Natural Fibre Composites and their Applications in Aerospace Engineering

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Abstract

Fiber- reinforced polymer composite materials are fast gaining ground as preferred materials for construction of aircrafts and space crafts. In particular, their use as primary structural materials in recent years in several technology- demonstrator front - line aerospace projects worldwide has provided confidence leading to their acceptance as prime materials for aerospace vehicles. Fibre polymer composites alongside aluminium alloys are the most used materials in aircraft structures. The use of composites in civil aircraft, military fighters and helicopters has increased rapidly since the 1990s, and it is now competing head-to-head with aluminium as the material of choice in many airframe structures. The use of composites in gas turbine engines for both civil and military aircraft is also growing. The main reasons for using composites are to reduce weight, increase specific stiffness and strength, extend fatigue life, and minimise problems with corrosion.

12.1 Introduction

Fibre reinforced polymer (FRP) composites are the most promising and elegant materials of the present century. Their durability and integrity in various service environments can be altered by the response of its constituents i.e., fibre, polymer matrix, and the existing interface/interphase between the fibre and polymer matrix, in that particular environment. Their susceptibilities to degradation are dependent on the nature of environment and the different and unique responses of each of the constituents. All these structures and components are exposed to some environment during their service life. The environmental conditions can be high and low temperatures, high humidity, UV light exposure, alkaline environment and may be more severe if there is a cyclic variation of temperature, hygrothermal environment and low earth orbit space environment [1]. A widespread application spectrum of FRPs covers almost every type of advanced engineering structures. Their usage includes various components in aircraft, helicopters, spacecraft, boats, ships, offshore platforms and also in automobiles, chemical processing equipment, sports goods, and civil infrastructure such as buildings and bridges [2]. The behavior and performance of advanced structural FRP composites cannot be explained only in terms of specific properties of its constituent fibre and matrix but the existing interface/ interphase between fibre and matrix has a great significance as well [3,4]. The presence of moisture at the interface canmodify interfacial adhesion thereby affecting the mechanical performance of the FRP composites. The energy associated with UV radiation is capable of dissociating the molecule bonds in the polymer matrix and may lead to the degradation of the materials. The border surface between the fibre and the matrix is a result of the linking of constituents; it has its own morphology and chemistry and represents the critical area in fibre-reinforced composites [3,5,6].

Composite materials have gained popularity (despite their generally high cost) in high performance products that need to be lightweight, yet strong enough to take high loads such as aerospace structures (tails, wings and fuselages), boat construction, bicycle frames and racing car bodies. Other uses include storage tanks and fishing rods. Natural composites (wood and fabrics) have found applications in aircraft from the first flight of the Wright Brothers' Flyer 1, in North Carolina on December 17, 1903, to the plethora of uses now enjoyed by man-made (engineered) composite materials on both military and civil aircraft, in addition to more exotic applications on unmanned aerial vehicles (UAVs), space launchers and satellites. Their adoption as a major contribution to aircraft structures followed on from the discovery of carbon fibre at the Royal Aircraft Establishment at Farnborough, UK, in 1964. However, not until the late 1960s did these new composites start to be applied, on a demonstration basis, to military aircraft. Examples of such demonstrators were trim tabs, spoilers, rudders and doors. The most common use for polymers is the matrix phase of fibre composites. Polymers are the 'glue' used to hold together the high-stiffness, high-strength fibres in fibre–polymer composites. Early manufacturing processes for lightly stressed components were small scale, involving significant elements of manual intervention in the process. They relied on the low density and high stiffness and strength of the raw materials to deliver the required performance. As the size, stress values and criticality of the parts all increased, manual input has declined dramatically, substituted by complex, sophisticated robotic machinery. The robots have delivered consistency, freedom from defects and increased processing speed to cope with manufacture of wings and fuselage sections of large civil aircraft. However, the essentials of this prepreg route have remained unchanged, and there are still issues of the cost effectiveness of this route. In parallel, manufacturing researchers are pursuing lower cost options. In this chapter the prepreg route in its various guises will be described and the state of the art in alternative processes contrasted with it. In the past, the principal drivers for the use of fiber reinforced composites for aircraft components were:

• Reduced weight

• Cost reduction

• Improved performance

The emphasis has now shifted towards environmental issues. Hence the prime driversare now:

• Reduced fuel burn

• Reduced pollution

• Reduced noise

Taylor [7] states that 'increasing the use of composites to replace aluminium in the manufacture of airframes brings about numerous performance advantages such as the potential for weight reduction (due to higher specific strength and modulus), increased flexibility of design (due to the ability to build performance in specific directions), greater corrosion resistance and improved fatigue resistance. Weight reduction leads to improved fuel efficiency'. Furthermore, the reduced number of fasteners on a composite structures give a more aerodynamic surface to the aircraft compared to riveted aluminium. One of the major difficulties associated with composite manufacture is that of void formation during impregnation and cure [8]. As these gaseous voids become entrapped within the matrix, stress concentrations can be established within the matrix. These may originate in a number of ways, including:

• During mixing of the resin formulation.

