Physics of Failures in Aging Aircraft Systems and Components

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ABSTRACT

Continuous all-round research efforts have been made worldwide over the past decades for failure analysis of aeroengine and structural parts in both civilian and military aircraft and helicopters. A great deal of progress has been made, though, with the introduction of new designs, materials and service as well as operating demands, unforeseen problems are often encountered. Shrinking resources, budgetary constraints, high maintenance and replacement cost and environmental restrictions impose newer controls and approaches for managing aircraft industries. The goal of this paper is to conduct a review of the progress made over the past decades in analyzing and controlling the aging and failure problems with aircraft. The work includes: 1). damages and failure modes and mechanisms in aircraft and helicopters from physics viewpoints; 2). modeling and analytical solutions for failures in polymer matrix composites and ceramic. The domain of research on the subject is quite vast and may extend from metallic alloys to newer materials (polymer/ceramic composites, aluminides), from traditional to advanced structural designs, advancements in processing technology and many more. The paper focuses on historical failures and lessons learned based on the structural integrity concept, failure modes and mechanisms, failures of various aircraft components, structural composite failure mechanisms, and case studies.

1.0 INTRODUCTION

Aging and subsequent failures of aircraft structural components can have catastrophic consequences, with the resultant loss of lives and aircraft. For critical sub-systems, any failures have serious effects in terms of cost, safety, environmental effects or consequential damages, and therefore the development and implementation of preventive measures are of utmost importance. Investigations and analyses of damages and failures in aircraft structures are of vital importance in delaying and preventing these unwanted events. Historically, the majority of structural component failures has been in metallic materials, reflecting the predominance of metallic structures in aircraft. Since the mid-1980s, an increasing number of aircraft manufacturers have been making use of fiber-reinforced polymer composites, ceramics and other advanced materials for structural components (Findlay et al, 2002). Unfortunately, some significant issues arising from aircraft aging have not been recognised and addressed until fatal accidents had occurred. Airworthiness issues that arise in many aging aircraft have often been a direct consequence of the gap between the current and former maintenance practices. Conservative maintenance approaches are followed to avoid any failures and components are often replaced early before they reach the end of their actual service life, making the approach effective, but not always efficient (Tinga et al, 2019).

The primary goal of this paper is to analyse the principal failure modes and mechanism as identified for various aircraft engine and structural components. Some of the historical failure events associated with civilian and military aircraft are presented first to document the experience from failures. This is important for understanding the development of the concept of structural integrity in aircraft maintenance and research starting at the design concept stage based on the static strength-based analysis. The developments have mainly progressed over three time periods, 1930 to 1940, 1940 to 1955 and 1955 to the present.

2.0 HISTORICAL FAILURES AND STRUCTURAL INTEGRITY CONCEPT

There have been a large number of classical aircraft failures over the past century, the analysis of which has largely facilitated design, material selection and airworthiness aspects in order to prevent damage evolution and failures (Wanhill et al, 2015). This section briefly presents a few of failure events in Table 1 and lessons learned. Columns 2 and 3 in the table include the lifetime consumed before failure in each case and the principal causes for the failures. The evolution of aircraft structural integrity has been concerned largely with the service behaviour of high-strength metallic materials, particularly aluminium alloys.

Table 1: Classical aircraft failures and the development of structural integrity concepts (Wanhill et al, 2015).

Classical failures	Life time	Cause(s) of failure	Lesson learned
De Havilland Comet - first commercial jet transport, entering service in 1952	aircraft accumulated 1231 pressurization cycles in service	Out of plane bending caused inside principal stress to be significantly higher to cause early fatigue failure	Fatigue design based on Safe-Life not be guaranteed; Fail-Safe design requiring fatigue testing, crack growth analysis, life prediction and Residual Strength requirement.
USAF Boeing B-47 bomber aircraft crash in 1958 - a radically new design, with six turbojet engines	1200 – 2400 flight hours.	Shortcomings due to static loads, overload and fatigue at the critical wing to fuselage area	Need to control fatigue, make accurate and conservative Safe-Life fatigue predictions, need for full-scale fatigue tests.
USAF General Dynamics F-111 Crash in 1969	107 flight hours over a year	Undetected manufacturing flaw led to limited fatigue cracking and fast fracture and loss of wing	USAF mandated Damage Tolerance, possibility of cracks or flaws in a new structure must be considered; initial damage must grow slowly and not large enough to cause failure
Air Boeing 707 crash in 1977	47,621 airframe flight hours since 1963	Fatigue failure from a fastener hole in the upper chord of the rear spar of the right-hand stabilizer.	Need for full-scale fatigue testing; inspect ability is equally important even with the fail-safe design approach.
Aloha Airlines Boeing 737 Accident in 1988	35,496 airframe flight hours	Large loss of pressure cabin skin caused by rapid link-up of fatigue cracks in the same longitudinal skin splice. Fatigue cracks began at the knife-edges of rivet holes.	The rapid decrease of residual strength, with a loss of Fail-Safe capability both in terms of Residual Strength and adequate time for inspection.

