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A review on the application of high-performance fiber-reinforced polymer composite materials

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Abstract

Composites have been identified as the most promising and discriminating material now accessible in the twenty-first century. Currently, composites reinforced with high-performance fibers of synthetic or natural materials are gaining traction as the market's need for lightweight materials with high strength increases. Outstanding performance not only does a fiber-reinforced polymer composite have a high strength-to-weight ratio, but it also exhibits excellent qualities such as increased durability, stiffness, damping property, flexural strength, corrosion resistance, wear, impact, and fire. Composite materials have found uses in various industrial sectors, including mechanical, construction, aerospace, automotive, biomedical, and marine. Because their constituent elements and fabrication techniques primarily determine the performance of composite materials, it is necessary to investigate the functional properties of various fibers available worldwide, their classifications, and the fabrication techniques used to fabricate the composite materials. A survey of a broad range of high-performance fibers is offered, together with their qualities, functionality, categorization, and production procedures, to identify the optimal high-performance fiber-reinforced composite material for crucial applications. Due to their superior performance in a wide variety of applications, high-performance fiber-reinforced composite materials have emerged as a viable alternative to solo metals or alloys.

Keywords: High-performance fiber-reinforced polymer composites; Durability; Stiffness; Damping Property; Flexural Strength

1. Introduction

Two or more component materials having substantially varied physical or chemical characteristics are often utilized to make composites, which may be employed in a wide range of industries. Carbon, glass, aramid, ultrahigh-molecular-weight polyethylene (UHMWPE), ceramic, quartz, boron, and novel fibers such as poly (p-phenylene benzothiazole) (PBO) fibers are examples of high-performance composites (HPC). High modulus, high tensile strength, and good heat resistance are only some of the characteristics of these fibers. Most HPC matrix materials are polymers, metals, alloys (such as aluminum and magnesium), and ceramics. Polymers, metals, alloys (such as aluminum and magnesium), and ceramics (such as unsaturated polyester resin) are the most common (aluminum oxide, zirconia, silicon nitride, silicon carbide, etc.). Designed for particular purposes that need extraordinary strength, stiffness, heat resistance, or chemical resistance, high-performance fibers are engineered for specific uses that require excellent strength, stiffness, heat resistance, or chemical resistance. Fibers come in a broad range of qualities fibers. High-performance fibers are often niche goods in the more significant fiber industry. However, some are mass-produced in considerable numbers.

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2. Fiber: An Overview

2.1. Natural fiber

Natural fibers (NFs) are a widely accessible and easy-to-find substance in nature. They show biodegradability, cheap cost per unit volume, high strength, and particular stiffness as excellent material qualities. Composites composed using NF reinforcements seem to have several advantages to synthetic fibers, including lower weight, cost, toxicity, pollution, and recyclability. For current applications, these economic and environmental advantages of NF composites make them the preferred choice over synthetic fiber-reinforced composites [1-3].

Natural fibers contain comparable structures with varied contents depending on the kind. The use of natural fibers, both long and short, in thermoset matrices has resulted in high-performance applications. Because of their excellent tribological qualities, Sisal fiber (SF)-based composites are often utilized for automotive interiors and furniture upholstery. Tensile strength increased with fiber volume when SFs were reinforced with polyester composites. In contrast, the tensile strength of 12.5 MPa was reported in 6 mm long sisal fibers when reinforced with polyethylene (PE) composites [4-5].

When compared to GF-reinforced composite with a propylene matrix, hemp composite demonstrated a 52 percent improvement in specific flexural strength. The flexural and tensile strength of a composite material containing 5% maleic anhydride-grafted polypropylene (MAPP) by weight combined with a polypropylene (PP) matrix reinforced with 15% alkaline-treated hemp fibers increased by 37 percent and 68 percent, respectively [6-7]. The tensile and flexural strength of polylactic acid (PLA) thermoplastic composites with kenaf fiber reinforcement are 223 MPa and 254 MPa, respectively. Additionally, eliminating absorbed water from the fibers before laminating improves kenaf fiber laminates' flexural and tensile characteristics. Previously, polyester samples with no reinforcements had flexural strengths, and moduli of 42.24 MPa and 3.61 GPa, respectively, but composite material with 11.1 percent alkali-treated virgin kenaf fibers in the unsaturated polyester matrix had flexural strengths and moduli of 69.5 MPa and 7.11 GPa. [8-10].

A sound transmission loss (STL) test was used to study flax fiber-reinforced polypropylene composites' sound and vibration characteristics (FF and PPs). Because the material has strong sound absorption capabilities, the findings demonstrate an increase in stiffness, damping ratio, and mass per unit area due to increased transmission loss. A material's tensile characteristics were improved by using short flax fiber (FF) laminates. In addition, with 45 fiber orientations, material strength and shear modulus rose by 15% and 46%, respectively. According to research on the free vibration properties of ramie fiber-reinforced polypropylene composites (RF/PPs), the higher the fiber content in a polymer matrix causes slippage between the fiber and the matrix, resulting in an increase in the damping ratio during flexural vibration. This suggests that increasing the fiber content improves the damping qualities of the RF/PP composite [11-13].

2.2. Synthetic fiber

Chemically synthesized fibers are synthetic fibers, and they are further classed as organic or inorganic, depending on their composition. Because the fibers' stiffness and strength are so much greater than the matrix's, they serve as a load-bearing component in composite structures [14-16].

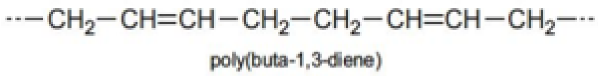
As a result of their exceptional strength and durability, thermal stability, resistance to impact, chemical, friction, and wear, glass fibers (GFs) are the most often used synthetic fibers. When dealing with glass fiber-reinforced polymers (GFRPs), standard machining processes may be sluggish and complicated, with limited tool life. At the end of their service life, however, GFs have drawbacks that must be disposed of [17].

