The Need for Aerospace Structural Health Monitoring: A Review of Aircraft Fatigue Accidents

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ABSTRACT

Aircraft accidents involving catastrophic fatigue failure have the potential for significant loss of life. The aim of this research was to investigate trends in aircraft fatigue failure accidents to inform aerospace Structural Health Monitoring (SHM) system Research and Development (R&D). The research involved collecting 139 aircraft fatigue failure accident reports from the Aviation Safety Network database, which were coded using a directed content analysis. The trends and features of the categorical data were then explored using an ex-post facto study. The results showed that fatigue failure accidents have increased at a rate of $(3.4 \pm 0.6)\times10^{-2}$ per year since the 1920's. Over the period of the study there were 2098 fatalities in 57 fatal accidents, giving (15.1 ± 1.6) fatalities per accident and a fatal accident percentage of $(45 \pm 10)\%$. While there is a desire to further improve safety for large transport category aircraft, results indicate that smaller aircraft and operators have seen a relative increase in fatigue failure accidents, and hence are also in need of SHM systems. Engine and undercarriage systems have the greatest number of fatigue failure accidents associated with them, suggesting these should be the focus of SHM R&D.

1. INTRODUCTION

1.1. Aim

The aim of this work is to understand the need for aerospace vehicle Structural Health Monitoring (SHM). This technology has the ambitious goal of improving the safety and service life of future robust or ageless aerospace vehicles (Price et al., 2003). To inform the Research and Development (R&D) of these systems requires answers to the questions, what are the most common features of aircraft fatigue failure accidents, and how have these changed over time? This understanding will provide a better insight of the specific requirements for SHM systems, and how they can best be utilized for their intended purposes, to improve safety, and increase the service life of aerospace assets. This last point is important, given aircraft have a significant capital cost associated with their acquisition and operation.

1.2. Background

1.2.1. Fatigue

The definition of fatigue according to ASM International is "the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point (or points) and that may culminate in cracks or complete fracture after a sufficient number of fluctuations" (F. C. Campbell, 2012a). This process has been extensively studied since 1838, and knowledge and understanding has developed since that time (Schütz, 1996).

A fatigue load is one that is not strong enough (well below the yield strength of the material) to cause permanent deformation in a single cycle (F. C. Campbell, 2012a). However, multiple continuous cycles of an applied load can result in nucleation (crack formation) at regions of high stress concentration. These high stress regions result due to manufacturing errors, abrupt changes in geometry, material imperfections and other stress concentrating factors. Continuous fatigue loading cycles cause the crack to grow progressively creating permanent damage around that region. Local damage will continue to grow until the undamaged

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section can no longer support the applied loads which may result in sudden fracture ending the life of the component.

Due to an applied fatigue cycle, two modes of failure exist for metals, these are ductile fracture and brittle fracture (F. C. Campbell, 2012b). Ductility is a measure of a material's ability to permanently deform due to an applied load before failure. Brittle behavior generally takes place in materials with high hardness and strength where little to no permanent deformation occurs before fracture. Some materials such as steel, exhibit a ductile-to-brittle behavior as temperature decreases. While steel at room temperature under high tensile load will sustain a plastic deformation without failure, at a lower temperature it will fracture in a brittle manner. This is relevant to aircraft where the operating environment see sustained operation at -56.5^{o}C.

For polymers, such as those used in carbon-fiber reinforced plastic (CFRP), the fatigue behavior is very different and case dependent as they are highly anisotropic. The fatigue response will depend on the intraplanar stress and strains in the ply or laminae, which differ based on the orientation of the fibers. As polymers consist of the matrix and fibers, the response of each material to the same applied load is different. The direction of which the load is applied also plays a major role in the response of the part as the direction along the high strength fibers would withstand higher loads compared to the matrix loaded side (F. C. Campbell, 2012d).

The fatigue mechanics of composite materials can be very complex and their behavior difficult to predict. Unlike metallic alloys, fatigue in composites is generally characterized by an accumulation of damage as opposed to a single crack and can occur through a variety of mechanisms such as; fiber breakage, matrix cracking and delamination (Harris, 2003). Furthermore, due to use of fiber reinforcement and the exceptional tensile strength of the material, composites can exhibit a behavior akin to that of a fatigue limit observed in metals under tensile loading. However, under flexural loading, the composite can begin to crack and eventually delaminate, resulting in sub-laminates that are highly prone to buckling under compression, drastically reducing the life of the composite (Harris, 2003). Damage can often be very difficult to detect and even in the case of visual evidence, difficult to ascertain the extent of damage through the thickness of the laminate. Fatigue life testing in laboratory settings presents with large scatter, preventing confidence in the use of life prediction techniques. Application of quantitative methods is difficult due to interaction of the numerous damage mechanisms. As a result, design measures are often employed to enforce a no-growth philosophy such that the material should unquestionably outlast the structure's lifetime (Harris, 2003).

There are two types of fatigue cycles, High-Cycle Fatigue (HCF) and Low-Cycle Fatigue (LCF). HCF occurs when loads below the yield stress are applied which allows for a longer "service life". HCF leads to elastic deformation where the part returns to its initial condition after unloading. LCF loads are higher than the yield stress and result in a shorter "service life". LCF leads to permanent plastic deformation where the severity of this deformation depends on the average effective stress amplitude of the applied load. The response of the material to the applied load (HCF or LCF) will depend on the ductility of the material. The more ductile it is, the larger the number of cycles that can be withstood before fracture (F. C. Campbell, 2012c).

1.2.2. Aircraft Inspection

All aircraft are required to complete an annual or a 100-hour inspection (Civil Aviation Act, 1988; FAA, 2018). Most commercial aircraft will be utilized in flight operations far more frequently than non-commercial aircraft, and hence instead of an annual inspection they undergo a 100-hour inspection. These inspections can be completed in a single instance or could be split into four to six inspection cycles in accordance with government regulations. However, these inspection cycles must be completed within 12 months to be certified as an annual inspection (Civil Aviation Act, 1988; FAA, 2018).

Large or turbine powered aircraft undergo a continuous inspection program which include both routine and detailed inspections. The detailed inspections are categorized into 'checks', A-check, B-check, C-check and D-check. These categories are in place as detailed inspections take a long time which will ground an aircraft keeping it out of service for the duration of the inspection. As such, these 'checks' are completed throughout the life of the aircraft in accordance with the FAA and CASA regulations. The A-check is the least comprehensive and occurs frequently while the D-check is very comprehensive involving disassembly, removal of parts and detailed inspection of components and systems. As such, the D-check is not frequently done and might occur only three to six times during the service life of an aircraft (FAA, 2018).

Before the technician starts the maintenance or inspection process, the parts are cleaned and wiped thoroughly. A detailed checklist is followed which is split into different groups to facilitate the inspection process. These are the fuselage and hull, cabin and cockpit, engine and nacelle, landing gear, wing and center section, empennage, communication and navigation, propeller, and miscellaneous. These groups include subcategories that cover all parts of the aircraft which should be accounted for during the inspection process. The history of maintenance of an aircraft must be outlined clearly in a logbook which must be kept up-to-date at all times (FAA, 2018).