Table 1 clearly and concisely illustrates how the design approach changed from Safe Life to Fail-Safe to full-scale testing and the damage tolerance approach. This has a close resemblance with the modes and mechanisms of failures observed in critical parts and components in aeroengines and aircraft structures.

2.1 Advances in Operating Conditions and Engine Output

To have complete knowledge and understanding of the progressive damages and failure mechanisms in aeroengines, one has to review the progressive changes in the engine operating conditions and outputs. These are summarized in Table 2 to give an understanding of the basic causes for the damage and failures. Over the past five decades, the aircraft design and operations have been modernized with enhanced capabilities, with a consequent shift in nature (modes and mechanisms) of aging and failure processes due to significant changes both in operating demand and engine output. Engine thrust is increased by almost four times from 10.5 to 93 kilo pounds and almost eight times per aircraft; fuel consumptions were reduced significantly as the engine efficiency increased. In addition, the turbine entry temperature (TET) had been almost doubled with significant achievement through materials and cooling technology (Clarke et al, 2005; Winstone et al, 2008; Rolls Royce, 2005).

Table 2: Progress in aeroengines capabilities over the past five decades.

Aircraft and year	Capacity Passengers	Engines	Range in miles	Thrust in LBF	Turbine entry temperature, ºC
De Havilland Comet IV	76	RR Avon RA29	2870	10500	900
Boeing 707 (1960)	181	RR Conway	5700	17500	1020
Lockheed (1989)	256	RR RB211-22B	4100	42000	1250
Boeing 747-400 (1995)	416	RR RB211-524	7000	58000	1350
Boeing 777-200	301	RR Trent 899	8800	93000	1550
Airbus A380 (2007)	555	RR Trent 900	9200	80000	1580

3.0 MODES AND MECHANISMS OF FAILURES

3.1 Failure Probability

Before discussing various mechanisms associated with failures, it is interesting to review and analyse the probability of aging and failures of different engine components. Historical data is provided in Table 3. The aeroengine system program is broken into four modules dealing with hot gas components (turbine blades), turbine disc, fan and compressor airfoils and rotor-bearings. Turbine blades and discs composed of Ni-base superalloy are key components of modern turbine engines and subjected to high temperature and load conditions. The durability of these components in the hot section (>1100 °C) is the life cycle limiting factor. The probability of turbine engine component failures during their service lives is listed in Table 3 (Patnaik et al, 2004; Evans et al, 2001; Clarke et al, 2003).

Table 3: Probability distribution of component service failures in aircraft engines.

Component	Probability of Failure
Compressor	16 %
Turbine	45 %
Rotor	11 %
Combustor	5 %
Auxiliary	1 %

The major problems of aging and failures occur in the turbine section because of the severity of operating conditions in terms of temperature, stress and environments, including corrosion, oxidation, erosion etc.

3.2 Aging and Failures

Aging is a process where structural and functional integrity of aircraft, avionics, and subsystems will degrade with time under their operational environments. FMECA reports for failure mode and criticality of components, system and platforms as compendia. Aging is inevitable and thus need to be managed.

Damage is a function of engine system/subsystem type, operational conditions and flight/operation time. Any mechanical/structural component or subsystem failure is generally preceded by metallurgical damages. Failure mechanism(s) and their analysis demand thorough knowledge and understanding of the formation and propagational growth of the damages. Internal damages grow from inherent impurities, inclusions or similar inherent sources in new or repaired parts. All surface damages are known to significantly affect aerothermodynamic and fuel efficiency performance and operability.

External damages include (Immarigeon et al, 2000):

● **Fretting** – Small amplitude oscillatory motion between two contacting surfaces. Fretting occurs in joints (bolted, keyed, press-fitted, shrunk or riveted), lowering both low cycle fatigue (LCF) and high cycle fatigue (HCF) lives and affecting splines, couplings, clutches, spindles and seals.

● **Erosion -** Hard particles cause gradual removal of the component surface. Eroded blades with changed shape and surface roughness are a classic example. Erosion causes changes to the modal response of the blades, with high frequencies leading to HCF.

● **Oxidation damage –** Turbine blade tip oxidation causing coating spallation and faster wear off. Oxidation reduces the thickness of blades, vanes, internal cooling passages and provides sites for HCF/LCF crack formation or nucleation

Internal damages result mostly from the combined action of stress, and heat-reducing component strength and other mechanical properties facilitating nucleation and growth of damage leading to distortion, collapse and failure. Internal damages are insidious in nature and thus difficult to monitor, predict and control (Immarigeon et al, 2000).