• During filling of the cavities in components of more complex shape.

• Due to the complex nature of the textile reinforcement since air can become entrapped in the interstices of the fabric structure. This can be particularly evident when coarse yarns (or tows) are used or in complex three-dimensional (3-D) structures, e.g. braided or woven, and may be most prevalent at the tool/composite interface.

• During the complex chemical reactions which take place during the cure of thermosetting resins, as volatile gases are released and become encapsulated in the cross-linked resin [9].

A critical requirement of any process is that it is able to minimise void formation and ensure uniform distribution of resin as well as fibres throughout the component. These are major factors, alongside cost and flexibility in manufacturing different types of component, in assessing the merits of any particular manufacturing technique. These process variations must be understood at the design stage.

Launching a heavy lift system into low Earth and geosynchronous orbits generally costs €5000–15 000/kg and €28 000/kg, respectively. Because of increasing oil and gas prices, the demand for lightweight materials in the aerospace industry is tremendous. Even in general aviation, fuel costs account for around 50% of the operational costs. Consequently, over the last three decades, the usage of fibre-reinforced polymer (FRP) composites in these applications has increased from less than 5% by structural weight (Boeing 737) to 50% (Boeing 787), contributing over 20% more fuel efficiency.

12.2 Advantages of natural fiber composites

Natural fibres are an abundant and renewable resource, so their cost is relatively low compared with other conventional fibres. They are eco-friendly and biodegradable, and reduce the problem of solid waste production when used to replace non-degradable fillers. Due to their inherent properties, natural fibres are flexible. Because of their non-abrasive behaviour, the filler loading within the polymer matrix can be used in larger quantities than non-organic fillers as it is unlikely to cause damage to machinery or health during manufacturing. Natural fibres possess many advantages, such as low density, and relatively high mechanical properties, such as specific modulus and specific strength natural fibres have recently become more attractive to researchers as an alternative reinforcement for fibre-reinforced polymer. They are extracted from renewable sources and provide a new generation of reinforcements for polymer materials. These eco-efficient fibres have been used as substitutes for glass fibre and other synthetic polymer fibres in diverse applications. Natural fibre composites help to preserve non-renewable resources, which are the main source for most materials used in current applications. Natural fibre based materials are produced in smaller quantities than petroleum based products and their applications are directed towards different area. Natural fibres have a low density and can provide reinforcement capable of imparting high specific mechanical properties to a composite when compared with many synthetic fibres such as glass, carbon and Kevlar in advanced applications. As natural fibres are derived from renewable natural resources, their production requires less energy. They also eliminate many of the problems related to environmental degradation, which means that the disposal of natural fibre composites (NFCs) is easier, safer and less expensive when compared with advanced fibre composites. NFCs also provide impressive acoustic absorption properties, which are useful in building construction. Energy consumption for the pre- and post-harvesting/cultivation facets of the natural fibre separation process is lower than that of synthetic fibre production processes. The principal advantages of using natural fibres in composites are therefore lower cost, sustainability and low density.

The fibres are very often surface treated during manufacture to prepare adhesion with the polymer matrix, whether thermosetting (epoxy, polyester, phenolic and polyimide resins) or thermoplastic (polypropylene, Nylon 6.6, PMMA, PEEK). The fibre surface is roughened by chemical etching and then coated with an appropriate size to aid bonding to the specified matrix. Whereas composite tensile strength is primarily a function of fibre properties, the ability of the matrix to both support the fibres (required for good compression strength) and provide out-of-plane strength is, in many situations, equally important. The aim of the material supplier is to provide a system with a balanced set of properties. While improvements in fibre and matrix properties can lead to improved lamina or laminate properties, the all-important field of fibre-matrix interface must not be neglected. The load acting on the matrix has to be transferred to the reinforcement via the interface. Thus, fibres must be strongly bonded to the matrix if their high strength and stiffness are to be imparted to the composite. The fracture behaviour is also dependent on the strength of the interface. A weak interface results in a low stiffness and strength but high resistance to fracture, whereas a strong interface produces high stiffness and strength but often a low resistance to fracture, i.e., brittle behaviour. Conflict therefore exists and the designer must select the material most nearly meeting his requirements. Other properties of a composite, such as resistance to creep, fatigue and environmental degradation, are also affected by the characteristics of the interface. In these cases the relationship between properties and interface characteristics are generally complex, and analytical/numerical models supported by extensive experimental evidence are required.