These inspections utilize Non-Destructive Testing (NDT) techniques, which are essential, given that the components are likely to be returned to service on an operational aircraft; that is, the components must be inspected without damaging or destroying them. There are many commonly used NDT methods in the aerospace industry; including (FAA, 2018):

- Visual Inspection: is the simplest form of inspection where trained personnel look at aircraft parts for any scratches, major damage, or any discrepancies. Visual inspection may be aided by devices such as borescopes to see inside structures.
- Tap Testing: for composites is the simple act of tapping on the surface and listening to the sound, which can give an indication of any underlying damage. Typically, the technician taps the surface with a specifically designed hammer and listens for an atypical acoustic response.
- Ultrasonic Inspection: is widely used in the aerospace industry as it can detect manufacturing defects and in-service damage. It operates by sending ultrasonic pulses from a piezoelectric transducer through the test specimen. Cracks or voids are detected as they have a different acoustic impedance to defect free areas. There are multiple methods to apply the ultrasonic inspection, some need access to both sides of a part and need access to just one side, meaning the part does not have to be removed from the aircraft. It can be used for all types of materials.
- Liquid Penetrant Inspection: is used for metals where a bright visible dye is applied on a part then cleaned. After which, a developer is sprayed on the part to draw the dye onto the surface revealing any surface breaking. This method only works for metals and can only show surface or near surface cracks.
- Thermography: can be either active or passive. Active thermography is the most common and is achieved by applying external heat to the surface of the material. The surface is then monitored using an Infra-Red (IR) camera as it cools. While a homogenous material will dissipate heat uniformly, cracked regions will dissipate heat slower. The IR camera detects these “hot spots” on the surface as well as some subsurface damage. Passive thermography detects the heat generated from cracks and damage growth. This method is not very common as the part needs to be damaged enough to generate the required amount of heat, dictated by the sensitivity of the detection system.
- Eddy Current Inspection: consists of a conductive metal coil charged with an AC current which generates a magnetic field around it. When it is placed at close range to a conductive material, an Eddy current is produced. Surface and near-surface cracks are detected when they interrupt the flow of the Eddy current. This method does not work very well if the cracks are parallel to the current and do not disturb its path. There is some progress in research regarding the use of this method for other materials such as CFRP, but it is mainly used for metals.
- Radiographic Inspection: detects damage using x-rays, gamma-rays, or high-energy neutrons. Voids or damage absorb much less radiation than solid or undamaged areas; the resultant radiography image highlights this contrast, showing the size and shape of voids and damage. Radiography can not only detect damage and voids, but it can also detect corrosion damage and intermolecular inclusions. However, cracks that lie perpendicular to the radiation path cannot be detected.
- Acoustic Emission: uses sound waves emitted from damage. These sound waves are emitted due to the release of strain energy from microcracking.
- Magnetic Particle Inspection: magnetized a part then the surface is coated with small magnetic particles such as iron filings. Surface cracks or corrosion areas create a flux leakage which attracts the iron filings. Once all the filings are stationary, the regions of cracks can be determined. However, this method only works for surface cracks of ferromagnetic materials such as steel and nickel-based alloys.
- Magnaglo Inspection - is similar to magnetic particle inspection; however, in magnaglo inspection, the part is magnetized using a fluorescent particle solution under ultra-violet light.

1.3. Significance

The de Havilland Comet 1 disaster on 10 January 1954 when Comet G-ALYP (Yoke Peter) crashed into the sea after attempting a climb to 27,000 ft highlighted material fatigue failure in the aviation industry (Withey, 1997). The Comet is picture in Figure 1. The Comet fleet was grounded after a similar incident occurred on 8 April 1954 with the Comet G-ALYY (Yoke Yoke) (Withey, 1997). As a result, an inquiry was established, and intensive works began to reconstruct the Yoke Peter wreckage as well as to conduct extensive testing on the Yoke Uncle to determine exactly what the cause of the crashes was. As a result of testing and thorough forensic work, it was concluded that a series of fatigue cracks originating from the corner of cabin windows resulted in sudden cabin failure and breakup of the Yoke Peter (Withey, 1997).

Figure 1. The Comet G-ALYX (Yoke X-Ray), equivalent to the aforementioned Comet 1’s (RuthAS, 1953).

Whilst de Havilland had performed structural assessments of average sections of the cabin and obtained the fatigue life based on these results, full-scale assessment of the airframe had not been performed (Withey, 1997). Furthermore, the structure used for fatigue testing had been previously tested under static load conditions, possibly causing plastic deformation in the regions of high stress concentration that had artificially increased the measured fatigue life of the craft (Withey, 1997). The result was crack growth from regions of high-stress concentration such as holes and cut-outs. The Comet 1 had been designed with a safe-life fatigue methodology, such that the airframes should have been retired before significant structural damage had occurred (Wanhill, Molent, Barter, & Amsterdam, 2015). It was seen as a result of these incidents that many aspects of fatigue analyses could not be or were difficult to account for, resulting in an industry-wide shift to fail-safe design techniques (Wanhill et al., 2015).

The development of best fatigue design practices continued with numerous milestone cases including the 1969 F-111 incident in which a fighter lost its left wing after only 107 accumulated airframe hours and was executing a maneuver at less than half the design limit load (Wanhill et al., 2015). The result of the incident was the development of damage tolerant methodologies by the US Air Force (Wanhill et al., 2015). Damage tolerance designs consider if a component is capable of performing the intended function when damaged such that it can continue to operate safely between the prescribed scheduled maintenance and inspection cycles (Miller, 2000). This provides a balance between economics of operation and the cost of safety.

Fatigue remains a significant problem for the aviation industry with an estimated 55% of aircraft structural failures attributed to some form of fatigue damage (Findlay & Harrison, 2002). Goranson (1998), reflected on how 85% of service problems could be attributed to differences between the operating stresses and those used in the fatigue analysis, calling on the need for a standardized fatigue process. The research further noted how some aircraft were being repaired when corrosion was detected and no preventative means were taken, creating a significant opportunity for the initiation of fatigue growth.

Aging aircraft pose a serious safety problem as the accumulation of fatigue damage increases over time. Widespread fatigue damage is the greatest threat to the aging fleet. Multiple Site Damage (MSD) and Multiple Element Damage (MED) can result in the link up of numerous small cracks that would otherwise be deemed safe, creating the means for catastrophic failure (Goranson, 1998). Despite numerous advances in both material and structural sciences and intensive maintenance regulations by governing bodies, fatigue accidents still plague the aviation industry. The work notes how "timely damage detection is the key element to ensuring structural damage tolerance", indicative of a world where fatigue damage can never be completely eliminated, but in which it must be promptly detected, located and repaired (Goranson, 1998).

At an estimated cost of $3.1 million (Australian) per in-flight fatality in 2019, airframe reliability is both an economical and safety issue. This number was calculated from the 2003/2004 result reported by BITRE (formally BTRE), factoring inflation through to 2019 (BTRE, 2006). During that time (2003-2019) there have been 400 fatalities associated with fatigue accidents, giving a total cost of $1.237 billion (Australian).

2. LITERATURE REVIEW

2.1. Previous Surveys and Reviews

One of the most infamous cases of aircraft fatigue is associated with the de Havilland Comet 1. Withey (1997) summarized the events of the Comet failures that largely unveiled the issue of fatigue to the aviation industry. Furthermore, Withey applies modern fracture mechanics to assess the failure of the Comet, techniques that were not available at the time of its design.

Schijve (1994) highlighted four major milestone aircraft accidents that have changed and educated aviation perspectives of material fatigue. The work showed that cooperation between the three major stakeholders; the aircraft industry, airlines and airworthiness authorities is essential to find better solutions in pursuit of improved safety. Furthermore, the author reflects on how fatigue performance can be improved through new "design concepts, production technology control and new materials", particularly highlighting the use of fiber-metal laminates. Schijve (1994) also comments on the dangers of an aging aircraft fleet, noting how 46% of aircraft in 1991 were over 15 years old and 26% over 20 years. Schijve (2009) provided a personal impression on the history of aircraft fatigue and design against fatigue; specifically, whilst the bulk of fracture mechanics is well understood, an understanding of the crack initiation and final failure modes lacks full comprehension. (Schijve, 2009) also encouraged the contribution of both industry and university to solve the issue of fatigue due to the multi-disciplinary nature of the problem.