● **Microstructural damages -** One of the most common, insidious and harmful damages is the deterioration of material microstructure during service. This can occur commonly because of the operational stress, high temperature, internal residual stress and corrosive media. Plastic strain accumulation due to the presence of temperature and stress by combined creep and fatigue causes microstructural damage(s), leading to failure. Creep deformations leads to creep cavities, growth and coalescence, leading to crack nucleation. Cycle dependent micro-damage accumulation is another example.

● **Metallurgical aging** occurs in hot gas path components where coarsening and agglomeration of precipitates occur, reducing mechanical strength and toughness. γ' precipitate in Ni-base superalloys and carbide coarsening in cobalt-superalloys are two examples of metallurgical aging.

● **Distortion and cracking** - Creep deformation may lead to component distortion, e.g., vane air foil bowing or lengthening; untwist of turbine blades is an example when distortion leads to HCF failures.

3.2.1 Physics of Failures

The basics of understanding and analysing failures of aircraft structure and engines can be demonstrated with the help of a bathtub curve, as presented in Figure 1.

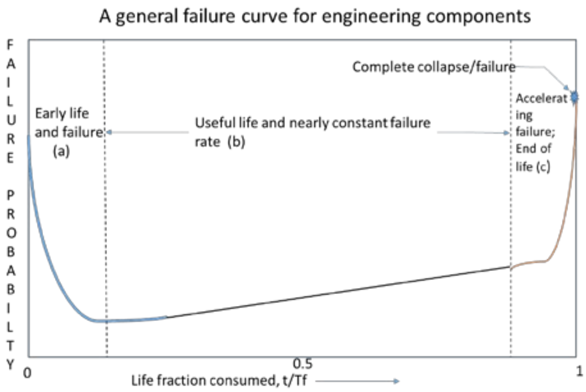


Figure 1: Competing component failure probability illustrating the physics of failure in broader perspectives in aerospace and other engineering industries.

Three regions (a, b and c in Figure 1) are demonstrated. The general shape of the curve is like a bathtub having three distinct regions (Varde, 2010). With tremendous technological advancements and achievement in aerospace, the failure phenomena are represented with the help of the curve in Figure 1. However, the probability levels associated with each regime have dramatically changed. For example, the failure probability for the infant mortality rate (reg. 1) used to be around 50- 68 percent. With maturity in design, wide-ranging availability of materials and their selection process, availability of advanced processing techniques and workmanship, the failure rate has been markedly lowered down to 10-25 percent.

Reg.1 (early life**)** – High failure rate that diminishes very quickly, such as reflecting the high mortality rate for a child. This is mostly related to quality, manufacturing, designing, learning-related teething problems. Any gross mistakes made during production and operational set up are generally related to this stage.

Reg. II (long useful life**)** – Secondary stage reflecting nearly constant failure rate with a small slope, as a result of a routine operational and related damages;

Reg. III (end of life**)**- Tertiary or final stage of life when the changes of failure accelerate and eventually terminate in complete collapse or failures. At this stage, considerable amounts of age-related problems accumulate, increasing the risk of failure.

4.0 MECHANISMS OF AEROENGINE AND STRUCTURAL FAILURES

Aeroengine components are operated under particularly severe conditions, including the combination of both high mechanical stresses and elevated temperatures in chemically aggressive environments. These normal operational requirements will eventually promote both cyclic and time-dependent failure mechanisms related to creep-fatigue damages. Therefore, the use of adequate preventive inspection techniques is mandatory in order to maximize the safety and reliability of these components during service (Silva et al, 2009).

Typical failure mechanisms encountered in the aerospace industry are listed below (Patnaik, 2004; Evans et al, 2001; Clarke et al, 2004, Wood, 1999; Clarke et al, 2005) :1-Low cycle fatigue; 2-High cycle fatigue; 3-Thermo-mechanical fatigue; 4- Hot corrosion; 5- Cyclic oxidation; 6-Fretting fatigue; 7-Creep deformation; 8-Wear and abrasion; 9-Erosion; 10-Microstructural degradation; 11-Distortion and cracking; 12- Foreign object damage.

Table 4 reports the prevalence of the failure modes as discussed earlier based on different mechanisms, as presented in Section 3.0. The failure frequencies in the aerospace industry are compared with those encountered in other industries. Failures under fatigue are more frequent in aerospace as compared to the failures in other industries.

Table 4:Frequency of failures in aircraft and other engineering industry for different mechanisms (Findlay et al, 2002).

Failure mechanism	Engineering components	Aircraft Components
Corrosion	29	16
Fatigue	25	55
Brittle fracture	16	-
Overload	11	14
Hot corrosion	7	2
Stress corrosion cracking (SCC) /corrosion fatigue and hydrogen embrittlement (HE)	6	7
Creep	3	-
Wear/abrasion/erosion	3	6

4.1 Corrosion and Fatigue Failures

In view of the high frequencies of failures in aircraft (both military and civilian) as reported in previous sections, the essential features of two mechanisms, namely corrosion and fatigue are discussed briefly in the following sections. These two mechanisms constitute more than 70 percent of the total failures in the aircraft industry and have received the maximum attention.