Fibre Reinforced Polymer (FRP) composites are prone to damage from the initiation and propagation of delaminations (i.e. areas in which separation occurs in the polymer-matrix resin in which the fibres are embedded). Delaminations may also occur between the polymer and fibre layers in the form of fibre-matrix debonding. In FRP composites, delaminations are hence located in planes defined by the fibre layup, and they propagate or grow in these planes if the applied stresses are large enough [10,11]. Initiation of delaminations is typically caused by impact followed by propagation and growth due to cyclic thermo-mechanical service loads or results from manufacturing defects. Another source of delamination initiation is machining (e.g. cutting) of FRP composites, as discussed in detail by Lasri et al. [12].

Refinements in fibre process technology over the past 20 years have led to considerable improvements in tensile strength (w4.5 GPa) and in strain to fracture (more than 2%) for PAN-based fibres. These can now be supplied in three basic forms, high modulus (HM, w380 GPa), intermediate modulus (IM, w290 GPa) and high strength (HS, with a modulus of around 230 GPa and tensile strength of 4.5 GPa). The more recent developments of the high strength fibres have led to what are known as high strain fibres, which have strain values of 2% before fracture. The tensile stress strain response is elastic up to failure, and a large amount of energy is released when the fibres break in a brittle manner. The selection of the appropriate fibre depends very much on the application. For military aircraft, both high modulus and high strength are desirable. Satellite applications, in contrast, benefit from use of high fibre modulus improving stability and stiffness for reflector dishes, antennas and their supporting structures [12]. One advantage of fabrics for reinforcing purposes is their ability to drape or conform to curved surfaces without wrinkling. It is now possible, with certain types of knitting machine, to produce fibre performs tailored to the shape of the eventual component. Generally speaking, however, the more highly convoluted each filament becomes, as at crossover points in woven fabrics, or as loops in knitted fabrics, the lower its reinforcing ability.

12.3 Types of natural plant fiber

There are six basic types of natural fibers. They are classified as follows: bast fibers (jute, flax, hemp, ramie and kenaf), leaf fibers (abaca, sisal and pineapple), seed fibers (coir, cotton and kapok), core fibers (kenaf, hemp and jute), grass and reed fibers (wheat, corn and rice) and all other types (wood and roots). The natural fiber reinforced polymer composite’s performance depends on several factors, including fibers chemical composition, cell dimensions, microfibrillar angle, defects, structure, physical properties, and mechanical properties, and also the interaction of a fiber with the polymer. In order to expand the use of natural fibers for composites and improved their performance, it is essential to know the fiber characteristics. The hydrophilic nature of fibers is a major problem for all cellulose-fibers if used as reinforcement in hydrophobic plastics such as PP, PE etc. The moisture content of the fibers is dependent on the content of non-crystalline parts and the void content of the fibers. Overall, the hydrophilic nature of natural fibers influences the mechanical properties. The main disadvantages of natural fibers in reinforcement to composites are the poor compatibility between fiber and matrix and their relative high moisture absorption. Therefore, natural fiber modifications are considered in modifying the fiber surface properties to improve their adhesion with different matrices. An exemplary strength and stiffness could be achieved with a strong interface that is very brittle in nature with easy crack propagation through the matrix and fiber. The efficiency of stress transfer from the matrix to the fiber could be reduced with a weaker interface.

Traditional fiber-reinforced composites use various types of glass, carbon, aluminum oxide, and many others as reinforcing component. Natural fibers, especially bast (bark) fibers, such as flax, hemp, jute, henequen and many others were applied by some researchers as fiber reinforcement for composites in recent years. [13-16]. Advantages of natural fibers over man-made fibers include low density, low cost, recyclability and biodegradability [17–19]. These advantages make natural fibers potential replacement for glass fibers in composite materials. Mechanical properties of natural fibers, especially flax, hemp, jute and sisal, are very good and may compete with glass fiber in specific strength and modulus [20,21]. Table 1 lists the mechanical properties of some natural and man-made fibers. Natural fiber-reinforced composites can be applied in the plastics, automobile and packaging industries to cut down on material cost [22].