2.2. Previous Accident Case Studies

Salam, Tauqir, Haq, and Khan (1998), examined the failure of a ball bearing in an aircraft engine compressor. It was found that in the 5 hours since the part had been previously serviced, the cage of the bearing had become misaligned that resulted in loading eccentricities, large deformations, and rapid fatigue failure of the component. The failure of the cage was determined based upon analysis of the fracture surface. Similar work examined a similar incident of failure of the central main bearing of a turbine engine (Tauqir, Salam, Haq, & Khan, 2000). Machining marks had resulted in early fatigue failure of the bearing cage. The work concluded that the failure of the bearing was the result of its design.

A number of other propulsion systems and elements have been found to suffer from fatigue. Lourenco, Von Dollinger, Graça, and de Campos (2005), examined the failure of a helicopter rotor grip that showed over half of the fracture surface as having beach marks. They concluded that the fatigue failure of the grip initiated from corrosion pitting due to the helicopter being exposed to a corrosive maritime environment. Fatigue failure on the turbine and compressor of a gas turbine is common. Ejaz, Salam, and Tauqir (2007), examined the crack of a fighter aircraft that resulted from failure of the 9th stage compressor disk of the turbine engine. They concluded that the failure was a result of fatigue crack growth, originating from a hole that had followed machining marks, resulting in a final catastrophic length of 30 mm. Similar work by Lourenço, Graça, Franco, and Silva (2008), analyzed the failure of the fifth compressor blade of a turbine engine as a result of fatigue. They traced the initiation of the failure to corrosion pitting that acted as a stress concentration and ultimately resulted in a decreased lifespan of the component. While gas turbine engines operate at very high pressures and temperatures, fatigue is an issue in piston engines. Infante, Silva, Silvestre, and Baptista (2013), examined the failure mechanics of a crankpin journal for an ultralight aircraft engine. Noting that fatigue is the most common cause of failure in crankshafts in which misalignments can result in loading eccentricities and high stress concentrations that result in undue stresses and early fatigue failure. They concluded that the crankpin failed due to combined contribution from an undercut fillet, lubrication hole and possible forging defects.

Similar to engines, undercarriage and associated systems are also exposed to high load, temperatures, and pressures (in terms of hydraulic fluids). Le May (2010), summarized three cases of fatigue failure; landing gear, roller bearing, and a gas turbine blade failure, none of which resulted in fatalities. Infante, Fernandes, Freitas, and Baptista (2017), assessed the cause of a nose landing gear; two thirds of the total fracture surface showed beach marks with the remaining surface indicative of sudden failure. The beach marks were deemed a result of cyclical bending stresses from the 17,000 lifetime landings. It was concluded that the failure was a result of fatigue in the presence of higher-than-expected loads. These conditions are similar to those of traditional mechanical flight control systems. Kubryn et al. (2018), investigated the fatigue of tensile steel cables and their use in aircraft control systems. Showing significant standard deviation, the authors indicated that the results of the durability tests were "surprising" and were most likely due to variances in cyclical-bending the cables experienced during operation.

High cycles and loads are not the only reason for fatigue failure, materials and manufacturing have are also potential causes. Sujata, Madan, and Bhaumik (2014), analyzed the failure of the main fuel pump of a fighter aircraft. The work revealed that the failure occurred because of fatigue fracture of one of the pump springs, caused by corrosion pitting as an effect of improper storage of the spring stock material. Similar work of fuel systems highlighted the role of manufacturing in aircraft fatigue accidents (Sujata, Madan, Raghavendra, Jagannathan, & Bhaumik, 2019). This work examined the failure of a fighter aircraft due to fuel leakage. Tracing the failure to fatigue fracture of a fuel supply pipeline, the authors noted that the pipeline, whilst showing significant deformation, was a result of improper brazing in its manufacturing and not that of low-cycle fatigue.

2.3. Fatigue Failure Analysis Techniques

Other relevant literature has focused on techniques to analyze fatigue failure. Berkovits (1995), proposed a method of analyzing the fatigue failure of a component whereby the loading on the component could be estimated by examining the crack depth and growth rate as well as the material properties and stress concentrations, derived from finite element analyses. Other work on fatigue failure analysis (Jones, Pitt, Constable, & Farahmand, 2011), presented variations of the Frost-Dugdale crack growth law for the analysis of short cracks in Region I of fatigue analysis. This work revealed good correlation between the generalized Frost-Dugdale growth law and experimental material data. While materials science is essential for analysis, sensing is also essential. Bohacova (2013), showcased the use of eddy current NDT techniques to detect a short crack located under the head of a rivet as well as a manufacturing defect that had occurred in an aircraft glider structure. Several NDT techniques can be applied to the analysis of fatigue failure. However, the case is much more complex for composite materials (Zimmermann & Wang, 2020), given they fail quite differently to metallic structures and that metallic fatigue theory cannot be directly applied to their composite counterparts. Slattery and Cizmas (2018) present the concept of entropic inequality and its uses in fracture mechanics on complex structures to predict fatigue failure and lifespan. The authors note that entropy inequality is often an overlooked parameter and is as important as "mass, momentum, and energy balances."

3. MATERIALS AND METHODS

3.1. Research Design

This study utilized an exploratory design (Leedy & Ormrod, 2013), utilized in previous post-accident research (Khan, Ayiei, Murray, Baxter, & Wild, 2020). The first stage of the research involved qualitative directed content analysis (Hsieh & Shannon, 2005). This provided data for a quantitative ex-post-facto study typical in post-accident analyses (Ayiei, Murray, & Wild, 2020; Kharoufah, Murray, Baxter, & Wild, 2018; Wild, Murray, & Baxter, 2016). In this approach, the categorical data from the aircraft fatigue related accidents were extracted, and then the qualitative narratives were coded with a predetermined (directed) coding structure, to generate additional categorical variables. Once coded, all the data was analyzed in an ex-post-facto study, to analyze the trends over time to assess if any observed differences were statistically significant.

3.2. Data Collection, Cleaning, and Coding

Data was collected from the Aviation Safety Network (ASN), which is a service provided by the Flight Safety Foundation (Aviation Safety Network, 2020). A limitation of the ASN is that it has no inbuilt search function; to work around this, Microsoft Bing was utilized (Google was initially utilized, but it returned less results, even when requesting duplicates not be excluded). In this search, the site was limited (using “site:”) as the ASN database, and the title of the results was limited (using “intitle:”) as it was noted that all reports generated the title that commenced with “ASN Aircraft Accident”, with only the record number at the end changing. It was also noted that as a multilingual database, limiting the title also limited the results to English, preventing duplication. The search term used included a single keyword, “fatigue”. While this was not the most efficient search, it was the most effective. That is, fatigue is also a human factor in aviation safety (Kharoufah et al., 2018); hence, for each search result (approximately 380), the narrative was checked to determine if it was a technical or human factor case of fatigue, for inclusion or exclusion respectively.

All the accidents in the ASN database are pre-coded with:

- Date,
- Aircraft type,
- Number of fatalities (crew, passengers, and external),
- Location and country (country given as a flag, which included an alt text field),
- Operator and type of operation,
- Phase of flight,
- Date (year) of the aircrafts first flight, and
- Accident category (aircraft fate, given as A1 a hull loss, or A2 repairable).

Other characteristics were also included, but were not of interest (registration, serial number, flight number, and departure and destination airports); some cases also included total airframe hours, and cycles. These were not commonly available, although would have been an interesting independent variable for fatigue.