4.1.1 Metallic Corrosion

Corrosion is a degradation of materials because of a chemical attack by their service environments. Extensive work has been carried out on the rates and types of corrosion observed in different materials so that selecting a suitable material in terms of corrosion resistance for a known environment is relatively straightforward. In aircraft structures, however, the strength to weight ratio can be a more desirable property than corrosion resistance, and in these circumstances, the most suitable materials cannot always be used. In cases like this, measures must be taken to limit corrosion, which commonly involve the use of a coating, such as a paint system or corrosion preventative compounds, to act as a barrier to the environment (Findlay et al, 2002).

4.1.2 Stress Corrosion Cracking and Hydrogen Embrittlement

Stress corrosion cracking (SCC) is a mechanical-environmental failure process in which tensile stress and environmental attack combine to nucleate and propagate a crack to fracture. Failure by stress corrosion cracking is frequently caused by simultaneous exposure to an apparently mild chemical environment and to a tensile stress well below the yield strength of the material. The stress required for failure can originate from in-service conditions or from residual stress during component manufacturing (Findlay et al, 2002).

4.1.3 Pitting Corrosion

Stainless steel, titanium alloys, and compressor parts are highly susceptible to pitting damages due to high concentration of chloride ions in their operating environments. Corrosion pits lead to crack nucleation sites for HCF and LCF and catastrophic failures. Figure 2 shows the corrosion pitting around the root of the compressor blade and sites for stress concentrations.

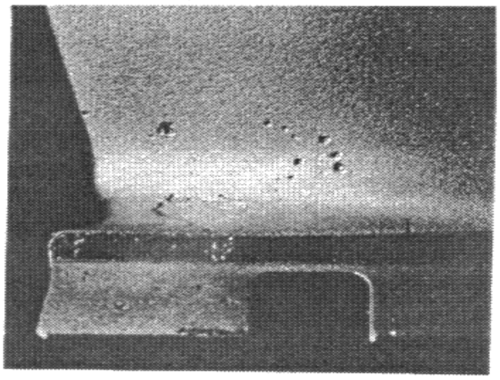


Figure 2:Typical corrosion pit formation around the compressor blade roots (Findlay et al, 2002).

4.1.4 Hot Corrosion

Hot gas path components, including internal cooling passages, are mostly susceptible to this degradation. Deleterious mixtures of residual sulphur in fuel and ingested marine air (NaCl) will combine to form sodium sulphate. High-temperature oxidation/sulphidation can process by reactive contaminants in hot corrosion while protective coatings fall in damaged. Operating experience under CMAS environments being worse than and aggravating the baseline silica erosion.

4.2 Fatigue Failures

Structural fatigue has produced a number of aging aircraft losses, and has been the most significant contributor to the major structural failures of civil and military aircraft. Fatigue failure in Hawaii suffered sudden structural failure and explosive decompression is a classic example. The investigation found de-bonding and fatigue damage that had led to the failure. The aircraft involved had completed 89,680 flight cycles with an average flight time of only 25 minutes, almost all of flights being in the marine environment of the Hawaiian Islands, a service life that allowed corrosion to increase the likelihood of fatigue. For fatigue failures, three components are responsible, namely tensile stress, a region of stress concentrations and large number of stress fluctuations (Findlay et al, 2002). Fatigue damage in a failed structure and component is characterized by three distinct regimes: i-crack nucleation region; ii-crack propagation region; iii-Final sudden failure regime. The propagating crack reaches a critical size, at which point the fracture toughness is exceeded, and the structure cannot support the applied loads, and sudden rupture occurs.

There are many variables that influence fatigue, some of which are the mean stress, peak stress, frequency of loading, temperature, environment, material microstructure, surface finish, and residual stresses. Many of these factors are taken into account when determining the Safe Life of a component and, therefore, the majority of fatigue failures in aircraft causing catastrophic failure tend to be those that develop as a result of unforeseen circumstances. Material surface defects such as forging laps, or surface cracking can increase the local stress, producing a concentration at these points that could cause fatigue to occur much faster than would be expected (Findlay et al, 2002).

4.2.1 Fatigue in Military Aircraft

The severe operating conditions for components in military aircraft provide a wide range of failure modes and introduce many factors that can influence those failures (civil versus military). For many years, the Fail-Safe design approach, in which the load path redundancy allows the aircraft structure to survive failure before the crack is detected, has been the mainstay of civil aircraft design. In view of the lower rate of aircraft loss due to structural failure, this approach has been largely successful. In contrast, high-performance military aircraft rely on their performance on highly stressed structures with reduced redundancy, accepting a somewhat higher risk. Furthermore, military aircraft can operate under service conditions, which are more severe than their civil counterparts are; examples include dust-laden environments, heavy and repeated exposure to salt water, and operation from rough airstrips (Clarke et al, 2005; Gurgen et al, 2015).