Carbon fibers (CFs) are used instead of GFs in specific applications because they are more rigid. Although synthetic fibers such as aramid, basalt, polyacrylonitrile, polyethylene terephthalate, or polypropylene fibers offer some advantages, they are rarely used in thermoplastic short-fiber-reinforced polymers (SFRP) for their desired properties; they have been used in specific applications. Numerous uses for carbon fiber-reinforced polymer (CFRP) composites have been discovered in many industries. When carbon fiber weight percentage rose from 10% to 30%, Young's modulus of solids and foams increased by 78% and 113%, respectively. When carbon fiber/polypropylene (CF/PP) was utilized to manufacture composite foams made by microcellular injection molding, the cellular structure improved by 35 percent [18-20].

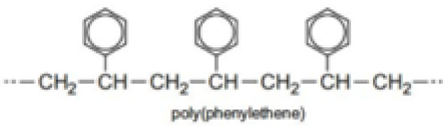
Compared to carbon fibers, graphene fibers are a new kind of high-performance carbonaceous fiber with higher tensile strength. Numerous graphene fiber features, such as their ability to be knitted into supercapacitors, micromotor, solar cell textile, and actuator applications, have shown promise in a wide range of industrial applications. Polymer composites containing graphene reinforcements demonstrate a 150 percent increase in Young's modulus, a 27.6 percent increase in shear modulus, and a 35 percent increase in hardness using molecular dynamics simulations. A 35 percent decrease in the coefficient of friction and a 48 percent decrease in the abrasion rate were obtained [21].

2.3. Polymers: an overview

The outcome of numerous molecules of a simple substance joining together is called a polymer, and the process is called polymerization. Monomers are simple compounds with molecules that combine to produce polymers. The polymer comprises a backbone of atoms to which atoms or groups of particles are attached. Polymers are macromolecules, which are massive molecules. Simple molecules have chemical characteristics that are comparable to those of these molecules. If a polymer has a carbon-carbon double bond, such as poly (but-1, 3-diene), it will undergo additional reactions with hydrogen or bromine, for example.



It will undergo substitution reactions, such as nitric acid, if it has an aromatic ring, as in poly (phenylene) (commonly referred to as polystyrene)



The most considerable distinction between smaller molecules and polymers is their physical features, not their chemical ones. Their more significant sizes result in significantly stronger intermolecular forces, leading to substantially higher melting temperatures and the hardness and flexibility they are known for. When the polymer chains pack together in a regular pattern, as in HPDE (high-density poly (ethene)), and contain crystallinity zones, the intermolecular pressures are considerably more significant. It dissolves when heated, and the crystallinity is lost. The temperature at which this happens is known as the melt transition temperature, Tm since it does not have a distinct melting point. The polymer becomes amorphous above this temperature. The rearrangement of electrons occurs during the conversion of a monomer to a polymer. The repeating unit is the unit in a square bracket. The repetitive unit and structural unit are the same while converting styrene to polystyrene. [22].

Classification of Polymer:

1) Natural Polymer 2) Synthetic Polymer

2.3.1. Natural Polymer

Natural polymers are materials found in nature or derived from plants or animals. Natural polymers are essential in life since they are the foundation of our human forms. Proteins and nucleic acid, for example, are examples of natural polymers. Cellulose, natural rubber, silk, and wool are all examples of materials that may be foreman bodies. Similarly to starch, which is a natural polymer composed of hundreds of glucose molecules. Natural rubber is a polymer made from the latex of a rubber tree. Honey is another example of naturally occurring polymers that have a wide range of applications in daily life. Natural polymers are found in plants and animals (latex from rubber trees) (honey from bees). [23].

2.3.2. Synthetic Polymer

Synthetic polymers are those that are manufactured in a laboratory. It's also referred to as artificial. It is possible to identify a wide range of synthetic polymers, such as polystyrene, nylon, PVC, synthetic rubber, Teflon Teflonxy, and more. Carbon-carbon bonds form the backbone of most synthetic polymers, generally generated from petroleum oil in a controlled setting. Polymerization occurs due to heat and pressure applied in a catalyst, which changes the chemical bonds between monomers. A trigger is a substance that initiates or speeds up the chemical reaction between two monomers. Synthetic polymers are used in the creation of many everyday items. These applications lie within the categories of thermoplastics, thermosets, elastomers, and synthetic fibers. For the design of plastic materials, this book focuses on thermoplastic polymers that are synthesized. Compares some of the qualities and features of natural polymers to synthetic polymers are given below- [24].

Table 1 Compares some of the qualities and features of natural polymers to synthetic polymers

Natural Polymer	**Synthetic Polymer**
It happens on its own(Naturally occur)	artificially generated
Molecules with comparable chain lengths	Depending on the reaction circumstances, chain lengths might vary greatly
Repetition that is similar but not identical	Repetition of a single, identical element
The qualities are regulated by the natural response.	By manipulating the reaction, it is possible to get highly designed qualities
Biodegradable is usually the case	Biodegradability exists in several synthetic polymers
The backbone may be composed of carbon, oxygen, or nitrogen	Carbon makes up the majority of the backbone