Based on the aircraft type, further codes were produced: engine type, number of engines, and maximum takeoff mass, which are all commonly used in safety reports as independent variables. The aircraft type was also used to code the aircraft manufacturer; where the manufacturer no longer existed, it was linked to the entity that had acquired the organization or type (for example, Douglas became McDonnell Douglas, which merged with Boeing). The difference in the date (year) of the accident and the date (year) of the aircraft’s first flight was used to determine the aircrafts age (in years) at the time of the accident. It should be noted that six of the entries were missing the aircraft’s first flight date, and it was subsequently sourced from other sources (baaa-acro.com, Grumman goose central, and airport-data.com). The country was converted into the corresponding world region (continent), using a simple lookup table. Modifications were made to phase of flight, such that this corresponded to the state phase of the flight in which the aircraft was operating when the fatigue failure occurred. There were 14 cases where the phase of flight was re-coded. Finally, each of the narratives was then coded according to the ICAO occurrence categories and EASA safety issues (Wild et al., 2016), as well as to identify the specific system or component that failed

3.3. Analysis

The data analysis had two parts, these can be categorized as the parametric and non-parametric components. The parametric analysis considered the number of accidents as a function of the variables of time and age. In the non-parametric analysis, while time was still a dimension, this was converted in the non-parametric ordinal variable of prior to 1995 (1926-1994) and after 1995 (1995-2019). These two groups split the data into two first halves ($n_1 = 70$, $n_2 = 69$). The non-parametric analysis utilized all the categorical variables above.

3.3.1. Parametric Analysis

For the parametric analysis, two regression tools were utilized to measure the association between the variables. For the count variables Simple Linear Regression (SLR) was utilized. Specifically, four SLR models were tested, two for accidents and fatalities, each against the decade of occurrence and the age of the aircraft. For the fatalness, which is a dichotomous variable (fatal or not), a logistic regression model was utilized, for both the year of occurrence and age of the aircraft. For all the regression models, the statistical hypotheses tested were:

H_0: $\beta = 0$

H_A: $\beta \neq 0$

The null hypothesis states that the model coefficient (β) between the dependent and independent variables is zero, and therefore there is no association between the variables.

3.3.2. Non-Parametric Analysis

To identify changes in the proportions of categorical variables over time requires the use of a Pearson’s Chi squared test for independence. The test for independence is ideally suited when accidents (safety occurrences) are categorized into two nominal (or ordinal) variables simultaneously (Wild, Gavin, Murray, Silva, & Baxter, 2017). In this work, a single categorical variable (those identified in Section 3.2) is used, and each of these distributions is divided into two equal halves (1926-1994, and 1995-2019). The expected data is the "average" of these, such that no difference is assumed, and hence the two halves are not independent. The statistical hypotheses to be tested are:

H_0: $P_{1926\text{-}1994,n} = P_{1995\text{-}2019,n}$

H_A: $P_{1926\text{-}1994,n} \neq P_{1995\text{-}2019,n}$

The test is therefore being conducted to determine if the proportion of the aircraft fatigue accidents from 1926-1994 are the same as the aircraft fatigue accidents from 1995-2019 (the null hypothesis), or they are independent (the alternative hypothesis). The chi squared test statistic, or χ^2, is given by (Berman & Wang, 2011),

$$\chi^2 = \sum_{i=1}^{n}\sum_{j=1}^{m}\frac{\left(O_{i,j} - E_{i,j}\right)^2}{E_{i,j}} \tag{1}$$

where there are m groups (n=2), and n options for each for each categorical variable. The number of degrees of freedom, df, is given as (n – 1)(m – 1) for each test. To assess how much the two groups differ relative to the total number of observations, the relative percentage different (Δ) can be utilized, which for a test for independence between 2 groups is given by,

$$\Delta_j = \frac{\left(O_{2,j} - O_{1,j}\right)}{\sum_{i=1}^{2}\sum_{j=1}^{m} O_{i,j}} \times 100\% \tag{2}$$

That is, Δ is the difference between the observed group values for each option of the categorical variable is divided by the total number of observations and is converted to a percentage.

4. RESULTS AND ANALYSIS

4.1. Parametric Study

4.1.1. Decade Count

The trend in terms of the number of aircraft fatigue accidents is shown in Figure 2. There is a statistically significant increasing trend ($\beta_D = 0.3436$, $p < 0.001$). That is, the number of aircraft fatigue accidents is increasing by approximately 3.4 per year. It should be made clear that the data from the ASN only includes fixed wing aircraft with passenger capacities greater than 12. This means most General Aviation (GA) aircraft as well as all rotor wing aircraft, and their associated accidents are excluded from this study. This will be discussed further in Section 5.2. While some older studies can show significant numbers historically (G. S. Campbell, 1981; G. S. Campbell & Lahey, 1984), if a source of data was readily available to capture all global aircraft accidents, it would likely show the same trend, a linear increase in fatigue accidents. An exponential trend was also tested, which resulted in a lower significance. Assuming the growth is linear, this would be relative to an exponential growth in traffic, which when combined would produce an accident rate that is decreasing overtime.

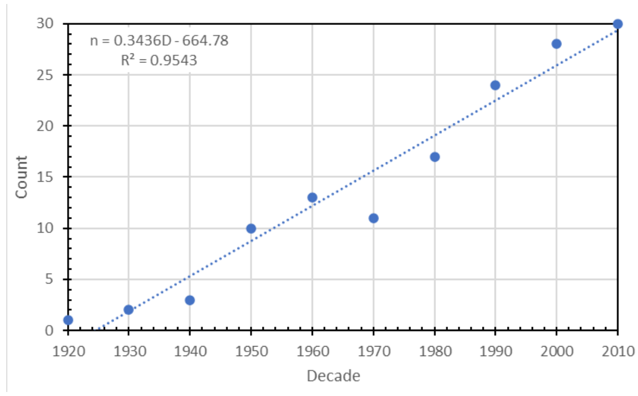

Figure 2. Simple linear regression for number of accidents (n) as a function of the decade (D) in which the fatigue failure accident occurred.

4.1.2. Age Count

Given fatigue is associated with the aging aircraft issue, it was initially hypothesized that the number of accidents should increase as a function of age ($\beta_a > 0$). Figure 3 shows the number of aircraft fatigue accidents in each age group (5 years each). While this is clearly not linear, the result of the regression ($\beta_a = 0.3836$, $p < 0.001$), means the alternative hypothesis, which in this case is that ($\beta_a <= 0$) is clearly true, and hence needs to be accepted. It should be noted, that as expected, the distribution of accidents follows more of a Poisson distribution, with the peak in the 10 to 15 years old range. If this distribution is compared with the similar distribution for maintenance related accidents (Khan et al., 2020), there are significantly more fatigue accidents that occur at less than 10 years of age, and significantly less for 10 to 30 years of age, when looking in age groups of 10 years, up to 50 ($\chi^2 = 64$, $v = 4$, $p < 0.01$). This indicates that contrary to the initial hypothesis, fatigue failures are more likely to occur with an aging airframe. Specifically, 50% of aircraft fatigue failure accidents occur with an aircraft that was less than 15 years of age.

4.1.3. Year Fatalness

While raw count of the number of aircraft fatigue accidents is a key metric, the severity of those is also important to understand. The most significant of these is in terms of the fatalness of the accident; that is, whether the accident results in a fatality. Looking at how fatalness has changed as a function of time provides a useful insight, as it enables us to determine if while the number of aircraft fatigue accidents has increased, as their severity also increase. Figure 4 shows the dichotomous fatalness (0 = not fatal, 1 = fatal) as a function of the year in which the accident occurred. The results for the logistic regression are statistically significant

(McFadden's pseudo r^2 = 0.135, χ^2 = 17, & p <0.001). So, while for the first half of the data the outcome was more likely to be fatal than not. The point of even odds corresponds to 1983. That is, since 1983 an aircraft fatigue accident has been less likely to result in a fatality.

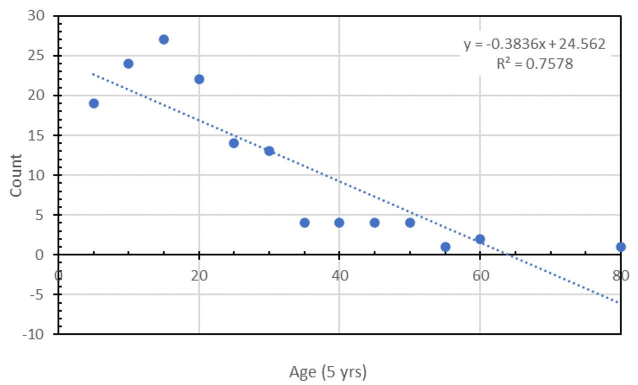

Figure 3. Simple linear regression for number of accidents as a function of age of the aircraft at the time of the fatigue failure.

