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Carbon-fiber reinforced PEEK polymer Composites as a Futuristic Material for Aircraft Structures

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Abstract

Polymer based composite materials are becoming the most useful materials for aircraft structures due to their designable advantage, specific strength, less cost, low weight, and high performance. The most widely researched polymer composites in the last few years were epoxy thermoset polymers reinforced with carbon fiber (CF) to improve the structural properties further. However, the CF reinforced epoxy polymer has some limitations related to its recyclability, manufacturing, and sensitivity to moisture which can degrade its structural properties. So, to address these limitations and replacement of epoxy polymer in aircraft structure, a thermoplastic polymer can be a perfect candidate due to its excellent mechanical properties and resistance to chemical and moisture absorption. Among the various thermoplastic polymer-based composite, poly ether ether ketone (PEEK) polymer attracting many researchers interest due to its unique properties like high strength, flexibility, high damping, resistance to weather conditions, and chemicals. These properties make PEEK composite to sustain with high dynamic loads during flight operation. This present report aims to investigate the applicability of PEEK composite and its properties for aircraft structure. The review result showed that the carbon fiber reinforced composite has provided excellent structural, weather resistance, and flame resistance, low temperature properties. Also, concluded that the CF-PEEK composite is open a new getaway toward the futuristics material for aircraft structure.

Keywords: Carbon fiber; PEEK polymer; Thermoplastic composites; Aircraft structures; Mechanical properties

1. Introduction

The aviation sector promoted the development of polymeric materials for aircraft structures due to its lightweight and high strength performances requirement. The polymer-based composites reinforced with fibers provide excellent mechanical properties with low density which make them an ideal candidate for the aircraft structure design [1]. Polymers are the organic materials that consist of carbon and chemically bonded with hydrogen, oxygen, and other non-metallic substance. A polymer is made up of very large no of molecules with many repeating units of monomers. In polymers, each molecule can be consisting either of long chain or complex network of branches that are covalently bonded together. Also, in some circumstances, this chain network can be also connected by van der waals forces [2]. The polymer can be divided mainly into two groups of polymers-

1.1 Thermoset polymers

Thermosets are cross-linked polymers that are connected with a 3D network of chains. These polymers are obtained by mixing of monomer and oligomer with a hardener. A comparison of mechanical properties and glass transition temperature of different thermosets is shown in Figure 1 [3]. It indicates that the thermosets polymer shows a high glass transition temperature and good tensile strength due to crosslinking between chains, which endorse the use of these polymers into aircraft structures.

1.2 Thermoplastic polymers

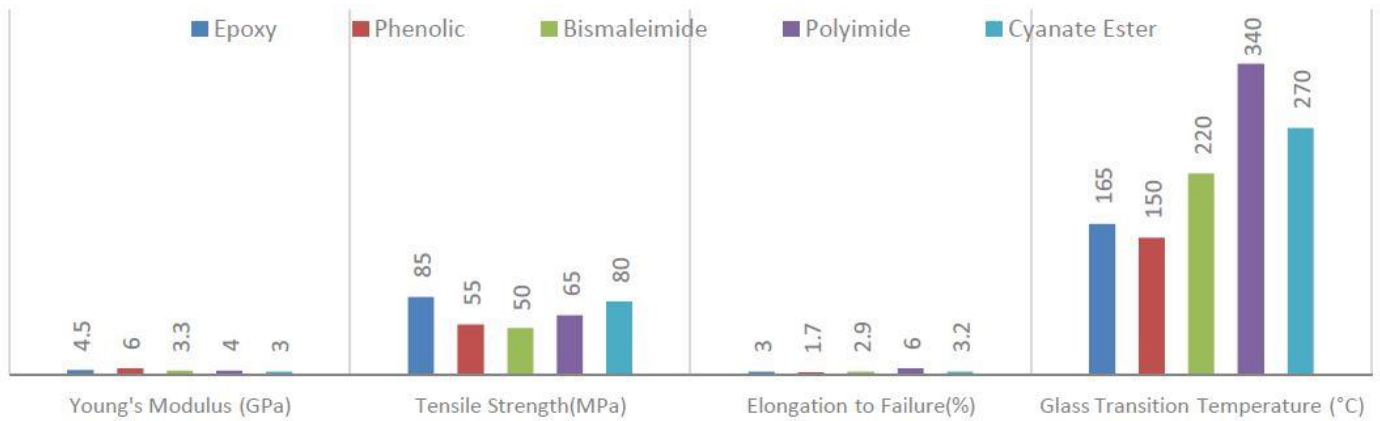


Figure 1. Comparison of mechanical properties with glass transition temperature for different thermosets used in structures [3].