2.4. Composite

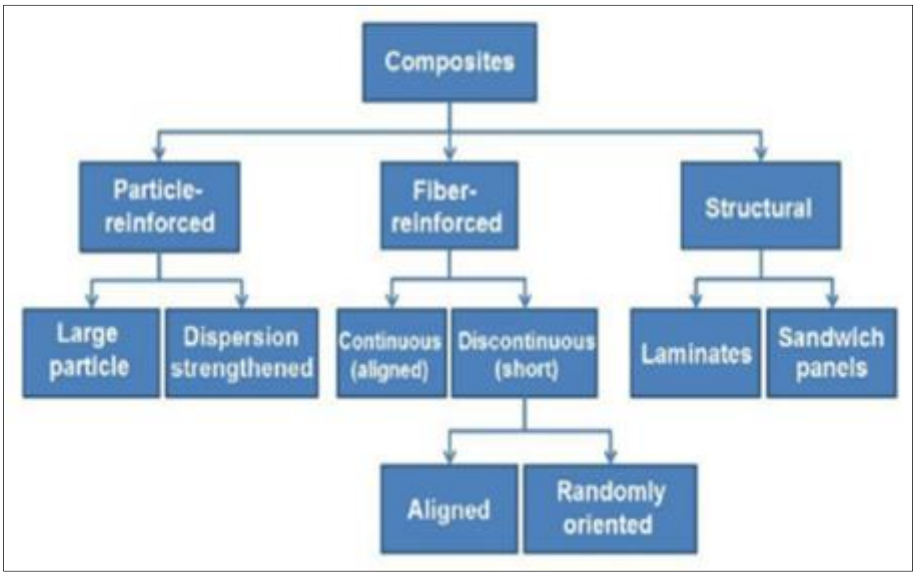


Figure 1 Classification of Composites[25].

2.5. Development and applications of Composite materials

Composite materials and structural parts composed of composite materials have advanced at a breakneck pace throughout the previous decades. The reasons for this development are significant advancements in the material science and technology of composite constituents, the demand for high-performance materials in aircraft and aerospace structures, the development of potent experimental equipment and numerical methods, and the availability of efficient computers. The advancement of composite materials enables a new material design that allows for an ideal material composition concerning structural design. Achieving the practical and proper use of composite materials needs tight collaboration across many engineering disciplines, including structural design and analysis, material science, material mechanics, and process engineering. The following table summarizes the significant areas of composite material research and technology are:

- a thorough examination of the component and composite materials properties; material selection and optimization for the intended use
- development of analytical modeling and solution techniques for determining material and structure behavior

- creation of experimental techniques for characterization of materials, determining stress and deformation states and predicting failure
- modeling and analysis of creep, damage, and life prediction
- development of new and more efficient manufacturing and recycling processes, among other things

The primary motivation for composite research and use was to save weight in contrast to structures made of traditional materials such as steel, alloys, and so on. However, focusing just on material density, stiffness, and strength when considering composites is a relatively limited perspective of the potential of such materials as fiber-reinforced plastics since they often outperform traditional materials such as metals in various ways. Fiber-reinforced polymers are exceptionally resistant to corrosion and exhibit magnetic, electromagnetic properties. As a result, they are employed in chemical plants and other constructions where non-magnetic materials are required. Additionally, carbon fiber reinforced epoxy is utilized in medical applications because of its X-ray transparency. With non-aerospace or non-aviation applications, cost competitiveness with conventional materials became critical. Recently, quality assurance, repeatability, predictability of structure behavior during its life, and recycling have become vital criteria. Composites are used in dishwashers, dryers, freezers, ovens, ranges, refrigerators, and washers in the appliance industry. Throughout the equipment, composites were employed in various components, including consoles, control panels, handles, kick plates, knobs, motor housings, shelf brackets, side trims, and vent trims. Because composites may be made from a range of different materials, they provide designers with more creative freedom. It is also possible to mold complicated structures with the use of composites since they are quickly developed. To satisfy a specific need, materials might be made to order. Most woods and metals are heavier than composite materials; on the other hand, certain metals have a lower density than composite materials. They outlast other materials in terms of toughness. The items are unaffected by extreme weather or strong chemicals. Components made of composites have a long life lifetime and need minimum maintenance. The design options for composite items are almost limitless because of the wide variety of reinforcing materials, matrices, and production techniques available. Composites may be tailored to satisfy the needs of rural areas by selecting a manufacturing method that is more suited to their needs. Composite materials are currently being researched. There is much interest in nanomaterials (materials with very tiny molecular structures) and bio-based polymers. To maximize the advantages of composites, many elements must be taken into consideration: a) idea generation, b) material selection and formulation, c) material design, d) product manufacturing, e) industry and f) laws. [26,27,28].

2.6. Fiber-reinforced polymer composite materials

Composites are made up of fibers embedded in a matrix structure and classed according to the length of the fibers. Continuous fiber reinforcement composites have long fiber reinforcements, while discontinuous fiber reinforcement composites have short fiber reinforcements. The term "hybrid fiber-reinforced composites" refers to materials reinforced with two or more kinds of fibers in a single matrix structure. Fibers may be arranged unidirectionally or bidirectionally in the matrix structure of continuous fiber composites, and they transfer loads exceptionally efficiently and effectively from the matrix to the thread. Discontinuous fibers must be long enough to transmit loads effectively and inhibit the propagation of fractures from preventing material failure in the case of brittle matrices. The arrangement and orientation of fibers in a composite material determine its characteristics and structural behavior. The use of chemically treated natural fibers improves qualities such as impact toughness and fatigue strength. Traditionally, dispersed phase fibers of glass, carbon, basalt, and aramid were employed in fiber-reinforced polymer (FRP) composite materials. Natural fiber polymer composites (NPCs) have significant features that have potential uses in the modern industry since researchers are presently pushed to produce environmentally benign materials in response to rigorous environmental regulations. Numerous fibers are available for composite materials, most of which are classified as Natural or Synthetic fibers [29].

