, the use of gold quantum dots in the development of FRP composites can be considered. As summarized in this discussion, FRP composites excel in multiple areas:

High Strength-to-Weight Ratio: essential for industries like aerospace, FRP composites deliver robustness without the burden of mass, enabling more efficient designs and fuel economies.

Flexibility and Mold-ability: the adaptability of FRP composites permits the realization of intricate shapes, essential for complex engineering applications.

Corrosion Resistance: offering a viable alternative to metals, FRPs withstand corrosive environments, reducing maintenance costs and extending service life.

Design Versatility and Durability: the malleability of FRP composites during manufacturing aligns with the demand for custom designs, while their fatigue resistance ensures longevity even under cyclical stress.

While FRP composites stand as a transformative class of materials, ongoing research is crucial to enhancing their performance attributes and uncovering novel applications. Future developments may yield FRP composites with even greater environmental resilience or tailored properties for specific industry needs. Thus, the continued exploration of FRP composites holds the promise of furthering their pivotal role in modern material science and engineering.

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Declarations

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