4.2.2 Case Study of Fatigue Failure

A helicopter undercarriage tube failure occurred catastrophically on landing after 1300 flight cycles, which is well below the expected life (Findlay et al, 2002). Detailed failure investigation based on metallography and micro fractography revealed the cause of premature failure. Fracture surface examination using SEM revealed ductile appearance predominantly indicating static ductile overload, as evidenced in Figure 3. Towards the origin of overload region, fatigue striation observed indicating that crack originated under fatigue, turned to fast fracture under overload condition and catastrophic fracture. This will predict the number of load cycles required to propagate the fatigue crack to failure (Figure 3). The number of load cycles predicted from analysis suggests that the fatigue crack had nucleated almost from the beginning of service life of the component. The origin of the fatigue crack occurred at a notch in the surface of the tube. The notch would have produced a stress concentration in the surface of the tube, thus reducing the time required for fatigue cracks to develop.

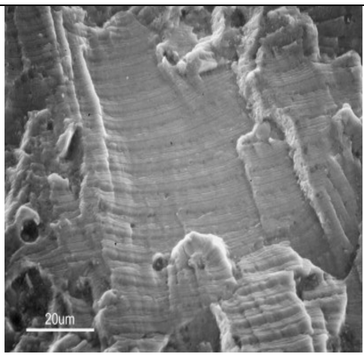
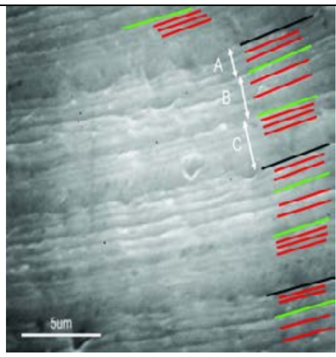
	
Striations observed on the fracture surface	Striations and Bands on the fracture surface

Figure 3: Micro fractography of the origin of fatigue crack leading to premature and catastrophic failures. The striations profile and spacing facilitate identifying the origin of fatigue crack in the microstructure and also estimate the life spent under fatigue as well as predict the life in a component (Findlay et al, 2002).

5.0 FAILURE MODES AND ANALYSIS IN AGED COMPONENTS

This section discusses the essence of aging and failures as experienced in some of the components (Lam et al, 1991; Binard, 1991; Moble, 1999; Rybnikov et al, 2005; Kumar et al, 2007).

a) **Vane stators -** Its main function is to direct the flow of expanding gas to drive the various turbines, where vanes are typically made of cast nickel and cobalt-base superalloys with coatings on top. Air and fuel mixture during combustion is tightly controlled since more fuel means higher temperature resulting in overheating. Contaminated fuels and/or fuels contaminated with foreign particles are likely to deteriorate the corrosion resistance capability of the coating, causing erosion that may eventually lead to the fracture of vane airfoils.

b) **Fuel nozzle -** Type 321 corrosion-resistant steel is normally used for heat shielding for fuel nozzle applications. Cracking in the fuel nozzle was essentially due to chloride-induced stress corrosion cracking Binard, 1991). Chloride contamination occurred during packaging.

c) **Bearings** - Damages occur in bearings mainly due to misalignment of supported shafts, improper balance of rotating assembly, lack of lubrication, surface damage by hard particles, overloading etc. Prime causes of bearing failures include lack of sufficient lubrication, contaminations, both over and underloading (skidding), improper cooling, manufacturing defects and lack of quality control.

d) **Gear -** Common failure problems are due to fracture of gear teeth. Bending fatigue cracking originates at the root.

e) **Shafts -** Usual breakdown mechanisms for shafts are fatigue due to torsional overload. Fatigue failure is mostly related to manufacturing defects such as sharp fillets, machining marks or handling damage.

f) **Combustors and combustion components -** These fail because of over firing, inadequate cooling air flow control, water injection for NO_x control, defective fuel nozzle spray pattern, and combustion instabilities (Moble, 1999).

g) **Coating failure in compressor rotor blades** - Blistering is reported to be one cause of coating breakdown. A standard polymeric coating is an epoxy.

5.1 GTE Blade Failure

Systematic failure investigations and analysis help in identifying the root cause(s) of the gas turbine engine (GTE) failures. This enables remedial measures to prevent recurrence of such failures. Turbine blades made of nickel or cobalt-based superalloys are used in aeroengines. These blades are subjected to complex loading conditions at elevated temperatures (Larsen et al, 2005; Inman, 2005; Patnaik et al, 2002). Increased demand for gas turbine engines has been to produce power from high-temperature high-pressure gas with higher efficiencies. The turbine blades are considered as the most critical components in which failures occur most frequently. Approximately 45 percent of failures in aeroengines are reported to arise from turbine blades due to very high temperature and rotating stress, under the influence of oxidizing environments (Rao et al, 2014; Viswanathan, 2001).