Composite reinforcements come in a variety of shapes and sizes, including fibers, flakes, and particles. Each of these materials contributes unique qualities to composites, and so has a distinct set of uses. Among the many types, fibers are the most frequently utilized in composite applications, and they have the most effect on the composite materials' qualities. These reasons include the high aspect ratio of the fibers' length to diameter, which enables sound shear stress transmission between the matrix and the threads, and the ability to process and produce the composites parts in various forms using various processes. To strengthen polymer matrix composites, a variety of fibers have been used. Carbon fibers (AS4, IM7, etc.), glass fibers (E-glass, S-glass, etc.), aramid fibers (Kevlar® and Twaron®), and boron fibers are the most frequent. For ages, glass fibers have been employed as reinforcement, most notably by Renaissance Venetian glassmakers. Continuous-glass fiber filaments of commercial significance were first made in 1937 by a joint effort between Owens-Illinois and Corning Glass [30].

manufacturing is selecting the suitable fibers and matrixes that provide the desired characteristics for engineering applications. Historically, the qualities of composites such as moisture absorption, tensile strength, compressive strength, and hardness were all considered. This results in significant resource waste, both in terms of money and time. As a result, statistical techniques became advantageous for studying and forecasting the characteristics of the composite material in question. Numerous modern studies have shown the potential for bio fibers such as kenaf, flax, jute, hemp, and sisal to be utilized in place of synthetic fibers such as aramid, carbon fiber, and glass fiber that are often employed in the construction of vehicle components. One of the most frequently utilized natural fibers in a composite structure is a plant fiber composed of cellulose, hemicellulose, lignin, and pectin. Each analytical technique offers distinct advantages that help engineers make informed decisions about matrix, fiber, and end-use application selection. Fiber Reinforced Polymer (FRP) reinforcements for concrete buildings have been extensively examined in several research institutes and professional organizations across the globe. The benefits of FRP reinforcements include corrosion resistance, non-magnetic characteristics, high tensile strength, lightweight, and simplicity of handling. Because of this, brittle failure is often referred to as a linear elastic response in tension up to the point of failure, also known as a brittle failure. They are also vulnerable to fire and high temperatures, making them less durable. Bending weakens them significantly and makes them vulnerable to stress-rupture consequences. They are also more expensive than typical steel reinforcing bars or prestressing tendons in cost per unit weight and force bearing capability. The most crucial structural engineering issues are the lack of plasticity and poor transverse shear strength of FRP reinforcements. The combination of these properties may lead to premature tendon rupture, such as in shear-cracking planes in reinforced concrete beams when dowel action occurs. Due to the force exerted by the dowel, the tendon has less residual tension and shear resistance. Solutions and usage constraints have been provided, and advancements are likely to continue shortly. Increased market shares and demand for FRP reinforcements are predicted to reduce the cost per unit considerably. There are still certain instances when FRP reinforcements are a viable and economically sound alternative to steel. Repairing and reinforcing concrete buildings with bonded FRP sheets or plates and using FRP meshes or textiles or fabrics in thin cement products are examples of these applications. In relative terms, the cost of repairing and restoring a building is always more than the original construction cost. Repairs often need a modest amount of repair supplies but a lot of time and effort to complete. Because labor costs are so high in wealthy nations, the price of raw materials is almost irrelevant. Because of this, Fiber Reinforced Polymers - The Science of Concrete Repair was born. The more cost-effective the repair, the higher its performance and durability must be. This suggests that the cost of FRP repair materials is not a significant constraint in the repair process [31].

Concerns about fossil fuel depletion, air pollution, and acidification related to FRP composite manufacture seem to limit its use as an environmentally viable material. Unlike steel and wood, structural components of FRP composites cannot be reused to fulfill the same function in another construction. A life-cycle study may show that FRP composites can provide direct and indirect advantages over traditional materials regarding environmental effects in infrastructure applications. As composite materials have progressed, so has the technology behind them. On the other hand, composite materials must meet various requirements before being utilized in a sustainable environment. There is a lack of standardized data on FRP composite materials' durability

- Structural mem's service life may be predicted by integrating durability data and methodologies of Composite fibers are made of FRP
- Methods and methodologies for life cycle assessment-based material selection alterations to structural components and systems.
- Composites must be structurally and economically feasible before they can be regarded as a natural alternative [31].

Glass fibers, cloth, mat, or roving contained in an epoxy or polyester resin matrix are the most common fiber-reinforced polymer composites. It is possible to increase the strength and stiffness of thermosetting resins by adding boron, polyamide, or even carbon fiber to them. Compared to steel, carbon-fiber composites have a rigidity five times higher. The exceptional qualities of epoxy and polyester composites make them ideal for a wide range of applications, including modern jet aircraft components, vehicle parts, boat hulls, rocket motor casings, and chemical reaction containers, amongst many others. Although thermosetting resins such as epoxy and polyester resins have the most striking features, numerous thermoplastic resins may also make considerable gains in performance. In addition to polycarbonates and polyethylene, glass-reinforced composition resins include polyesters and polyesters. These thermoplastics have replaced metals for numerous applications due to their low cost and enhanced characteristics thanks to one-step injection molding techniques. Hybrid systems may be developed using different matrix materials, such as polyimide resin, an ideal glass fibers matrix, and a high-performance composite. These include single-crystal ceramic whiskers (such as those made of sapphire) and other metallic fibers, such as polymers [such as poly(vinyl alcohol). Fiber-reinforced composites offer two advantages- They are both a)robust and b)light, making them a perfect match. While steel is frequently more powerful, it is often heavier. For this reason, composites may be utilized to lighten vehicles, hence reducing their fuel consumption significantly [31].

These physical or chemical pretreatments may be applied to fibers to alter the fiber surface and internal structure to increase adhesion at the interface and the incorporation of matrix resins into the fibers. For FRP-confined cylindrical concrete columns, size impact relies on failure mode; there is no side effect if failure is plasticity dominated. Shear banding causes fracture-dominated losses resulting from plastic dilatation in concrete; FRP cylinders of small size fail in giant columns, whereas FRP cylinders of large size succeed. Contained high-strength concrete (HSC) and ultra-high-strength concrete (UHSC) exhibit very ductile compressive behavior when adequately contained. However, if the HSC or UHSC are not properly restricted, the FRP tube-encased or FRP-wrapped specimen's axial compressive performance is degraded. FRP thickness and confinement technique have no impact on the strain reduction factor (k), but k diminishes as substantial compressive strength increases for concrete structures. It is important to note that the cross-sectional shape, specimen size, and manufacturing procedure influence the behavior of concrete-filled fiber-reinforced polymer tubes (CFFT) under concentric compression. Newly designed rectangular and square CFFTs with internal FRP reinforcement demonstrate extremely ductile behavior compared to traditional CFFTs when considering cross-sectional form. Further research has revealed that the compressive behavior of CFFTs is unaffected by the size of the specimen. As a consequence of this link, fibers with a greater modulus of elasticity result in lower strain factors, which more closely mimic concrete brittleness in the fabrication of CFFTs [32,33].