Thermoplastic is the molecular chains polymer that relates to weak secondary van der Waals forces. Whereas the thermosets polymer connected with the strong cross-linked bonds between the molecular chains. So, thermoplastic polymers have low strength and glass transition temperature as compared to thermosets. Therefore, the use of thermoplastic in aircraft structures is very small than the thermosets polymer. But in now days, their use in structures is continuously increasing with some modification because of having high toughness, impact resistance, and working temperature. Figure 2 showing the comparison of mechanical properties and working temperature between different thermoplastics available for aircraft structures [3].

to very low strength, and low working temperature [5,6]. For example, In Figure 3 Epoxy polymer shows lower mechanical properties as compared to different materials used for aircraft structure, whereas the Epoxy polymer modified with carbon fiber shows the higher properties. So, this figure clearly implies that composite of polymer (reinforcement in the polymer) could be applied in aerospace structure efficiently.

In this review paper provides a comprehensive overview of carbon-fiber reinforced PEEK polymer (CF-PEEK) composites and their potential use in aircraft structures. Furthermore, the properties of PEEK polymer composites, their current research and development efforts, and the

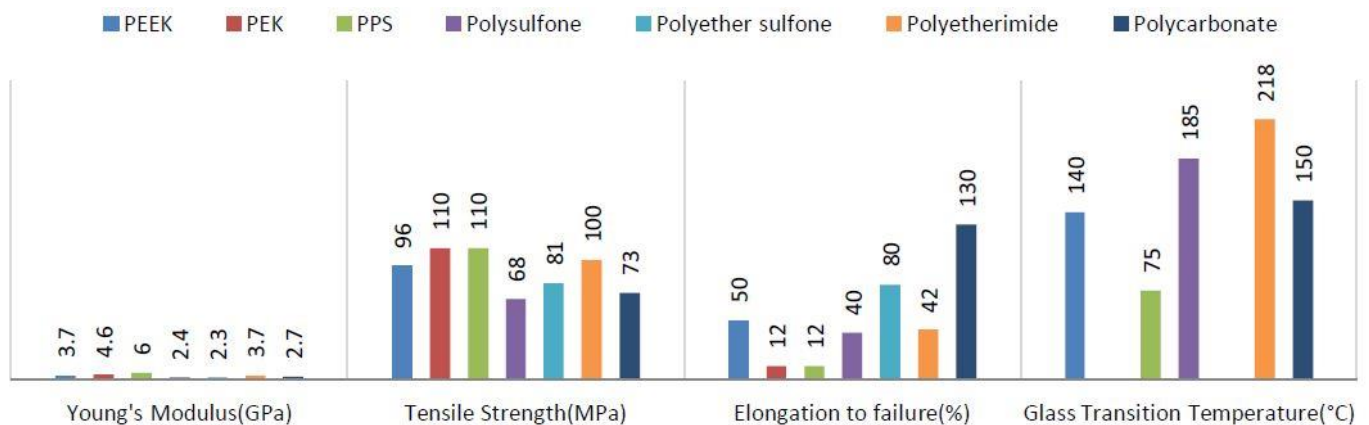


Figure 2. Comparison of mechanical with glass transition temperature for different thermoplastic used in structures [3].

1.3 Polymer matrix composites

The polymers are used in aircraft structures because of their excellent properties like lightweight, high toughness, low cost, and high corrosion resistance [4]. But the polymer cannot be used on its own as aircraft structural materials due

limitations of these materials in aircraft structures were discussed. Overall, this review paper aims to provide a thorough understanding of the potential benefits and limitations of CF-PEEK composites in the context of the aerospace industry.