Fiber	Density (g/cm^3)	Elongation (%)	Tensile strength (MPa)	Young's modulus (GPa)
Cotton	1.5–1.6	3.0–10.0	287–597	5.5–12.6
Jute	1.3–1.46	1.5–1.8	393–800	10–30
Flax	1.4–1.5	1.2–3.2	345–1500	27.6–80
Hemp	1.48	1.6	550–900	70
Ramie	1.5	2.0–3.8	220–938	44–128
Sisal	1.33–1.5	2.0–14	400–700	9.0–38.0
Coir	1.2	15.0–30.0	175–220	4.0–6.0
Softwood kraft	1.5	–	1000	40.0
E–glass	2.5	2.5–3.0	2000–3500	70.0
S–glass	2.5	2.8	4570	86.0
Aramide (normal)	1.4	3.3–3.7	3000–3150	63.0–67.0
Carbon (standard)	1.4	1.4–1.8	4000	230.0–240.0

In order to expand the use of natural fibers for composites and improved their performance, it is essential to know the fiber characteristics. The physical properties of each natural fiber are critical, and include the fiber dimensions, defects, strength and structure. There are several physical properties that are important to know about for each natural fiber before that fiber can be used to reach its highest potential. Fiber dimensions, defects, strength, variability, crystallinity, and structure must be taken into consideration. An exemplary strength and stiffness could be achieved with a strong interface that is very brittle in nature with easy crack propagation through the matrix and fiber. The efficiency of stress transfer from the matrix to the fiber could be reduced with a weaker interface. Physical methods include stretching, calendaring, thermo treatment, and the production of hybrid yarns for the modification of natural fibers. Physical treatments change structural and surface properties of the fiber and thereby influence the mechanical bonding of polymers. Physical treatments do not extensively change the chemical composition of the fibers. Therefore the interface is generally enhanced via an increased mechanical bonding between the fiber and the matrix. Cellulose fibers, which are strongly polarized, are inherently incompatible with hydrophobic polymers due to their hydrophilic nature. In many cases, it is possible to induce compatibility in two incompatible materials by introducing a third material that has properties intermediate between those of the other two. There are several coupling mechanisms in materials (e.g., weak boundary layers, deformable layers, restrained layers, wettability, chemical bonding, and acid–base effect). The development of a definite theory for the mechanism of bonding using coupling agents in composites is a complex problem. The main chemical bonding theory alone is not sufficient. So the consideration of other concepts appears to be necessary. These include the morphology of the interphase, the acid–base reactions in the interface, surface energy and the wetting phenomena.

12.4 Types of matrices

High temperature polymer blends (HTPBs) are typically used at $T \geq 140°C$ and maintain at least 25% of their room temperature (RT) properties at 154°C. Considering their expanding applications in such sectors as the military, aerospace, transportation, electronic, healthcare, and oil and gas industries, they need to have good processability, high mechanical performance, chemical resistance, fire retardancy etc. FRPs are very sensitive to intrinsic damage such as delamination (in particular), matrix cracking and fatigue damage. Several approaches have been adopted to tackle these, which include:

- improving the fracture toughness of the ply interfaces via epoxy/elastomer blends and
- reducing the mismatch of elastic properties (and stress concentrations) at the interfaces between the laminated plies

These materials also lack other required functional properties such as high electrical and thermal conductivity for electrostatic dissipation and lightning strike protection. Currently, it is believed that the best route to achieve multifunctional properties in a polymer is to blend it with nanoscale fillers. This is because of the three main characteristics of polymer nanocomposites:

1. reduced nanoscopic confinement of matrix polymer chains;
2. variation in properties of nanoscale inorganic constituents; many studies have reported that the mechanical, conductivity, optical, magnetic, biological and electronic properties of several inorganic nanoparticles significantly change as their size is reduced from the macroscale to the microlevel and nanolevel; and
3. nanoparticle arrangement and creation of a large polymer/particle interfacial area.

Composites are used in the airframe and engine components of modern military and civilian aircraft, with polymers accounting for 40–45% of the total volume of the material. Moulded plastics and fibre–polymer composites are used extensively in the internal fittings and furniture of passenger aircraft.

Another important application of polymers is as an adhesive for joining aircraft components. It is possible to produce high strength, durable joints using polymer adhesives without the need for fasteners such as rivets and screws. Adhesives are used to join metal-to-metal, composite-to-composite and metal-to-composite components. For example, adhesives are used to bond ribs, spars and stringers to the skins of structural panels used throughout the airframe. Adhesives are also used to bond face sheets to the core of sandwich composite materials and to bond repairs to composite and metal components damaged during service. Thin layers of adhesive are used to bond together the aluminium and fibre–polymer composite sheets that produce the fiber–metal laminate called GLARE, which is used in the Airbus 380 fuselage. The use of elastomers is usually confined to nonstructural aircraft parts that require high flexibility and elasticity, such as seals and gaskets. Polymers possess several properties that make them useful as aircraft materials, including low density (1.2–1.4 g cm–3), moderate cost, excellent corrosion resistance, and high ductility (except thermosets). Some polymers are tough and transparent which makes them suitable for aircraft windows and canopies. However, polymers cannot be used on their own as structural materials because of their low stiffness, strength, creep properties and working temperature.

Fig: Comparison of the advantages and disadvantages of polymers for aircraft structural applications [10].