A maleic anhydride-grafted polypropylene composite material (MA-g-PP) of bamboo fibers and polypropylene matrix was utilized as a compatibilizer. It has boosted impact strength by 37%, flexural strength by 81%, flexural modulus by 150%, tensile strength by 105%, and tensile modulus by 191% with the addition of 5 percent MA-g-PP and 50 percent fiber volume in the composites. The heat deflection temperature (HDT) of a chemically treated composite with an MA-g-PP compatibilizer rose by 23 °C to 38 °C when the fiber volume increased from 30% to 50%. As a result, the recommended optimized composition for bamboo fiber-reinforced polypropylene composites is 50% fiber volume, 1–6 mm fiber length, 90–125 m fiber diameters, together with MA-g-PP compatibilizer, which results in a maximum improvement in mechanical properties and higher thermal stability. As GFRP material was removed using CO_2 laser engraving, it was observed that surface roughness and machined depth were heavily dependent on the fiber direction. Composites made from T300 carbon fibers and 7901 epoxy resin to study the mechanical characteristics of uniaxial tension/compression and torsional deformations were fabricated using T300/7901 UD fiber-reinforced composites. It was discovered that matrix plastic deformation had no substantial impact on the projected ultimate load at failure when looking at micrographs of the fiber-matrix interface under various loads. Even with a decrease in fiber angle from 0 to 15 degrees, the final strength decreased significantly. SCF plays a crucial part in the failure prediction, and without it, transverse strength would be exaggerated. Laminated composites with a non-uniform temperature distribution have a higher critical load-bearing capability than curvilinear fiber-reinforced composite laminates with antisymmetric laminates [34].

3. Application of Fiber Reinforced polymer composite materials

3.1. Traditional Components Replaced with FRP Composite Components

Many projected FRP composite bridge applications demand FRP composite components to replace conventional ones. The analysis identifies reinforced-concrete Bridge decking as the most likely bridge component to need replacement owing to deterioration. If the concrete deck is not composite, replacing the deteriorating reinforced concrete deck with FRP is possible.When Utilized with a composite deck, the FRP deck cannot entirely replace the concrete deck's compression force in the positive-moment region. Installing an FRP deck reduces the capacity of the composite positive-moment component unless expensive carbon fibers are used. In new construction, using FRP composite materials may need more enormous girders beneath the deck. Costlier decking and heavier rafters add to the initial expenses associated with using FRP. That does not mean FRP will never replace the existing practice of using composite girders with the deck. Some non-composite construction features, such as toughness, may be overlooked instead of using heavier non-composite beams and an FRP deck. Even incremental material advancements, like the introduction of HPS, need new design concepts and structural forms to utilize the new properties fully. Deflection and fatigue, hitherto unaffected limit conditions, now provide unique cross-sections and design options. While well-established materials like steel are used, the profession is wary of fresh design concepts. [35].

3.2. Application in the civil sector

3.2.1. Bridge System

Recent research has incorporated inorganic/cementitious ingredients to generate fiber-reinforced inorganic polymer (FRP) composites. FRCP replaces epoxy in FRP composite structures to increase fire resistance. It is composed of Portland cement, phosphate-based cement, alkali-activated cement, and magnesium oxy-chloride (MOC). When exposed to fire, FRP maintains around 47% of its strength. Insulation, strength-to-weight ratio, and service life are all advantages of FRP sandwich material. So it has become a great alternative to metallic skins for sandwich composites in structural engineering. As well as bridge beams, decks, multifunctional roofs, cladding and roofing systems for buildings, railway sleepers and floating and protecting structures.

Sprayable ultra-high toughness cementitious composite (UHTCC) is used to build durable concrete buildings and restore old structures like bridges and tunnels. Compared to cast UHTCC, the UHTCC enhanced the durability of concrete structures. The stiffness of RC–UHTCC beams increased with the thickness of the UHTCC layer, successfully controlling the fractures forming in the concrete layer of the beam specimens. FRP composites have been tested as a structural material for bridges. Bridge components such as rafters, decks, and slab-on-girder bridge systems are FRP or FRP–concrete hybrids. The durability of hybrid FRP concrete decks is superior to RC decks. Polymers by the truckloads. Terrorist attacks and natural catastrophes pose unprecedented hazards to public civil infrastructure like bridges. Therefore, their impact and blast-resistant design have become a significant necessity in the design process. FRP has been used to reinforce and increase the impact resistance of RC beams, slabs, columns, and masonry walls. With increased strain rate, materials' load-carrying capacity, flexibility, energy absorption, and tensile strength improve. [36, 37, 38].

Figure 2 Reinforced composite (RC) beams [39].

3.2.2. Earthquake-resistant columns

Concrete-filled FRP tubes as earthquake-resistant columns and seismic retrofit existing RC columns are critical applications for FRP composites. [40].

3.2.3. Concrete slabs

Carbon epoxy and E-glass epoxy composite solutions restored the original capacity and strength of damaged, unreinforced, reinforced concrete slabs. Moreover, using FRP systems improved the structural capacity of unreinforced specimens by 500%, whereas steel-reinforced samples enhanced by 200%. [41, 42].