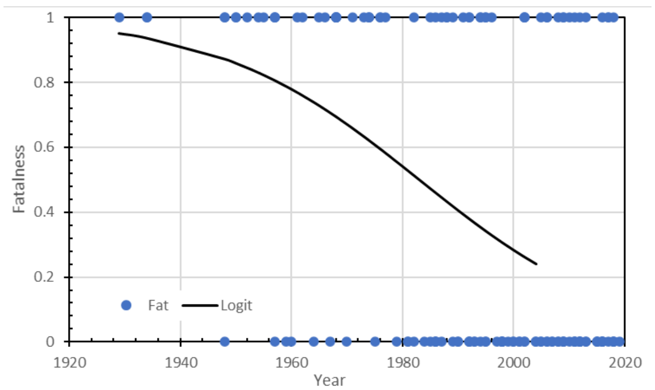

Figure 4. Logistic regression for fatalness (0 = not fatal, 1 = fatal) as a function of year in which the fatigue failure accident occurred.

4.1.4. Age Fatalness

Figure 5 shows the fatalness of an accident as a function of the aircrafts age. In contrast to the results of Section 4.1.3, there is no correlation between fatalness and age significant (McFadden's pseudo $r^2 < 0.001$, $\chi^2 < 0.001$, & p = 0.99). That is, if an older aircraft is involved in a fatigue accident, it is not more likely to result in a fatality.

4.2. Non-Parametric Study

Table 1 summarizes all the chi squared test results. Four of these are not statistically significant, specifically, region of occurrence (Reg), type of operation (Op), phase of flight (PoF), and occurrence category (OC). That is, none of these dimensions show any significant change between the period of 1926 to 1994 and 1995 and 2019. The remaining 8 categorical variables resulted in statistically significant differences. Specifically, fatalness (Fat), aircraft fate (Fate), aircraft manufacturer (Manu), mass category (Mass), engine type (ET), number of engines (#E), system of component that failed (Sys), and safety issue (SI). Each of these has changed between the two halves of the study.

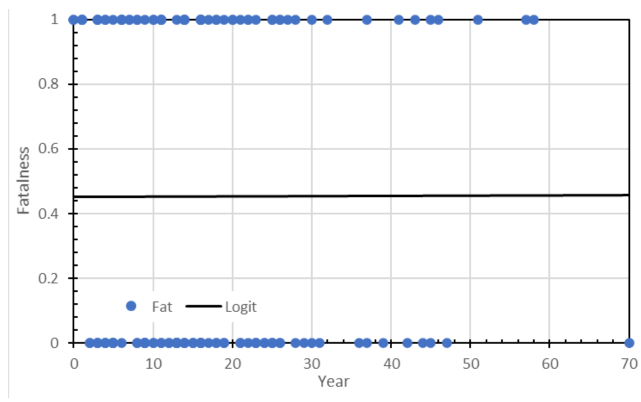

Figure 5. Logistic regression for fatalness (0 = not fatal, 1 = fatal) as a function of age of the aircraft at the time of the fatigue failure.

Cat.	χ^2	v	p	Conc.
Fat	15	1	<0.01	Re
Fate	4.2	1	0.04	Re
Reg	6.6	5	0.16	A
Op	6.5	6	0.37	A
PoF	8.1	5	0.15	A
Manu	24	9	<0.01	Re
Mass	13	3	<0.01	Re
ET	22	2	<0.01	Re
#E	12	4	<0.01	Re
Sys	17	5	<0.01	Re
SI	14	3	<0.01	Re
OC	5.9	6	0.44	A

Table 1. Chi squared test for independence results.

4.2.1. Fatalness

As in section 4.1.3, fatalness has decreased over time (Figure 6). The same conclusion is reach here with the non-parametric analysis. The number of fatal accidents has almost halved, which for the total sample of 139, corresponds to a 32% swing from fatal to not fatal. In the first half of the data, more than 50% of accidents were fatal, while in the second half, a less than 50% were fatal. Specifically, the average percentage of fatigue failure accidents that were fatal was (45 ± 10)%. In the first half of the data this was (61 ± 17)% and reduced to (29 ± 10)% in the second half.

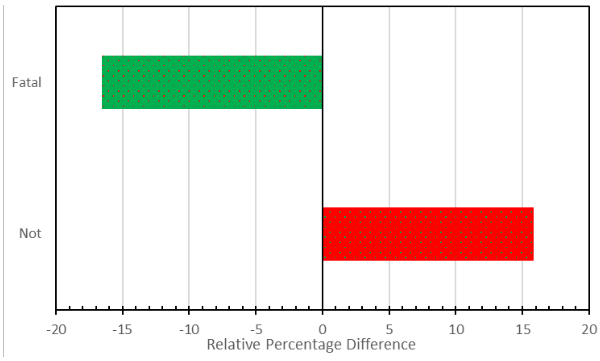

Figure 6. Deltas for fatalness of the fatigue failure accidents.

4.2.2. Airframe Fate

Like fatalness, which is a metric of severity for passengers and crew, the fate of the airframe is a metric of severity for the aircraft itself. As indicated in Table 1, there is a statistically significant change in fate from the first half of the data to the second half. Specifically, in Figure 7 the proportion of aircraft written off has decreased, although it is still more likely for the airframe to be written off. On average, the percentage of fatigue failure accidents that result in the airframe being destroyed is (68 ± 13)%. In the first half of the data this was (76 ± 19)% and reduced to (59 ± 16)% in the second half.

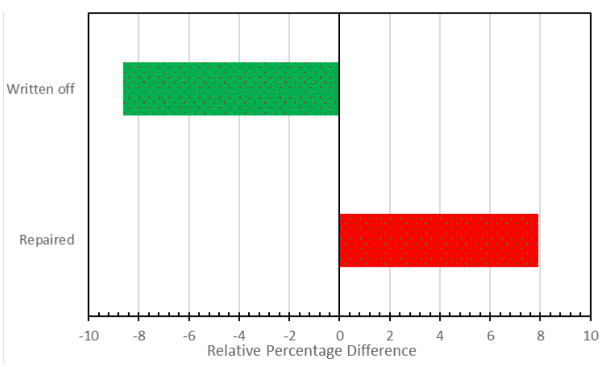

Figure 7. Deltas for airframe fate (destroyed or not).

4.2.3. Region

Figure 8 shows the distribution of aircraft fatigues accidents by the region in which the accident occurred. While North America (NA) and Africa (A) both show an increase, the results shown in Table indicate that the difference are not significantly significant. That said, previous research has identified issues in the significant growth in accidents in Africa (Kharoufah et al., 2018), especially relative to the traffic growth. The other regions, South and Central America (S&C A), Asia & Pacific (A&P), and Europe (Eu), all showed a statistically insignificant decrease.

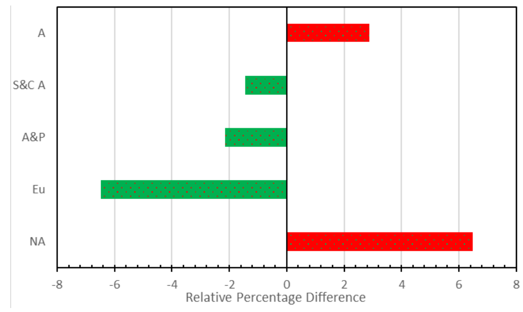

Figure 8. Deltas for world region in which the fatigue failure occurred.

4.2.4. Operation

The type of operation the aircraft was involved in when the accident occurred is an interesting feature. Figure 9 illustrates the insignificant result given in Table 1. Several of the operation types have seen no change in count numbers, e.g. international passenger service (Int), while there has been a small decline in domestic passenger (Dom) and cargo operation related accidents, and GA and Charter have experienced a small increase.