GTE turbine blades failures include oxidation, erosion and foreign object damage. Wide-ranging fuels are used in GTE, but contaminants such as sulphur, sodium, potassium, vanadium, lead, molybdenum etc. have deleterious effects and often become the source of hot corrosion failures. Common damage mechanisms for hot section turbine blades consist of overheating, creep, oxidation, low cycle fatigue and hot cycle fatigue, microstructural instability. Other contributing factors often include environmental attack, corrosion, cyclic loads, over firing, or inadequate refurbishment. Hot section blading is life-limited and require refurbishment or replacement at intervals dependent upon thermal exposure (Moble, 1999).

5.1.1 Thermal Fatigue Cracking of Rotor and Guide Blades

Edge cracking of GTE blades have been experienced in service due to improper blade cooling in advanced aeroengines. These edge cracking failures are also known as thermal cracking. In a coated rotor and guide vanes, coatings are also observed to be cracked due to mainly localized corrosion effects. X-ray and energy dispersive x-ray (EDS) spectrum analysis had reported that sulphidation and surface dealloying due to elevated temperatures were responsible for this corrosion fatigue failure of rotor and guide vanes (Dewangan et al, 2015). On the other hand, failure investigations in blades made from high-temperature alloys revealed a local increase in sulfur content after long-term operation. This sulphide–oxide corrosion attack was found around the regions of cracking (Rybnikov et al, 2005).

5.2 Turbine Blade Failure Case Analysis

A 100 MW, gas turbine engine used for marine applications failed and is used here as a case study to illustrate the mode and mechanisms of failure. The blades were made of nickel superalloy for long term service under exposure to elevated temperature and corrosive conditions. The analysis considered three locations of the blades, namely (root, midspan and tip) of the blade (Rao et al, 2014). No microstructural damage(s) due to operation at elevated temperatures were observed after the metallographic study, revealing that the turbine blades had been operating in designed/normal operating temperature conditions. The turbine blades might have suffered due to both low and high-temperature corrosion apart from erosion. Around the root of the blade, the blade surface colour was different (or changed from original), and surface texture appeared to be uneven and rough, indicating the presence of hot corrosion. At the tip of the turbine blade, certain thinning (reduction in tip thickness) was observed, indicating loss of material. The blade tip was subjected to two simultaneous failure mechanisms, namely hot corrosion and cyclic fatigue (Rao et al, 2014;

Viswanathan, 2001).

At the pressure side blade surface – considerable rubbing and scrubbing marks indicates loss of materials by erosion. Solid particles had caused damages on surfaces, and the particles seemed to have come from the compressor casing during the compression process or from protective coating materials used in the combustor. Multiple failure mechanisms were identified, such as hot corrosion, erosion and fatigue, to have damaged the turbine blade of gas turbine used for marine application (Rao et al, 2014; Viswanathan, 2001).

5.3 Turbine Disc Failure Analysis

Turbine disc technology retains the blades at high rotating speeds/temperatures and transmits the power to the high-pressure turbine shaft. Failure of a turbine disc will result in the uncontained release of large pieces of metal with extremely high kinetic energy (Winstone et al, 2008; Rolls Royce, 2005; Larsen et al, 2005). These put the safety of the entire aircraft at risk. The turbine disc is subjected to varying loading conditions during its operational period. Firstly, very high centrifugal stresses act on discs due to high rotational speed. Secondly, there are loads on the discs rim imposed by the rotating blades, and thirdly, the temperature gradient can induce high thermal stresses during engine starting and shut down period. The dual microstructure of turbine disc offers the best properties that are varied to best resist high and low-temperature loading (David Brown 2020).

6.0 COMPOSITES

Composites with various combinations of metal, polymer, ceramics and in different form and shape (fibers, particulates, laminates) and processing are available for industrial use, in particular for aerospace. Different types of composites exhibit a wide variety of properties and complex failure mechanisms. A common feature of these diverse composite materials is their inhomogeneity and marked anisotropic nature, resulting in physics of fracture mechanisms quite different from those of conventional metallic alloys. Understanding damage accumulation processes in composites has been very challenging to materials scientists and engineers for full exploitation of this new class of structural materials. This section is included in this paper in view of its increasing importance and usage (Thomas, 2016).