3.2.4. Sensors

Structural health monitoring (SHM) is a method that uses sensors to monitor the health of civil structures. Sensors, data collecting, and transmission systems are utilized to monitor structural behavior and performance during natural catastrophes like earthquakes. In addition, the SHM system can forecast environmental activities. [43, 44].

3.3. Mechanical

3.3.1. Mechanical gear pair

Polyoxymethylene (POM) reinforced with 28% glass fiber showed a 50% increase in load-bearing capacity and a 50% reduction in specific wear rate when used in mechanical gear pairs .The STE and mesh stiffness curves of a carbon–epoxy prepreg gear pair were equivalent to steel. The results demonstrated a considerable decrease in STE peak-to-peak, which enhanced the material's NVH performance [45].

3.3.2. Pressure vessel

Lightweight materials are in high demand in the automotive sector to improve fuel economy and reduce emissions. For example, FRP composites are used to safely store and transport gaseous fuels like hydrogen, whereas natural gas pressure vessels are used. Compared to metallic containers, FRP composite pressure vessels have higher strength and stiffness, better corrosion resistance, better fatigue strength, and lighter weight. [46].

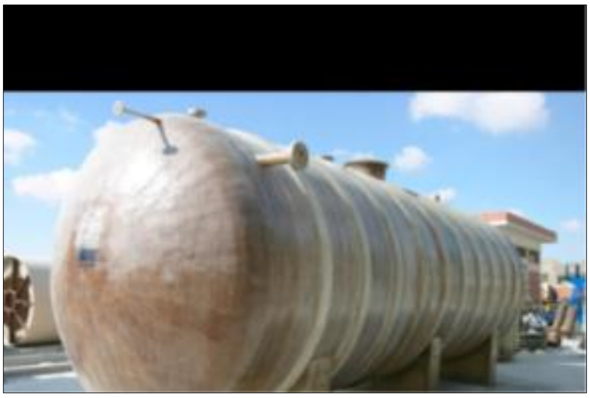


Figure 3 Pressure Vessel made of thermosetting resin, fiberglass reinforcement [47].

3.3.3. Hydraulic Cylinder

A dump truck's hydraulic system transports the earth using a telescopic hydraulic cylinder. A carbon fiber-reinforced epoxy resin composite replaces the steel cylinder, reducing weight by 96%. The hydraulic system was reduced by half when this composite telescopic cylinder was introduced [48].

3.4. Application in Automobile

3.4.1. Automobile Parts

Engine hoods, dashboards, and storage tanks are made with natural fiber reinforcements, including flax, hemp, jute, sisal, and ramie. Liability is assessed utilizing structural and impact stress analysis for these composite constructions made using the VARTM manufacturing technique. The outcome was a lighter material with improved stability and strength. Based on HIC testing, it was determined that composite constructions with natural fiber reinforcements are suitable for vehicle body components. [49].

3.4.2. Door Panel

Bamboo fibers boost the cell wall thickness of polyurethane composite constructions, improving sound absorption coefficient in car door panels [50].

3.4.3. Interior structures

The hybrid system comprises biodegradable natural fibers used as sound and vibration absorbers in automotive interiors. [51, 52].

3.5. Application in Aerospace

Due to its superior mechanical, tribological, and electrical qualities, FRP composite materials may be used in the aerospace industry to provide highly durable, thermally resistant, lightweight materials for aircraft construction. There are several advantages to using natural fiber-reinforced thermoset and thermoplastic skins for airplane interior panels, such as resilience to heat and flame, ease of recycling, lower weight, and lower cost. Even though FRP composites may be used in a wide range of aircraft applications because of their excellent mechanical qualities and lightweight construction, recycling them is a problem. Biodegradability and cheaper natural fiber/biocomposite materials have opened up new opportunities in the aerospace sector. [53,54].

3.6. Marine

For maritime applications, saltwater aging degrades the mechanical characteristics of all sorts of metals, alloys, and composites. The hybrid glass–carbon fiber–reinforced polymer composites (GCG2C) have a high flexural strength of 462 MPa and the slightest inclination to absorb water. As a result, the mechanical characteristics of hybrid (GCG2C)s composites are more stable. Moisture absorption qualities of fiber composites are determined by their structural or chemical makeup, allowing for various maritime applications. When exposed to a marine ecosystem, water molecules are absorbed into the material structure through diffusion. May use weight growth over time may be used to monitor diffusion in the material structure. The amount of water absorbed is proportional to the material's coefficient of distribution. While the diffusion coefficient is lower in composite materials, it depends on various variables such as the matrix material, the reinforcing material, and the manufacturing method. Moisture absorption leads to a lack of adhesion between the fiber and matrix in the composite structure, weakening the composite material's characteristics in the process. CFRP marine propellers have superior mechanical features such as a high strength-to-weight ratio, resistance to corrosion, fatigue, and temperature variations while requiring less maintenance. These characteristics make CFRP an ideal material for propellers in maritime applications. Hull Sandwich composite panels with glass or carbon fiber coverings and a polymeric core have been utilized to build whole hulls and marine craft structures [55,56,57].

3.6.1. Challenges in Fabricating FRC

A significant obstacle in producing FRC materials is a lack of knowledge on fiber-matrix characterization.

To use FRPCs in various disciplines, they must grasp their constituents' significant material qualities, fundamental structures, and the availability of manufacturing technology. For instance, to fabricate nanocomposites, one must acquire nanotechnology and the necessary tools and equipment. Additionally, the manufacturing technique used affects the ultimate qualities of the material. The amount of production affects the cost—the greater the volume of production, the lower the material cost. In the case of the car industry, increasing production volume entails a more considerable risk of investing in raw materials and creating a manufacturing setup following production rate and cycle time. Additionally, the intricacy of the product's design increases the cycle time, decreasing the manufacturing pace. The growing need for high-performance composites in aerospace and structural applications has accelerated the usage of petroleum-based materials, posing the problem of composite waste management. However, numerous researchers are now producing a variety of biocomposites based on natural fibers and bio-based polymers; however, not all of them are biodegradable.