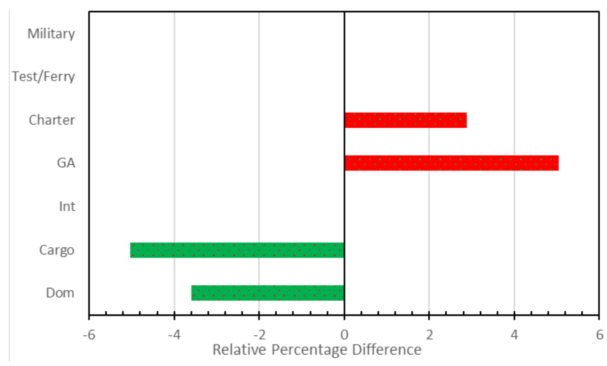

Figure 9. Deltas for type of aviation operation the aircraft was undertaking.

4.2.5. Phase of Flight

As with region and operation, phase of flight also shows a statistically insignificant change in distribution between the two groups. Figure 10 shows that fatigue failures during enroute (ENR) and approach (APR) have both decrease slightly between the two time periods, while all other phases of flight have slightly increased; these are, taxing (TXI), landing (LDG), initial climb (ICL), and takeoff (TOF). This suggests that there may be a trend such that failures that occur during these longer duration phases may be decreasing, while failures associated with high loads are increasing; this, however, is not significant.

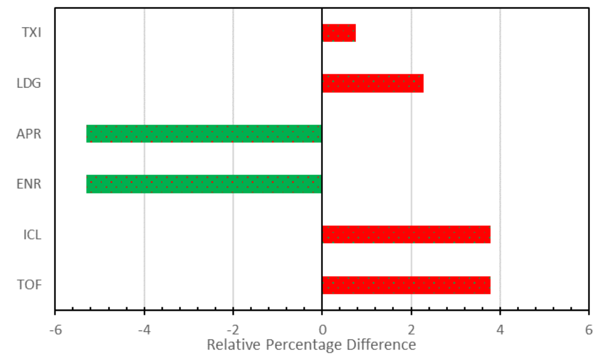

Figure 10. Deltas for phase of flight in which the fatigue failure occurred.

4.2.6. Manufacturer

Figure 11 shows the distribution of aircraft fatigue accidents by the relevant manufacturer. Table 1 indicates that the difference is statistically significant, which is the result of the single large increase for Textron. Textron are currently responsible for a significant number of small GA aircraft models. The increase in Airbus related fatigue accidents is primarily the result of more Airbus aircraft being delivered and operated in the second half of the dataset. It should be noted that some manufacturers showed a decrease because they have produced far less aircraft since 1995. The lack of former USSR aircraft in the dataset is the most interesting feature, given that other studies have shown links to their operation and accidents (Kharoufah et al., 2018).

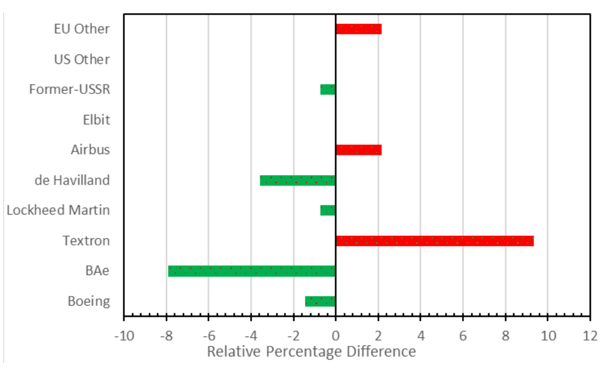

Figure 11. Deltas for aircraft manufacturer.

4.2.7. Mass

The aircraft mass typically refers to the maximum takeoff weight, or MTOW. Aircraft are categorized into mass groups based on their MTOW. The distribution of aircraft fatigue accidents by aircraft mass category in Figure 12 reiterate the results of previous features. That is, there is a significant increase in the light category (L, maximum takeoff mass below 5,700 kg), and a significant decrease in the medium category (M, maximum takeoff mass below 27,000 kg). Specifically, only $(3 \pm 2)\%$ of accidents involved a light aircraft in the first of the data, which increased to $(22 \pm 8)\%$ in the second half. These light aircraft represent GA operations and in include many Textron aircraft. Both heavy (H) and super heavy (SH) have remained constant.

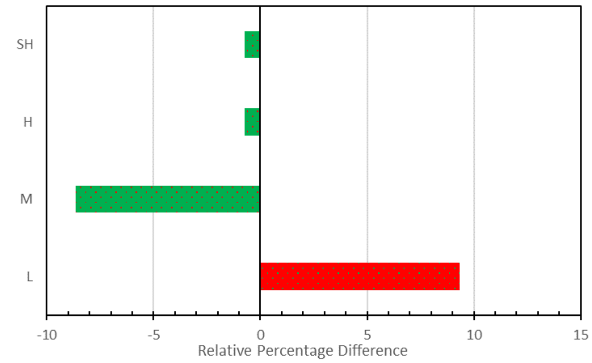

Figure 12. Deltas for aircraft mass category.

4.2.8. Engine

Figure 13 shows the distributions for both engine type and number of engines of the aircraft involved in the fatigue accidents. Both sets of data show a statistically significant change comparing pre 1995 to post. For engine type, the change reflects the change in the types of engines utilized in aircraft. That is, the significant reduction in piston engine (P) accidents is not due to radical improvements in fatigue lives and management of these engines, the prevalence of these engine has reduced over the period of the study. Piston engines are being displaced by turboprop engines (TP) for smaller aircraft and by jet engines for larger aircraft. Similarly, changes to the required number of engines explains the corresponding results. That is, ETOPS operations means that tri and quad engine aircraft are no longer necessary, and twin-engine aircraft have become the workhorses of both domestic and international air travel.

4.2.9. System or Component

Of most significance in this work, is the identification of the system or component which is associated with the fatigue event. Figure 14 shows the distributions before and after 1995 for the different systems which suffered a fatigue failure and resulted in an accident. The engine is the most common source of failure from the entire period and has also seen the greatest increase in fatigue failure accidents, which is statistically significant (see Table 1). An increase was also observed for undercarriage (UC) associated systems fatigue failure accidents. Both wing (structural) and control system failures have seen significant reductions over the same period.

4.2.10. Safety Issue

The four broad EASA safety issues are, Equipment Problem (EP), Human Factors (HF), Organizational Issues (OI), and Environmental issues (En). While fatigue is a material of mechanical failure of a component or system (an EP), the comparison between the two timeframes means the fact that 100% of accidents are associated with EP will not influence the analysis. That is, Figure 15 shows no change in the number of EPs. Given that the change in distribution is statistically significant as indicated in Table 1, the observe increase in OI and HF, coupled with the reduction in En, are all significant. The number of En in the 2nd half of the data indicates that fatigue failure is less likely to result from events such as turbulence, windshear, or thunderstorms. The increase in HF is associated with accidents where the pilot's response to the system failure was inadequate; also, a number of the modern accidents also have HF issues associated with cabin crew decisions during evacuations, making the situation worse. The most significant safety issues associate with fatigue failure accidents are organizational in nature. These are typically inadequate management of maintenance and inspection service.