6.1 Composite Failure Analysis

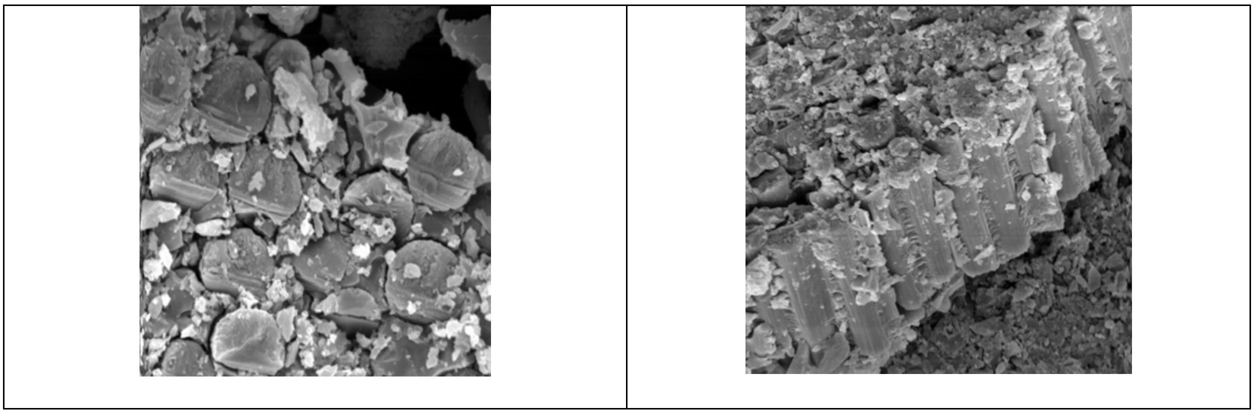
Failure mechanisms of composite systems are a complex multistage process, and completely different from traditional metallic systems. Failure processes and mechanisms in composites are far more difficult to analyze as the initial failure responsible for damage development. Mechanisms often change to another mechanism as the failure progresses, and also during the final steps before the collapse. The failure of composites manifests as a breaking of fibers, development of microcracks in the matrix, debonding between fibers and matrix, and delamination, in which there is a separation of different laminated layers (Thomas, 2016; Houston, 2019).

6.1.1 Fiber Composites

Fiber reinforcement is added to resin systems to increase the tensile strength and stiffness of the finished components. The main types of fiber reinforcement used in the advanced composite industry include carbon, graphite, aramid, ceramic, glass fibers, and in the future, carbon and boron nanotubes (Thomas, 2016). Composites used in aircraft mostly consist of fibers suspended in a matrix of epoxy resin. The Boeing 787 Dreamliner was the first commercial airplane to be constructed from 50% composite materials, mostly carbon fiber composites. Long continuous fibers are considered high performance since the mechanical properties are maximized in this form. This form is the most common type for aircraft applications (Clarke et al, 2005). There is a wide range of thermoplastic composites that are now used in components for the aerospace industry.

6.2 Failure Mechanisms

The damage zone in fiber composites can develop by a number of processes, namely fiber breakage, fiber micro-buckling, fiber pull out, matrix cracking, delamination and debonding. In most cases, a combination of all or some of the different mechanisms prevails (Knauss et al, 2001). The failure mode of unidirectional composite fracture is illustrated with the help of the fractographic investigation in Figure 4. Under tension, fibers of various lengths may be seen as sticking out of the surface, Figure 4(a). Compression failure can lead to the formation of a micro-buckled band in which each fiber suffers two bending failures, with associated markings on the ends of the fibers. Micro-buckling creates a failure, which is very localized on one plane.



(a) (b)

Figure 4: Microscopic view of a fractured composite blade illustrating the mechanisms, (a) bending fracture of individual fibers, and (b) presence of a "kink band" along the line of fracture (Clarke et al, 2005).

The failure behaviour of composites can be affected by several factors such as the composition of matrix and fiber, its content, the nature of the interfacial bonding, fiber orientation, stacking and sequence, void level, and the type of loading. Possible failure modes can include matrix cracking, fiber buckling, pull-out, and breaking, interfacial-bond failure and delamination. Failure mechanisms in fiber composites also depend on the nature of loading :1). under tensile loading – generally, matrix or fiber cracking, debonding; 2). under compressive loading - generally micro-buckling; and 3). under out-of-plane loading - generally delamination.

6.3 Analysis of Rotor Blade Failure

The rotor blades were made of carbon fiber epoxy resin. In each blade, the spar had fractured at the failure location producing relatively flat and featureless fracture surfaces. The tail rotor blade fractures were examined using an optical stereomicroscope, which revealed evidence of compression loading, splitting and crushing damage, at the trailing edges of the blades. Examination of the carbon fiber epoxy spar fractures showed that, while the fracture surfaces were generally flat, fracture actually occurred on numerous discrete planes that differed slightly in height and that some fibrous fracture occurred at the very leading edge of the spars (Figure 5) (Pell et al, 2006).