3.6.2. High-performance fiber-reinforced composites

High-performance composites (HPCs) are extensively utilized as advanced materials. They are formed of reinforcement (fibers, particles, fillers, etc.) and matrix (polymers, metals, ceramics, etc.). The orientation of continuous fiber reinforcements principally determines strength and modulus. In HPC, fiber reinforcements are spun from a variety of materials, including carbon, glass, and aramid, as well as ultrahigh-molecular-weight polyethylene (UHMWPE), ceramic, quartz, boron, and novel polymers such as poly (p-phenylene benzothiazole) (PBO). In HPC, the matrix is composed chiefly of polymers, such as epoxy resin, Bakelite resin, and unsaturated polyester resin. The matrix stabilizes the reinforcement, allowing it to take on the required shape, while the reinforced material enhances the material's overall qualities. Due to its superior attributes, lightweight, and cheap cost, high-performance composites have been extensively employed in aviation, aerospace, transportation, and military defense, among other applications. They have gradually supplanted conventional materials such as certain metals and their alloys. This research study reviews high-performance fibers and their performance, high-performance resins, production processes, mechanical characteristics, and applications of high-performance composites [58].

3.6.3. High-Performance Fibers

High-performance fiber is designed for a particular application requiring high levels of tensile strength, thermal stability, chemical resistance, and other performance-enhancing properties. Fibers come in many shapes and sizes, with a broad range of qualities. High-performance fibers are a specialized industry, although some are mass-produced in the overall fiber market. High modulus (>440 CN/dtex), high strength (>17.6 CN/dtex), or high heat resistance (>200 C) are all characteristics of HPC's high-performance fibers. Preforms, such as textile structures, are often produced from fibers in HPC to boost manufacturing efficiency.

Properties of High-Performance fiber: [59].

- The stiffness-to-weight ratio is quite high.
- Extremely powerful
- Corrosion-proof
- Exhaustion-proof
- Effect of Impact on Energy absorption
- The ability to withstand higher temperatures
- The ability to withstand chemicals

3.6.4. Types of High-Performance Fibers

Carbon fiber

- In 1963, the Royal Aircraft Establishment created the first carbon fiber, UK
- Other words, carbon fiber includes 90% carbon.
- It has a high degree of flexural and torsional stiffness

Carbon fiber is made from PAN, cellulose fiber, pitch fiber, and phenolic fiber precursors. It primarily consists of four stages:

- Production of the precursors
- Thermal stability between 100 and 4000 degrees Celsius
- Between 700 and 15000 degrees Celsius, carbonization occurs
- Graphitization at temperatures ranging from 1500 to 30000 degrees Celsius [60].

Carbon fibers come in a variety of forms

- Extremely high elasticity (500GPA)
- High elasticity (300-500GPA)
- The modulus in the middle (300GPA)
- Intensely low modulus (less than 100GPA).
- It has a lot of strength [60].

Carbon Fiber's properties

- G/cc Density: 1.81-1.96 • 22gpd of tenacity
- Lengthening: 0.38-1.8%
- 1500-3000 gpd is the recommended range for the modulus
- High resilience to wear and tear
- Vibration absorption is excellent
- The ability to conduct electricity well
- A high level of chemical resistance
- almost two-thirds Strongly fragile High
- •susceptibility to damage
- Low resistance to abrasion
- 0% is the strength of the loop [60].

Applications of Carbon Fiber

- Aerospace
- Road & marine transport
- Automobile hood
- Aircraft brakes
- Nuclear field
- Textile machinery
- Medical application

Carbon fiber has several outstanding features, including high tensile strength, a high tensile modulus, a low density, resistance to high temperatures, chemical corrosion, a high thermal conductivity coefficient, strong radiation resistance, and low expansion. Carbon fiber operates at temperatures ranging from 170 to 2,000 degrees Celsius. Except for a few strong oxidants, carbon fiber is impervious to the majority of acids and alkalis. Carbon fiber is very resistant to low temperatures and is not brittle at liquid nitrogen temperatures [60].

Carbon fiber disadvantages

Carbon fiber, on the other hand, has several drawbacks. Carbon fiber's exorbitant cost has kept it out of the hands of a broader audience than glass fiber. The carbon fiber intoxication at high temperatures is also poor. In the presence of oxygen, carbon dioxide is created at high temperatures. When bent and wound, carbon fiber is brittle and easily broken [60].

3.7. Aramid

It is a nylon that is very scented. The molecules contain a benzene ring. DuPont developed this aramid fiber to create a robust, high-temperature-resistant fabric. In 1960, Nomex developed the first aramid fiber.

The following fibers are commercially available:

- DuPont USA.
- Nomex® fiber
- Kevlar® fiber
- Teijin co Japan
- Technora® fiber
- Teijin Conex® fiber
- Twaran® fiber

3.7.1. Aramid fibers' fundamental structure and chemical content

1, 4-phenyl-diamine (para-phenylenediamine) and terephthaloyl chloride are the monomers of aramid fibers. Consequently, a polymeric aromatic amide is formed, with the benzene ring and amide groups changing. When they manufactured these polymer strands, they did it randomly. Aramid fibers are technically long-chain synthetic polyamides. Due to the extraordinary tensile strength of aramid fibers is often utilized in armor and ballistic protection applications. Aramid fibers, which have a characteristic yellow tint, are commonly used in innovative composite goods that demand great strength and lightweight. Aramid is composed of poly para-phenyleneterephthalamide (PPD-T) and is more correctly referred to as a para-aramid. It consists of para-substituted aromatic units that are orientated. Aramids are a kind of nylon. The para-aramid difference is critical because standard nylons, such as nylon 6,6, lack superior structural characteristics. However, aramid fibers such as Nomex or Kevlar are ring compounds based on the structure of benzene, not linear combinations like nylon. Thermal aramid is stable because of the aramid ring, while the para structure provides strength and modulus. Aramid filaments, like nylon filaments, are manufactured by extruding the precursor via a spinneret. Kevlar fibers are anisotropic due to the rod shape of the para-aramid molecules and the extrusion process; they are more robust and stiffer in the axial direction than in the transverse direction. On the other hand, graphite fibers are anisotropic, while glass fibers are isotropic. [61].