Thermoplastic	Thermoset	Elastomer
Advantages		
• Non-reacting; no cure required • Rapid processing • High ductility • High fracture toughness • High impact resistance • Absorbs little moisture • Can be recycled	• Low processing temperature • Low viscosity • Good compression properties • Good fatigue resistance • Good creep resistance • Highly resistant to solvents • Good fibre wetting for composites	• Low processing temperature • High ductility and flexibility • High fracture toughness • High impact resistance
Disadvantages		
• Very high viscosity • High processing temperature (300–400 °C) • High processing pressures • Poor creep resistance	• Long processing time • Low ductility • Low fracture toughness • Low impact resistance • Absorb moisture • Limited shelf life • Cannot be recycled	• Long processing times • Poor creep resistance • Low Young's modulus • Low tensile strength

Epoxy resin is the most common thermosetting polymer used in aircraft structures. Epoxy resin is used as the matrix phase in carbon-fibre composites for aircraft structures and as an adhesive in aircraft structural joints and repairs. There are many types of epoxy resins, and the chemical structure of an epoxy resin often used in aerospace composite materials. Epoxy resins are the polymer of choice in many aircraft applications because of their low shrinkage and low release of volatiles during curing, high strength, and good durability in hot and moist environments. Epoxy resin is used extensively in aircraft composite structures, but cannot be safely used inside cabins because of its poor fire performance. Most epoxy resins easily ignite when exposed to fire, and release copious amounts of heat, smoke and fumes. Federal Aviation Administration (FAA) regulations specify the maximum limits on heat release and smoke produced by cabin materials in the event of fire, and most structural-grade epoxy resins fail to meet the specifications. Phenolic resins meet the fire regulations, and most of the internal fittings, components and furniture in passenger aircraft are made of fibreglass–phenolic composite and moulded phenolic resin[23]. The use of thermoplastics in aircraft, whether as the matrix phase of fibre– polymer composites or as a structural adhesive, is small compared with the much greater use of thermosets. Some sectors of the aerospace industry are keen to increase the use of thermoplastics in composite materials, and the number of applications is gradually increasing. Thermoplastics provide several important advantages over thermosets when used in composite materials, most notably better impact damage resistance, higher fracture toughness and higher operating temperatures. However, thermoplastics must be processed at high temperature that makes them expensive to manufacture into aircraft composite components. Several types of thermoplastics are transparent, tough and impact resistant which makes them well suited for aircraft windows and canopies. The thermoplastics most often used in aircraft windows are acrylic plastics and polycarbonates. Acrylic plastics are any polymer or copolymer of acrylic acid or variants thereof. An example of acrylic plastic used in aircraft windows is polymethyl methacrylate (PMMA), which is sold under commercial names such as Plexiglas and Perspex. Acrylic plastics are lighter, stronger and tougher than window glass. Polycarbonates get their name because they are polymers having functional groups linked together by carbonate groups (—O—(C==O)—O—) in the long molecular chain. Polycarbonates are stronger and tougher than acrylic plastics and are used when high-impact resistance is needed, such as cockpit windows and canopies. In these applications, the material must have high impact resistance because of the risk of collision with birds. Although bird strikes do not occur at cruise altitudes, they present a serious risk at low altitudes, particularly during take-off and landing. Polycarbonate windscreens are also resistant to damage by large hailstones.

Hail damage to cockpit window

Bird hit damage on aircraft window

Elastomers are not suitable for use in aircraft structures because they lack stiffness and strength, but they do have exceptionally high elasticity with elongation values between one hundred and several thousand percent. This makes elastomers suitable when low stiffness and high elasticity is required, such as aircraft tyres, seals and gaskets. Many aircraft components that require a tight seal, such as window and door seals, use elastomers. These materials are used for their excellent elasticity; they can be easily compressed to make a tight seal without being damaged or permanently deformed. Although elastomers usually work well as seals and gaskets, they can gradually erode and degrade in harsh operating conditions, such as high temperatures.