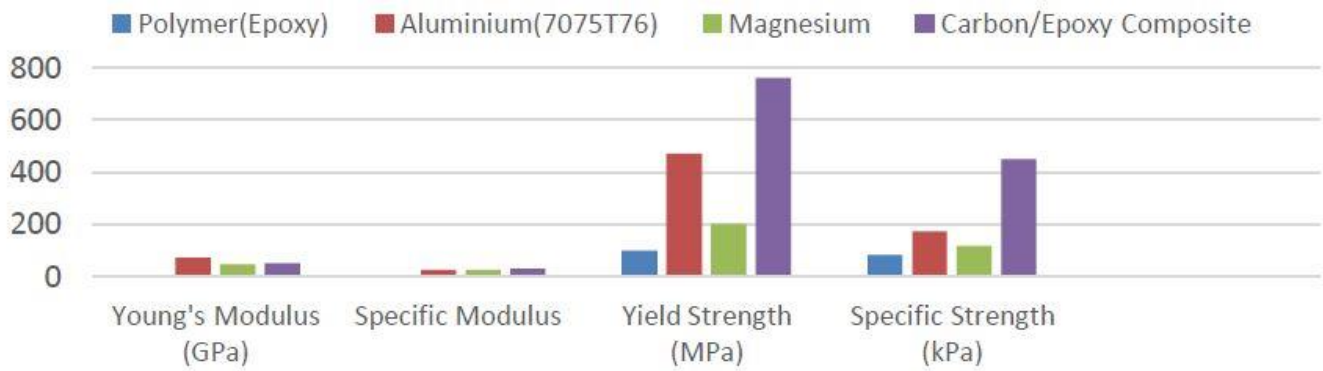


Figure 3. Comparison of mechanical properties of polymer with respect to used aircraft structure materials [3].

2. Materials for aircraft structures

The performance of aircraft structures has a continuous upward trend. The lightweight and excellent mechanical properties always push scientists and engineers towards the new structural solution and advanced materials for aircraft. In 2001, The council of European aeronautical research “ACARE” has recognized the various aircraft structural research areas which need to be achieved by 2050 [7]. Among various included research areas, 50% part of the research only has related to the reduction in fuel consumption per passenger per kilometre [8]. In consequence, the aerospace industry is now building all airplane with maximum use of composites like the Boeing787 and Airbus A380. They are using around 50% of the component with composite in their aircraft due to higher performance with low fuel consumption [9,10]. For example, the different composite parts such as spoiler, wings, vertical, and horizontal stabilizer, frame body, and ribs were adopted by the airbus during the manufacturing of the A380 aircraft. The weight of all composite parts comprises only 12 % of the total weight of the airplane [11,12]. From above mentioned scenario and the need of aircraft industry, it can be concluded that upcoming decade for aircraft will require more efficient and effective lightweight composite material that have multi functionalities such as flame retardant, excellent mechanical thermal properties, weather resistance, working at low temperature, low cost, low fuel consumption, easy manufacturing, easy recyclability, and high performances.

2.1 Requirement of aircraft structure

Aluminium alloys are the most common materials used for conventional aircraft structure because of their advantage of excellent mechanical properties.

But the density of these aluminium alloys is quite high, and the current demand of aerospace industry requires low density materials with excellent mechanical properties. So, the current industries have moved towards the polymer-based composites materials as the replacement of aluminium alloy. The most widely researched composites in the last few years were epoxy thermoset polymers reinforced with carbon fiber to improve the mechanical properties further [13]. However, the carbon fiber reinforced epoxy polymer has some limitations related to its recyclability, manufacturing, and sensitivity to moisture which can degrade its mechanical properties [14]. So, to address these limitations and replacement of Aluminium alloy and CF-epoxy polymer in aircraft structure, a thermoplastic polymer can be a perfect candidate due to its excellent mechanical and resistance to moisture absorption and chemical. Among the various thermoplastic polymer-based composite, PEEK polymer attracting many researcher's interests due to its unique properties for high performance for aircraft wings. Many researchers reported the PEEK candidate materials have high strength, high damping properties, resistance to weather and chemicals also with have a high hardness number to sustain high dynamic load during flight operation [13].

2.2 Current status

The existing materials used for aircraft structures are Aluminium alloy (Al7075) and CF-epoxy composites. The more details about these are mentioned below-

2.2.1 Al7075T6

This alloy is the most widely used material for aircraft structures. It consists of aluminium and zinc element. It offers excellent mechanical

properties and is resistant to wear and corrosion. But this alloy has some limitations due to embrittlement and high density which leads to catastrophic failure and high cost of the component, respectively.

2.2.2 CF-Epoxy composites

The carbon-fiber reinforced epoxy composite is widely used and researched material for aerospace structures. It provided excellent specific strength, lightweight, as compared to aluminium alloy. The main limitation of epoxy composite is sensitivity towards moisture, chemical, and recyclability.