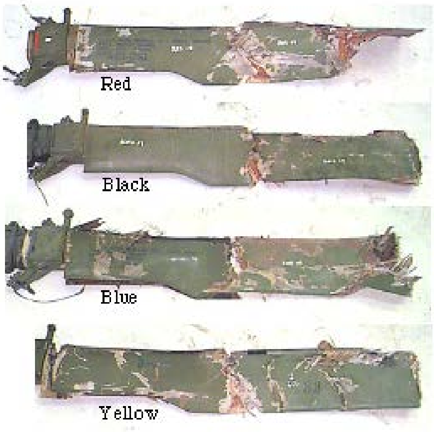


Figure 5: Rotor blade failure case study from a helicopter (Pell et al, 2006).

The SEM examination of the flat fracture regions revealed distinct features on the fracture surface of individual fibers that identified the failure mode as micro-buckling a common form of compression failure in carbon fiber materials (Figure 5). It also confirmed that fracture did occur on discrete planes, each separated in height by a distance of approximately five fiber diameters.

6.4 Helicopter Rotor Head Component Failure

The fracture planes of their helicopter rotor head component failure were relatively flat at the ends and more fibrous in the central region. This indicted that the fractures occurred as predominantly compression fractures at each end with some tension in the central region. The observations indicated that failures started as compression fractures that started at both the leading and trailing edges of the failed arms and progressed rapidly to final failure. Since composites are more susceptible to compression loading, compression fracture would have been the dominant failure mode (Pell et al, 2006). Porosity, delamination, matrix crack, fiber breakage and fiber-matrix debond are among the most common damages in composites.

6.5 Ceramic Matrix Composites

6.5.1 Structural Ceramics

Ceramic materials possess a high strength and modulus at elevated temperatures. However, their use as structural components is severely limited because of their brittleness. Many properties of ceramics and glass make ceramics attractive for aerospace applications. The most important ones are lightweight, high-temperature resistance, electrical insulation, high energy of ablation, resistance to corrosion, chemical stability, wear resistance, and ability to withstand vibration (Li, 2017; Naslain et al, 2004). The main driver is fuel efficiency with higher inlet temperatures of 1500-1600°C without the need for cooling channels.

6.5.2 Characterization and Applications

Ceramics and their composites for aerospace industries belong to oxides alumina and non-oxides carbides, nitrides and borides. The ceramics are uniquely characterized by their high dimensional and thermal stability, and their composition and microstructure that can be suitably optimized to obtain good combinations of mechanical, chemical, thermal properties. Much improved and desirable properties are obtained by adding reinforcing agents with ceramics, such as particles, whiskers and fibers. Notably, improved thermal shock and fracture toughness properties are greatly enhanced for ultra-high temperature applications (Li, 2017;

Naslain et al, 2004). Currently, silicon carbide (SiC matrix/SiC fibers) for use in jet engine turbines have been greatly focussed and mainly concentrated on the turbine blades and combustion liners. Other applications of ceramics in the aerospace industry include brakes, bearings, seals, and other wear-resistant components.

6.5.3 Failure Mechanisms

The major damage mechanisms of CMCs include, matrix multi-cracking, fiber/matrix debonding, fiber pull-out and fiber breakages. Several inspection techniques, such as acoustic emission, tomography, resistivity, ultrasonics, etc. have helped in identifying the damage development in CMCs. The oxidation effects of CMCs must be taken into account for their very high-temperature applications. The oxidation in deteriorating mechanical behaviour should be considered in the design of critical components (Lorgeril, 2015). SiC/SiC composites in steam environments has shown to develop damages very quickly, and thereby reducing the fatigue resistance markedly.

7.0 SUMMARY

The current design and airworthiness for modern aircraft (civilian and military) and helicopters owe heavily to the successful failure analysis (FA) of subsystems and components carried out over the past seven decades. Physics-based approaches have been most effective in understanding damage accumulation and failure modes of components in relation with material microstructure and operating environments. FA has been a continuous evolution process with tremendous advancements made in several directions, namely materials and characterization, processing, computer applications, inspections, including sensoring. FA has helped greatly to revolutionize design concept from traditional to Safe Life, from Fail-Safe to Damage Tolerant to meet severe operating conditions and mitigate greater risk.

Traditional metallic components failures are corrosion and fatigue. Among all mechanisms, failure probability caused by corrosion and fatigue has been 70 percent. Common damage mechanisms for hot section turbine blades consist of overheating, creep, oxidation, low cycle fatigue and high cycle fatigue, and microstructural instability. The mechanisms frequently encountered in polymer composites, include porosity, delamination, matrix cracking, fiber breakage and fiber-matrix debonding, leading to the most common damages found in composites. The major damage mechanisms observed in ceramic composites may include matrix multi-cracking, fiber/matrix debonding, fiber pull-out and fiber breakages.

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