12.5 Green Composites

Various saleable and industrial applications of FRPs are aircrafts and spacecrafts,ship and submarines, trucks and railways, automobiles, structures and prosthetics.Due to their high-specific stiffness and strength, fiber-reinforced polymer compositematerials have long been used in the aerospace industry and, with increasingfocus on lightweight vehicle manufactures due to environmental legislation, automotive applications are becoming more widespread. Other notable engineeringapplications include pressure vessels and wastewater pipes and fittings. The needto utilize the mechanical performance of materials and to avoid unreasonable over specification for aerospace applications was highlighted by Boeing, who estimated that it cost US$ 10,000 per pound (approximately UK£ 12,500/kg) to launch a satellite into orbit. Also of significance, when considered in terms of the levels of production and use, is that up to 40 % of the fuel consumption of a road vehicle is considered to be attributable to its inertia; the effects of inertia are particularly significant on the urban test cycle. With increasing environmental pressure, some vehicle manufacturers look towards an increased use of polymer composite materials for weight savings. Another driving force for efficient design with composites in high-volume production industries is the cost of the basic material. Because of the fact that composite material has characteristics that are as good as conventional materials, the use of natural fiber composites has begun gaining attractiveness in engineering applications. Properties like low density, lower material cost, renewability, and environmental friendliness are most important. In the past, various studies on natural fiber composites are carried out. Thus, the design of product using composites is extremely essential issue and it is imperative to know of various property predicting factors for the design of composites. As global societies continue to grow, increasing emphasis is being placed on ensuring the sustainability of our material systems. Topics such as greenhouse gas emissions, embodied energy, toxicity and resource depletion are being considered increasingly by material producers. Green composites deriving from renewable resources bring very promising potential to provide benefits to companies, natural environment and end-customers due to dwindling petroleum resources. The shift to more sustainable constructions in automotive industry is not only an initiative towards a more viable environment and cost efficiency but also a demand of European regulations. The latter are playing an important role as a driving force toward sustainable materials' use. According to the European Guideline 2000/53/EG issued by the European Commission, 85% of the weight of a vehicle had to be recyclable by 2005. This recyclable percentage has been now increased to 95% by 2015 [24]. Mercedes-Benz used an epoxy matrix with the addition of jute in the door panels in its E-class vehicles back in 1996 [25]. Another paradigm of green composites' application appeared commercially in 2000, when Audi launched the A2 midrange car: the door trim panels were made of polyurethane reinforced with a mixed flax/sisal material [26].

Green composites fabricated using plant fibers (cellulose) and resins such as modified starches and proteins have already been demonstrated in the interiors of automobiles while few examples have been shown for exteriors. Novel green composites have been tested in numerous studies in an attempt to explore their performance in several applications. The application of green composites in automobile body panels seems to be feasible as far as green composites have comparable mechanical performance with the synthetic ones. Conversely, green composites seem to be rather problematic due to their decomposable nature. The biodegradability issue is one problem that needs to be addressed when aiming to 100% bio-based composites application, especially when dealing with structural parts of exterior panels for future vehicles. More aspects have to be considered such as reproducibility of these composites' properties and their long life cycle as parts of the exterior body parts. Unfortunately, to the present the bio-thermoplastics' cost is a major barrier for their generalized use in the automotive industry but it is expected that soon manufacturers of these materials will turn up affordable solutions as their demand in industrial scale applications will no doubt tend to decrease their prices to more affordable levels. The trend can also be reversed in the sense that the necessity for environmentally conscious solutions can overturn the value chain and put a premium price on environmental impact of current solutions.

12.6 Limitation of natural fibers

Parallel to the advantages natural fibers bring with their use in composites they have also drawbacks regarding their performance, their behavior in polymeric matrix systems and their processing. First of all, natural fibers have an inability to provide a consistent pattern of physical properties in a given year; those properties can vary from every harvesting season and/or from harvesting region based on interchangeable sun, rain and soil conditions. Additionally, these variations can be surprisingly observed even in the same cultivation's population in between the crops. More precisely, their properties are essentially dependent on the locality, on the part of the plant they are harvested from (leaf or stem), the maturity of the plant and how the fibers are harvested and preconditioned in the form of mats or chopped fibers, woven or unwoven. All these factors result in significant variation in properties compared to their synthetic fiber counterparts (glass) [27]. Moreover important parameters are the type of ground on which the plant grows, the amount of water the plant receives during growth, the year of the harvest, and most importantly the kind of processing and production route. An approach to address this problem is to mix batches of fibers from different harvests. Blending fibers provides a hedge against variability in any single fiber crop. By having multiple suppliers of fiber and harvests, the ratio of fibers ensures relatively consistent performance in the finished part [28]. Alternatively, it is introduced to the market that a genetic transformed variety may guarantee products of constant quality [29]. One other major negative issue of natural fibers is their poor compatibility with several polymeric matrices. That may result in non-uniform dispersion of fibers within the matrix. Their high moisture sensitivity leads to severe reduction of mechanical properties and delaminating. Furthermore, low microbial resistance and susceptibility to rotting can act as restriction factors particularly during shipment and long-term storage, as well as during composite processing [30]. Similar to the case of wood composites, natural fibers and plastic are like oil and water, and do not mix well. As most polymers, especially thermoplastics, are non-polar (''hydrophobic'', repelling water) substances and not compatible with polar (''hydrophilic'', absorbing water) wood fibers and, therefore, poor adhesion between polymer and fiber may result [31]. In order to improve the affinity and adhesion between reinforcements and thermoplastic matrices in production, chemical ''coupling'' or ''compatibilising'' agents have to be employed [30,31,32]. Chemical coupling agents are substances, typically polymers that are used in small quantities to treat a surface in such a way that increased bonding occurs between the treated surface and other surfaces. Another primary drawback of the use of fibers is the low processing temperature required (limited thermal stability). The permitted temperature is up to 200 ^{0} C, above this limit the fibers start to degrade and shrink which subsequently results in lower performance of the composite. In general, when fibers are subjected to heat, the physical and/or chemical structural changes that occur are depolymerization, hydrolysis, oxidation, dehydration, decarboxylation, and recrystallization [33], and thus confine the variety of resins they can be blended with [34]. In order to avoid this processing defect, the range of temperatures has to be limited as well as the processing time [35].