2.2.3 CF-PEEK composites

The CF-PEEK is the most recently researched thermoplastic composite which provides the advantage of resistance to moisture and chemical, fire retardant, ease of manufacturing, and lightweight as compared to other convention materials used for the aerospace structure. The comparison of material is tabulated in Table 1.

Table 1. Mechanical properties for Aluminium alloy, CF-Epoxy, and CF-PEEK composite [13]

Properties	Al7075T6	CF-Epoxy	CF-PEEK
Density (kg/m ³)	2803	1491	1904
Poisson's ratio	0.32	0.28	0.45
Young modulus E (GPa)	72	122	173
UTS (MPa)	571	1031	2899
Yield strength (MPa)	502	946	2071

3. Properties of CF-PEEK composites

3.1 Mechanical Properties

Sudhin et al. [15] reported the mechanical properties of CF-PEEK composites through tensile and hardness testing as compared to CF-Epoxy.

3.1.1 Tensile

Figure 4 shows the reported stress-strain curve of CF-PEEK and CE-Epoxy. The Elastic modulus and ultimate strength are holding 7.7 GPa and 424 MPa for PEEK composite and 5.1 GPa and 311 MPa Epoxy composite. Furthermore, the strain at the failure for the PEEK composite was reported as 9.42% and 11.31 % for epoxy composite, respectively. The researcher investigated that the higher elastic modulus and ultimate strength of PEEK composite due to cross linking, a high percentage of carbon, and entanglement in

thermoplastic as compared to epoxy thermoset polymer.

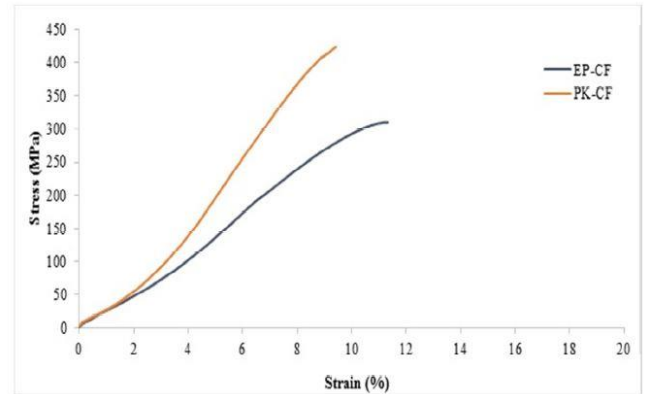


Figure 4. Stress-Strain curve of CF-PEEK and CF-Epoxy composite [15].

3.1.2 Hardness

The hardness value represents the resistance to abrasion for polymer. The researcher reported that the addition of carbon fiber into polymer resulted into the increase in shore D hardness [15]. The reported hardness value of PEEK and epoxy

polymers are 86 and 83, whereas the composites hardness value reaches to 93 and 88, respectively. The hardness value of PEEK shows a significant increase as compared to Epoxy because of adequate bonding and cross linking between matrix and fiber of thermoplastic. In conclusion, the researcher reported that the CF-PEEK composite has excellent mechanical properties than the CF-Epoxy and reported conventional aluminium material for aircraft structure. In the comparison of mechanical properties, Table 2 shows the different results obtained for PEEK and epoxy composites.

3.1.3 Thermal

Sudhin et al. [15] also reported the thermal properties of CF-PEEK and CF-epoxy composites through differential scanning calorimetry (DSC) both in the heating and cooling cycle. The authors also determined the melting point temperature (T_m), glass transition temperature (T_g), and

crystallization temperature (T_c) of composites and compared them with their neat form. The resulted data is listed down in Table 3.

Table 2. Comparison of mechanical properties obtained for composites [12].

Composites	Hardness	UTS (MPa)	Elastic Modulus (GPa)	Strain at failure (%)
CF-PEEK	93	424	7.7	9.42
CF-Epoxy	88	311	5.1	11.31

The researcher concluded that carbon fiber reinforced PEEK composites showing better thermal properties as compared to epoxy because of the entering of molten PEEK into carbon fibers and create a strong bond between PEEK matrix and carbon fiber. So, the researchers concluded that CF-PEEK also has high thermal stability at higher temperatures as compared to epoxy matrix.

Table 3. Thermal properties of polymer composites in heating and cooling cycle [15].