It is synthesized by condensing para-phenylenediamine and terephthaloyl (PPD-T) chloride. The resulting aromatic polyamide has aromatic and amide groups, giving it a rod-like structure. Due to the stiff rod-like structure, these polymers have a high glass transition temperature and low solubility, making manufacturing problematic using traditional drawing processes. Rather than that, as discussed later, they are melt-spun from liquid crystalline polymer solutions. The Kevlar fiber is an arrangement of parallel molecules, similar to a packet of uncooked spaghetti. A crystalline structure is an organized, untangled arrangement of molecules. Crystallinity is achieved using a manufacturing technique called spinning, in which the molten polymer solution is extruded through microscopic pores. When PPD-T solutions are extruded via a spinneret and dragged through an air gap to produce fibers, the liquid crystalline domains may orient and align in the flow direction. Kevlar can align long, straight polymer chains parallel to the fiber axis to a great degree. The structure is isotropic, with greater strength and modulus along the fiber's longitudinal axis than its axial axis. Additionally, the extruded material has a febrile design. This structure results in aramid composites with poor shear and compression characteristics. Hydrogen bonds develop between neighboring polar amide groups and keep the Kevlar polymer chains together. [61].

3.7.2. Aramid fibers provide several advantages

The primary benefits of Aramid are its high strength and lightweight. As with graphite, it possesses a slightly negative axial coefficient of thermal expansion, which enables the fabrication of thermally stable aramid laminates. Unlike graphite, it is very resistant to damage from impact and abrasion. When mixed with other materials such as epoxy, it may be rendered waterproof. It may be utilized as a composite material while preserving the elasticity of rubber. Its high tensile modulus and low breaking elongation, and excellent chemical resistance make it the ideal material for various composite structural components in multiple applications [61].

3.7.3. Aramid fiber disadvantages

Aramid fiber, on the other hand, has a few downsides. Due to the fibers' ability to absorb moisture, aramid composites are more environmentally sensitive than glass or graphite composites. As a result, it must be used in conjunction with moisture-resistant materials such as epoxy systems. Additionally, the compressive characteristics are poor. As a result, aramid fiber is not employed in bridge construction or anywhere else where this resistance level is required. Additionally, aramid fibers are difficult to cut and grind (e.g., special scissors for cutting, special drill bits). Finally, aramid is corrupted and degraded by ultraviolet radiation. As a result, they must be well coated [61].

3.7.4. Aramid Fiber Applications

- It is often utilized to strengthen polymer matrix composites using fibers.
- Applications for ballistic protection, such as bulletproof vests.
- Protective clothes such as gloves, motorcycle protective clothing, gaiters, chaps, and trousers for hunting.
- Sails for sailboats, yachts, and similar vessels.
- Industrial and automotive belts and hoses.
- Components of aircraft bodies.
- Seaworthy boat hulls.
- Cables made of fiber optics and electromechanical components [61].

3.8. Kevlar

3.8.1. Fibers made of KEVLAR

- It is a DuPont synthetic fabric that was initially developed in 1965.
- In addition to amide molecular groups, it has aromatic molecular groups
- Polymer chains are held together by hydrogen bonds formed by amide groups.
- The radial orientation of the Aromatic component offers an even greater degree of symmetry and structural strength to the fibers' interior structure.
- Spun fibers have polymer chains aligned parallel to the fiber axis in a crystalline configuration [62,63].

3.8.2. Kevlar Fiber's applications

- The armor system
- Reinforcement using rubber
- Cables and ropes
- Composites
- Bio-medical and electronic applications. [62,63].

3.8.3. Advantages of using Kevlar

- Steel wire has a lower tensile modulus
- Tenacity until the breaking point
- Extremely efficient use of kinetic energy
- Strength of 4-5 times that of steels
- tensile modulus is substantially greater than that of steel wire [62,63].

3.9. High-performance polyethylene

- It is a fiber made of thermoplastic plastic.
- It possesses extraordinarily long chains with millions of molecular weights, often between 3.1 and 5.67 million.
- Gel spinning technology was used to create this product.

- UHMWPE is made by covalently bonding ethylene monomers to generate ultra-high molecular weight polyethylene.
- UHMWPE molecules typically include between 100,000 and 250,000 monomers [64].

3.9.1. Applications of Polyethylene Fibers

- The use of prostheses
- Wire ropes and marine ropes
- Sailors use linen to cover their sails.
- Composite material is used in pressure vessel boat hulls, sports equipment, and impact shields.
- Netting to catch fish
- Reinforcement of concrete
- Clothes are designed to keep you safe.
- Its low dielectric constant makes it suitable for use in radar shielding.
- An industrial pond may be lined with this product to capture water that evaporates and to contain waste from the facility [64].

4. Conclusion

Most high-performance fibers are more costly than standard fibers, but the extra value they provide to the finished product makes up for the cost difference. The high-performance fibers are still predominantly produced in Europe, the United States, and Japan, despite paying for these materials. High-performance fiber is stiffer than regular performance fiber has more elastic behavior than standard fiber. It also has correct fiber and fibril alignment (greater axial orientation) throughout the structure. In the polymeric chain system of these fibers, there is no deformation. In certain ways, high performance fiber has more elastic behavior than standard fiber.

Compliance with ethical standards

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All authors state that there is no conflict of interest.

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