12.7 Techniques for improving performance

Throughout the last 40 years of using polymer composites in the aerospace sector, designers and manufacturing engineers have progressed from relatively small, lightly loaded components and sections of structure such as ailerons and fairings to heavily stressed and critical items such as the main wing and fuselage of the Boeing 787, the Airbus A400 M and the new Airbus A350 aircraft, which are constructed from up to 50% (53% in the case of the A350) carbon fibre-reinforced polymer composite (by weight of aircraft), and in which the main wings and fuselage are largely manufactured from composite materials. High fibre volume is essential for good aircraft structure performance. It is also important that distribution of both fibre and resin is uniform throughout the component. To illustrate, the simple rule of mixtures (ROM) approach for calculation of longitudinal modulus falls into the mechanics of materials category; the modulus of elasticity in the longitudinal direction (EL), which is the direction parallel fibres, is given as:

$$E_{\mathrm{L}} = E_1^{\mathrm{f}} V_{\mathrm{f}} + E_{\mathrm{m}}(1 - V_{\mathrm{f}})$$

where Vf is the fibre volume fraction of the composite, E^f_1 is the modulus of the fibre and Em is the modulus of the resin. The typical Vf values for aerospace autoclaved prepreg components is approximately 54%, aerospace RTM components could be 57%, and some new resin infusion and advanced pultrusion processes could be above 60%. Although the simple ROM approach predicts an increase in performance with increased Vf , in reality some important material properties such as compression after impact strength begin to diminish as the resin content becomes insufficient to support the fibres [36]. One of the major difficulties associated with composite manufacture is that of void formation during impregnation and cure [37]. As these gaseous voids become entrapped within the matrix, stress concentrations can be established within the matrix. These may originate in a number of ways, including:

• During mixing of the resin formulation.

• During filling of the cavities in components of more complex shape.

• Due to the complex nature of the textile reinforcement since air can become entrapped in the interstices of the fabric structure. This can be particularly evident when coarse yarns (or tows) are used or in complex three-dimensional (3-D) structures, e.g. braided or woven, and may be most prevalent at the tool/composite interface.

• During the complex chemical reactions which take place during the cure of thermosetting resins, as volatile gases are released and become encapsulated in the cross-linked resin [38].

Selection of both manufacturing process type and resin/fibre system will be influenced by the specific properties required for different parts of the aircraft. High fibre strength and stiffness combined with low density are obvious general requirements for all parts of the aircraft structure. These properties have been best achieved from composites produced using layup of unidirectional pre-impregnated fibres (known as prepreg) coupled with autoclave cure. The high levels of composite stiffness and strength achieved by prepreg technology, combined with the low density of the constituents, make components manufactured this way suitable for wing and fuselage structures. Compression properties in particular will reduce if fibre volume fraction is low. The upper wing skin and parts of the spar structure which are placed under compression loading will therefore benefit most from use of unidirectional prepreg material where control of fibre distribution is good.

As has been noted, early examples of polymer composite manufacture on aircraft often used prepreg coupled with manual layup techniques followed by an autoclave cure. This process can produce composites with straight fibres, high and uniform volume fraction and freedom from voids and porosity. Such composites thus achieve optimum stiffness and static strength. While the production cost may have been competitive with aluminium for limited production runs, generally the cost of manufacturing structures with composites via this labour-intensive route was greater than with aluminium. The performance advantages of composites in terms of stiffness and strength to weight had to be weighed against increased cost of manufacture. There has been therefore an increasing focus on reducing the cost of composite parts by reducing the costs of both materials and manufacturing processes [39]. Prepreg production processes for aircraft can achieve the best properties but at a relatively high cost. Alternative lower cost processes such as Vacuum assisted resin transfer molding have been developed, but while they have superior performance in some areas such as toughness, through-thickness properties and impact resistance, they have not as yet achieved the performance levels of which prepreg route components are capable. While smaller scale, lightly stressed components on the aircraft can be made by a variety of the lower cost techniques, the major aircraft structural elements in existing and projected aircraft of main wings, fuselage and empennage are exclusively manufactured using prepreg as the starter material and high capital cost robotic layup and autoclave techniques to process it. Unless raw material and process costs can be reduced, the benefits of composites will be realised only on a limited range of aircraft types [36].