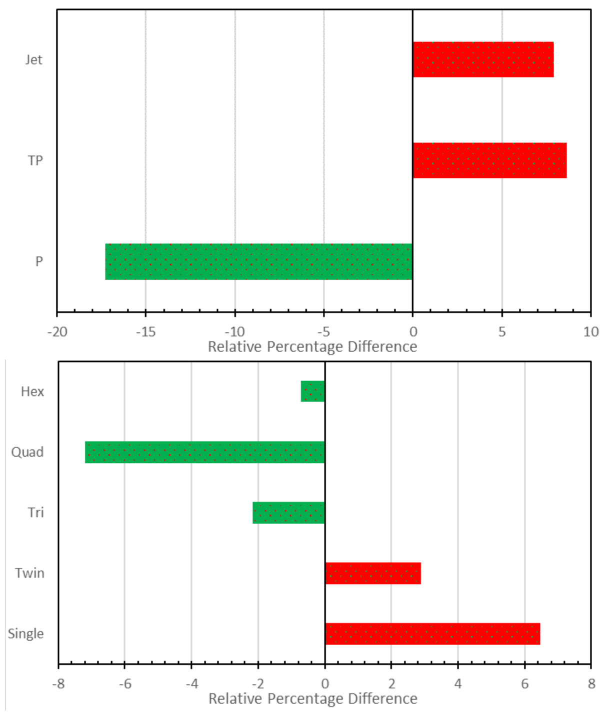

Figure 13. Deltas for aircraft engine properties, top) engine types, and bottom) number of engines.

4.2.11. Occurrence Category

The final feature investigated was the occurrence category. Figure 16 shows the distribution of these for the aircraft fatigue accidents. As indicated in Table 1, the results here are not statistically significant. The reduction in System Component Failure Non-Powerplant (SCF-NP) events and increase in System Component Failure PowerPlant (SCF-PP) events reiterates the results shown in Section 4.2.9, where engine fatigue failures have increased. Runway safety events have also increased, involving both Abnormal Runway Contact (ARC) and Runway Excursions (RE). Fire Non-Impact (F-NI) have also slightly increased.

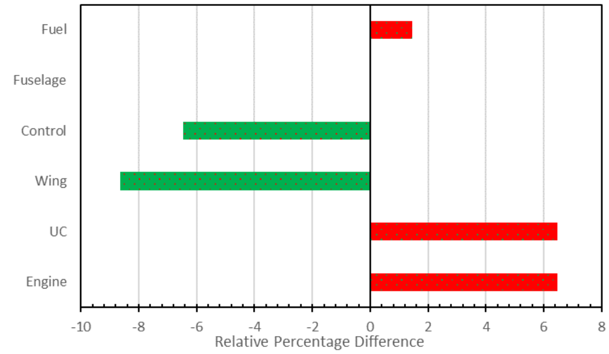

Figure 14. Deltas for failed aircraft system of component.

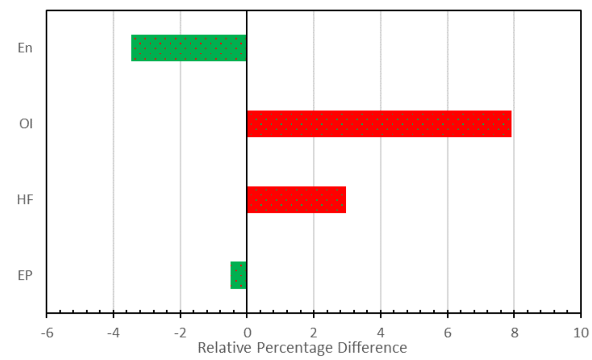

Figure 15. Deltas for EASA safety issues.

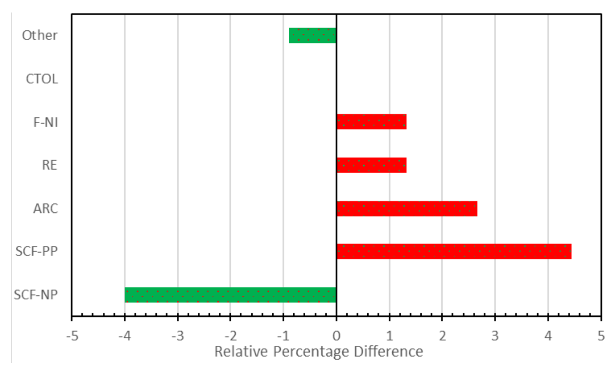

Figure 16. Deltas for occurrence category.

5. DISCUSSION

5.1. Findings

The number of aircraft fatigue failure accidents, for fixed wing aircraft with a passenger capacity of 12 or more, has increased since the 1920's. The rate of increase has been $(3.4 \pm 0.6)\times10^{-2}$ per year (using a 95% confidence interval), with 30 accidents occurring between 2010 and 2019. While the proportion of these accidents with fatalities has decreased over the period of the study (61% to 29%, 1926-1994 to 1995-2019, respectively, with the odd of a fatal outcome even in 1983), there is still an increase in fatal aircraft fatigue failure accidents, and the total number of fatalities from aircraft fatigue failure accidents. While the traffic over the same period has increased at an exponential rate, and as such, all fatigue failure metric relative to traffic have all decreased, there is clearly a need to mitigate fatigue failure to prevent accidents and fatalities.

Interestingly, the hypothesis that fatigue failure is associated with increasing airframe age is not supported by the data. Specifically, the number of accidents increases as a function of age up to 15 to 19 years old. At ages greater than 20, the number of accidents decreases as a function of age.

In essence the safety issue feature highlights that organizational managed inspection is a liability. This is the specific deficiency that autonomous in-situ SHM is trying to overcome. While scheduled and unscheduled maintenance are a crucial part of continued airworthiness, the human element in inspection systems represents a limitation (Giurgiutiu, 2014). Not only does this address organizational issues associated with the implementation, management, and operation of inspection and maintenance activities, it also addresses human factors issues in these operations (Drury, Prabhu, & Gramopadhye, 1990).

5.2. Recommendations for SHM R&D

While large numbers of fatalities are associated with large transport aircraft accidents, the results of the non-parametric analysis suggest that smaller aircraft and operators are of significant concern for the "average case". The "average case" is defined as having all the categorical features associated with the most significant increase between the first and second half of the dataset. For fatigue failure accidents, this would be a single engine, turboprop, Textron, light aircraft. This hypothetical case would involve either an undercarriage or engine fatigue failure, due to organizational issues around maintenance. The observed increase in fatigue failure of engine components indicates that SHM for engines should be more of a concern than SHM to detect structural failures associated with the fuselage and the wing. Given the market for both new and used GA aircraft are consistent, work into SHM systems aimed at small legacy aircraft is essential. The features analyzed in this research have identified several hotspots that should be the focus of any SHM system intended to be retrofitted to legacy small aircraft. In addition to the engine sections (both turbine and compressor of gas turbines), the undercarriage systems are a key area showing an increase in the number of fatigue failures between the two time periods of this study. Therefore, it is recommended that SHM R&D address issues for light GA aircraft, focusing in particular on engine and undercarriage systems. Retrofitted SHM systems for engines and the undercarriage would not need to involve significant airframe monitoring to have a significant positive impact on aviation safety.

While the "average case" utilized the categories with the most statistically significant changes over the period of the study, the "typical case" is defined as the statistically significant categories which have the highest raw counts. This corresponds to a heavy, twin engine, jet aircraft, specifically a Boeing, experiencing fatigue failure in the engine, likely due to organizational issues around maintenance. As such, it is worth looking at large transport category aircraft. There is a subset of 25 modern large transport category aircraft fatigue failure accidents which provide useful insights. These 25 accidents were all the accidents involving a Boeing and Airbus aircraft post B707 and A300, respectively. Of these, 13 experienced fatigue failure in the engine. The specific engine sections can be further subdivided showing fatigue failures in 7 events with compressor failures, 4 events with turbine failure, and 2 events with a fan failure. All 5 of the wing failures involved fatigue of the engine pylon, further highlighting the engine as a hotspot for SHM. There were 5 fuselage failures, 4 of them involving fatigue of the skin, and one involving fatigue of a bulkhead. The final 2 accidents included a single material fatigue failure of an undercarriage bearing support, and a fatigue failure of a valve in the hydraulics system for rudder control. While wide area fatigue crack detection is the end goal of much of the research effort into aerospace vehicle SHM, 52% of fatigue failure accidents of modern Boeing and Airbus aircraft involve the gas turbine, with only 16% involving fatigue cracking of the fuselage skin. Factoring in fatalness, 7 of the 25 accidents were fatal, 3 involved the fuselage, 2 the engine, and 2 the wing. Of the 7 fatal accidents, 5 were fatal for more than a single person (fatal for most if not all onboard); these 5 accidents included 1 engine, 2 wing, and 2 fuselage fatigue failure events. It is recommended that the monitoring of the engine and its mountings should be the primary focus of SHM, given more accidents are associated with fatigue failures of the engine. This is further supported by looking at all fatal accidents involving heavy and superheavy aircraft since 1995. Of these 11 accidents, 7 involve fatigue failure in the engine, while 3 involve fatigue cracking of the skin (2 on the wing, 1 on the fuselage).