Polymer	Heating Cycle		Cooling Cycle
	T_m	T_g	T_c
PEEK	370	155	327
CF-PEEK	375	162	326
Epoxy	137	85	-
CF-Epoxy	144	91	-

3.2 Environmental factors

PEEK based composite is used in many aerospace, space, and marine application. But during the aircraft structure application of PEEK composite, the weather also influences its properties. So, Batista et al. 2021 investigated the effect of different weather conditions like UV radiation exposer, and Hygrothermal on CF-PEEK composite [16].

3.2.1 Effect of UV radiation exposer

During the flight of aircraft at high altitude, they are exposed to intense UV radiation on their structure component which can result into the degradation of polymer composite through breakage of polymer chain bonds and oxidation through photons. During 900 hr exposer, weight loss was observed at a value of -0.08 % of CF-PEEK polymer (refer to Figure 5). The researcher reported that the reduction in weight % is due to

photo oxidation of PEEK, which leads to erosion of the laminate surface [16]. Also, low crystalline PEEK was safer to the UV radiation effect, after a long time of exposer.

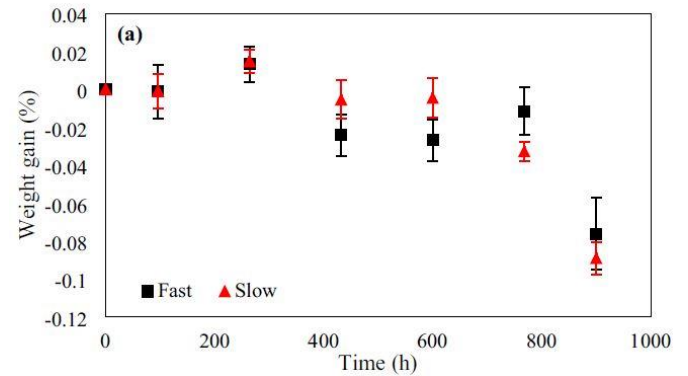


Figure 5. Weight gain of CF-PEEK polymer due to UV exposer with respect to time [16].

3.2.2. Effect of Hygrothermal

Moisture in the environment can promote permanent change in polymer composite due to hydrolysis of the polymer chain. The researcher reported that the weight gain percentage by increasing time, shows the increase in crystalline content and it's difficult for water diffusion in PEEK (Shown in Figure 6) [16]. This is because of the crystalline material possess a higher density and hinders the ingress of water into the matrix.

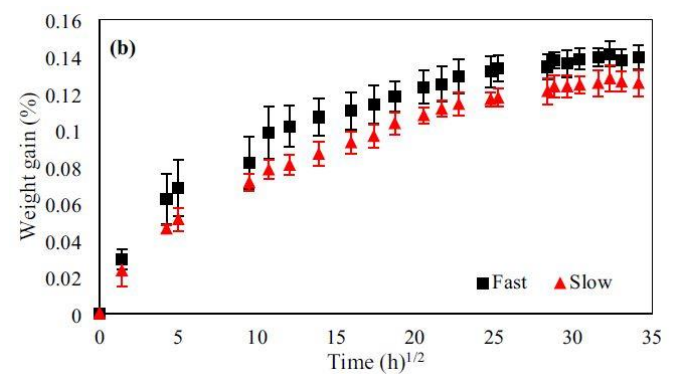


Figure 6. Weight gain of CF-PEEK polymer due to hygrothermal effect with respect to time [16].

The researchers also determined the effect of UV Exposer and hygrothermal on compression strength, interlaminar shear strength, and young modulus. They concluded that the degradation of samples due to UV light was due to high

crystallinity. And highly crystalline PEEK is more unsafe to the UV light. Also, the hygrothermal effect resulted in the improvement in compression strength, interlaminar shear strength, and young modulus due to an increase in crystallinity of PEEK. This is because of moisture allowed relaxation and reordering of polymer chains. So, PEEK polymer can be a good replacement for thermoset polymer due to its safe performance in wet environment.