12.8 Prediction of properties

Lightweight structures in aerospace applications are mostly made of polymer matrix composites. The size and shape of the structure, and its usage, e.g. as primary or secondary structure in aircraft, dictate the choice of the manufacturing process. While the early aerospace applications in defence were mainly performance driven, the cost of manufacturing today is of increasing concern. Therefore, the traditional design approach of 'defect-free' structures must be revisited. In fact, no structure is without defects; a low threshold of measurable defects is essentially what is taken to define the defect-free condition. If the cost of manufacturing is to be managed, i.e. reduced in a controlled way, then the effects of defects must be assessed. This requires a mechanics-based knowledge base on characterization of defects and quantification of their effects on specific performance characteristics. Reducing cost of manufacturing further requires that the manufacturing process be quantified with parameters that can be varied to minimize cost. Voids are the most common type of matrix defects and are found in virtually all PMC parts, whether manufactured by autoclave, liquid compression moulding or resin transfer moulding (RTM). Void formation can to some extent be controlled by manufacturing process parameters such as vacuum pressure, resin viscosity, cure temperature and consolidation pressure. In one study [40], for example, void morphology and spatial distribution in a circular disc of glass/epoxy was studied in an RTM process in which the resin was injected under pressure into a mould containing fibre bundle preform. The voids were found to vary in size, shape and spatial location. Fibre defects, as noted above, are fibre misalignment and waviness, and broken fibres. In composites, where fibres are assumed to be straight, parallel and oriented in intended directions, deviations due to misalignment and waviness can reduce initial properties, particularly compression strength and stiffness and lead to reductions in aircraft design limit load and design ultimate load capability in service. A study of the effect of fibre waviness in unidirectional composites under axial compression [41,42] showed that the stiffness and strength reduced severely due to this type of defect. Stress analysis and experimental observations indicated that the interlaminar shear stress developed due to fibre waviness was responsible for delamination and subsequent failure. Toldy et al. studied the flame retardancy of fiber reinforced epoxy resins. As for the flame retardancy of the reference systems, the inclusion of carbon fibres into the resin resulted in significant increase of flame retardant performance. In case of the flame retarded systems outstanding LOI and UL-94 results could be achieved both for the resin and for the composite. Concerning the heat release results, the simultaneous application of flame retardant and carbon fibres did not lead to the improvement that could be expected on the basis of additivity, due to the hindered intumescence caused by the plies of the reinforcing carbon fibres [43]

12.9 Applications in aerospace engineering

Adhesives used for bonding aircraft components and sandwich composites are usually thermosets, such as epoxy resin. Adhesives must have low shrinkage during curing to avoid the formation of residual tensile stress in the bond. Correct surface preparation is essential to ensure a high strength and durable bond is achieved with a polymer adhesive. The mechanical properties of polymers are inferior to aerospace structural metals, and their use is restricted to relatively low-temperature applications. Polymers transform from a hard and glassy condition to a soft and rubbery state during heating, and the maximum working temperature is defined by the heat-deflection temperature or glass transition temperature. Polymers often contain additives for special functions such as colour, toughness or fire. Radar-absorbing materials (RAMs) are a special class of polymer that convert radar (electromagnetic) energy to some other form of energy (e.g. heat) and thereby improve the stealth of military aircraft. RAM must be used with other stealth technologies such as design adaptations of the aircraft shape to minimise the radar cross-section. Structural components for aircraft made from fibre polymer composites frequently comprise duroplastics shaped in prepreg and resin transfer moulding (RTM) processes. Celanese adds that the greatest disadvantage of this process is the extensive drying times required for the matrix to cure,. FIBRE uses prepregs that contain additional inlaid thermoplastic fibres, as well as carbon fibres, to lend structure to the window frames. These prepregs are processed to form structural inlay preforms - versions made from multi-axial fibre inlays (MAG) are used to shorten cycle times. FIBRE also produced Tailored Fiber Placement Preforms (TFP) parallel for precise fibre alignment. The matrix of knit and weft fibres is formed in the subsequent consolidation in a variotherm press. In this process, the Fortron PPS fibres in the prepreg ensure homogenous matrix distribution. After consolidation, the structure inlays are sprayed with short fibre-reinforced Fortron PPS to add integral stiffening or functional elements which would be much more difficult to implement with continuous fibre-reinforced materials. The combination of thermoforming and injection moulding makes the process more costeffective and allows for higher production volumes in a shorter time [44].

Conclusion

12.11 References

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