5.3. Limitations and Assumptions

To provide the most useful insight into SHM system developments for future robust or ageless aerospace vehicles, the comparative nature of the non-parametric data was selected. Insight from comparing a specific type of accident to an important baseline can be invaluable; that is, it would be ideal to compare fatigue failure accidents (the sample) to "all accidents" (the population), if a suitable "all" is available. However, the wide variety of fixed wing aircraft accidents in the ASN databases means that a direct baseline does not exist. This represents a limitation in terms of the general comparison of aircraft fatigue failure accidents. While the ASN does produce some of its own summary statistics, it is not across all aircraft sizes and operations (they are typically for airliners, so large transport category aircraft operating scheduled services).

The ASN database also only includes accidents and does not provide data regarding incidents and serious incidents that result from fatigue failure in aircraft components and systems. The larger set of data needed to understand the role of fatigue failure on incidents is not readily available. That said, given that outcome of accidents is significant damage and/or injury (if not a hull loss or a fatality), research into accidents alone can be considered more important for aviation safety.

The next limitation to consider is the smallest aircraft size included in the ASN database. As previously mentioned, the ASN database includes known accidents involving aircraft capable of carrying 12 or more passengers. The ASN databases also only include fix wing aircraft and hence excludes rotor wing aircraft accidents. Furthermore, the number of military accidents included in the ASN is very limited. Looking at the case of Australia, we can get an idea of how excluding small fixed wing and rotor wing aircraft impacts the findings (ATSB, 2007). Table 2 summarizes the average ages for different categories of the Australian aircraft fleet in 1995 and 2005, and the difference between these. All categories except for medium turbofan aircraft (50,000kg < MTOW < 100,000kg) show an increase in average fleet age. Interestingly, the rotor wing fleets have similar ages to the turboprop fleet. The two biggest increases and highest fleet ages are associated with single and multi-piston engine aircraft, typically associated with GA. As such, the exclusion of some of these from the dataset may have an impact on the generalizability of the findings. Furthermore, if we look at the historical studies (G. S. Campbell, 1981), the types of aircraft surveyed do in fact include small GA aircraft, rotor wing, and a large number of military aircraft. Of the 1885 accidents surveyed in (G. S. Campbell & Lahey, 1984), about 200 of these were repeated failures in a small set of GA aircraft. Of the 1885, 419 were also rotor wing.

Category	‘95	**‘05**	**Dif.**
single eng. piston MTOW < 5,700kg	23	30	+7
multi eng. piston	21	31	+10
multi eng. turboprop	14	18	+4
turbofan MTOW < 50,000kg	11	16	+5
turbofan MTOW < 100,000kg	8	6	-2
turbofan MTOW > 100,000kg	8	11	+3
single piston eng. rotor wing	13	16	+3
single turboshaft rotor wing	16	23	+7
multi turboshaft rotor wing	12	15	+3

Table 2. Australian aircraft average ages from 1995 to 2005 for different categories

Finally, accident statistics are typically referenced to a relevant “work unit”. In aviation, this could be the number of departures and arrivals (referred to as the air traffic movements). This is consistent across all types of operations and scales. Unfortunately, given the diversity of operations considered across the globe, there are no reliable movement statistics that can be utilized as a reference. While IATA (the International Air Transport Association) reports annual movements, and these can be obtained for most of the years across the study, this data only includes large transport operations, and typically only scheduled operations. As such, without suitable global traffic across all aspects of aviation involving aircraft above the 12-seat capacity, and excluding rotor wing operations, accidents relative to movements is not possible to present.

5.4. Future and Further Work

With a suitable baseline, future work will investigate how fatigue failure accidents compare and contrast to “all” aviation accidents. This will highlight interesting features that make fatigue failure accidents unique in comparison to “all” aviation accidents. Similarly, other baselines could be utilized, along with a subset of the collected 139 accidents. That is, the small number of accidents from 2008 to 2019 could be compared to the accident dataset from ICAO.

To overcome the limitations identified, it would be helpful to understand incidents involving fatigue failure. This requires the identification of a suitable dataset that include incidents and serious incidents and has the ability to readily identify fatigue occurrences. It would be ideal to be able to determine if fatigue is more of an issue for accidents or for incidents.

The final consideration for future work is an update to the average fleet age data in Section 5.2. It would be interesting to understand how the average age of different categories of the Australian aircraft fleet have continued to change over the last 15 years. This would be helpful to understand if the relevance of developing systems and technologies that can be retrofitted to legacy small aircraft is essential.

6. CONCLUSION

This work has focused on an analysis of 139 aircraft fatigue failure accidents extracted from the ASN database. The primary motivation for undertaking this work was to develop an understanding concerning the need for SHM systems in aerospace vehicles. The work has been focused on an assessment of the features of aircraft fatigue failure accidents and their trends over time. To enable the data analysis, both parametric and non-parametric methodologies have been employed. The parametric method aimed to determine if there was an association between the dependent variable (number of fatigue accidents) and the independent variables (aircraft age and decade of occurrence). The parametric analysis showed that fatigue accidents have been increasing with a roughly linear trend at a rate of $(3.4 \pm 0.6)\times10^{-2}$ per year. The number of fatal accidents has also increased, although at a relative rate below the total number of accidents. Relative to the year, the point of even odds for fatalness was in 1983. Furthermore, the analysis unexpectantly revealed that fatigue accidents were more common in the early to mid-life of an aircraft, peaking in the 10 to 15-year-old age range and decreasing significantly beyond the age of 20 years; this was statistically significantly different to previous research looking at maintenance accidents previously reported (Khan et al., 2020), highlighting that fatigue failure occurs at younger airframe ages then maintenance accidents. There was no relationship observed between fatalness and the age of the aircraft for fatigue failure accident. The non-parametric analysis utilized a Pearson's Chi squared test to determine proportionality change in fatigue accidents in two equally sized samples in the year ranges of 1926 to 1994 and 1995 to 2019. In terms of fatalness, the average percentage of fatal fatigue failure accidents was (45 ± 10)%, starting at (61 ± 17)% and reduced to (29 ± 10)% between the two groups. In terms of aircraft fate, the average percentage of fatigue failure accidents resulting in the aircraft being destroyed was (68 ± 13)%, starting at (76 ± 19)% and reduced to (59 ± 16)% between the two groups. The key finding of the non-parametric analysis is that smaller aircraft and operators have seen the most significant increase in the number of fatigue failure accidents despite the larger number of fatalities associated with large transport aircraft. Based on the spectrum of aircraft fatigue failure accidents surveyed in this work, it is apparent that the application of in-situ SHM can be used to overcome current limitations in aircraft maintenance, primarily, the human element. That is, (24 ± 6)% of the fatigue failure accidents directly resulted from organization issues around aircraft maintenance and airworthiness. The growing number of GA fatigue failure accidents indicates that specific SHM systems that can be applied to new and existing small aircraft, focusing in particular on engine and undercarriage systems, need to be developed.

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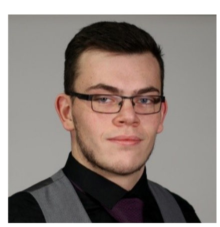
BIOGRAPHIES



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