3.3 Other factors

3.3.1 Flame retardancy

In now days fire safety has become the highest propriety in the aviation sector due to the use of polymer structures. So, checking the flammability or flame retardancy of a polymer before its use in aircraft has become a very essential need. To check the suitability of the PEEK composite for the aerospace structures, Sudhin et al. [15], reported the flame-retardant behaviour of CF-PEEK and CF-Epoxy which was characterized by using limiting oxygen index (LOI) test. This test was used to investigate the minimum require concentration of O₂ (oxygen) that was required to start flaming. Moreover, Table 4 shown the required oxygen for flaming. The LOI result indicates that the CF-PEEK was showing excellent flame retardancy as compared to another epoxy polymer. By comparing all composite, CF-PEEK was showing high thermal stability, which could be perfect candidature for aircraft structure.

Table 4. Percentage require oxygen for flaming [15]

Polymer	% Oxygen
PEEK	35
CF-PEEK	47
Epoxy	25
CF-Epoxy	32

3.3.2 Effect of Lower temperature

The aircraft materials have to carry out its duty at lower temperature range of -45 °C to 70 °C with different impacts due to aeronautical flight speed. So, it is necessary to know their performance in this wide temperature range. So, keeping in this mind, the Gonzalenz et al. [17] reported their effect of lower temperature on the CF-PEEK composite with different impact energy absorption capability. They determined force-displacement curve (Shown

in Figure 7) and observed no change in failure mode and some loss in ductility as temperature decreased. And, concluded that the impact energy of CF-PEEK decreases at lower Temperature impact conditions. So, this insensitivity towards the lower temperature can also with the use of SiO₂, Al₂O₃ filler material in the polymer matrix to increase the impact energy absorption [18]. Whereas, at ambient temperature, it shows good impact energy absorption, which was higher than the aerodynamic load during the flight of aircraft.

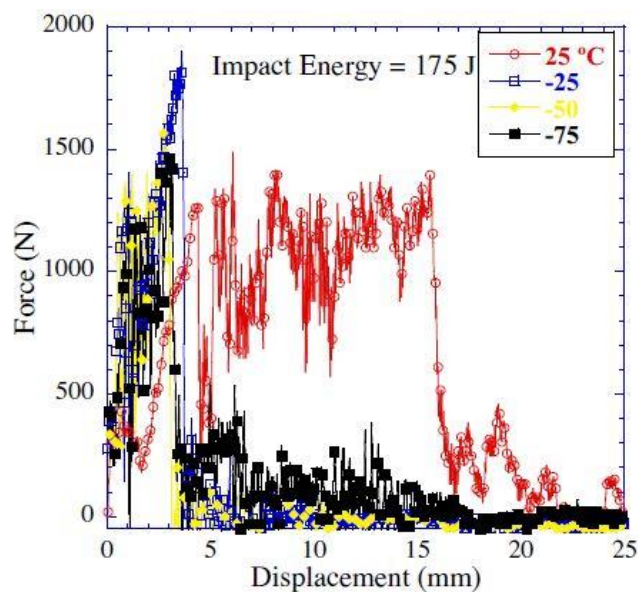


Figure 7. Force-displacement curve of CF-PEEK composites at different temperature [17].

4. Conclusions

In conclusion, this report successfully reveals important aspects related to the required properties for modern aircraft with the help of newly CF-PEEK thermoplastic composites. From this intense review, the following conclusions were drawn-

1. CF-PEEK composite has excellent mechanical properties than the CF-Epoxy and reported conventional aluminium material for aircraft structure. The tensile strength was also determined more than 100 MPa also with higher hardness as compared to epoxy composite. This result supported the minimum strength requirement of the aircraft structure.
2. CF-PEEK also have high thermal stability at higher temperature up to 155 °C which enables the thermoplastic material as the preferable material for aerospace industries.
3. CF-PEEK showing excellent weather resistance properties like resistance to UV exposer up to 900 hr and moisture absorption

up to. So, it can be a good replacement for thermoset polymer due to its safe performance in wet environment.

4. LOI index of CF-PEEK composites also has more than 47 % which could allow this polymer to become a good fire resistor, during the flight of aircraft.
5. At the environment temperature, CF-PEEK composite shows very high energy absorption ability, which is greater than the aerodynamic load during flight.

From the reported result by researchers and by combining them, it can be concluded that CF-PEEK composite material is a perfect candidate for aircraft structure with multifunctional properties like excellent mechanical, thermal, weather resistance, fire retardant, and temperature dependent impact resistance as compared to epoxy and conventional aluminium alloys. When we make aircraft structure material with a unique combination of properties, it will also take care of the “safety” and “reliability” of aircraft structure for the passenger.

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