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Statistical Analysis of Failure Cases in Aerospace

J. H. Lv, W. Z. Wang, S.W. Liu

***Abstract*—**The major concern in the aviation industry is the flight safety. Although great effort has been put onto the development of material and system reliability, the failure cases of fatal accidents still occur nowadays. Due to the complexity of the aviation system, and the interaction among the failure components, the failure analysis of the related equipment is a little difficult. This study focuses on surveying the failure cases in aviation, which are extracted from failure analysis journals, including Engineering Failure Analysis and Case studies in Engineering Failure Analysis, in order to obtain the failure sensitive factors or failure sensitive parts. The analytical results show that, among the failure cases, fatigue failure is the largest in number of occurrence. The most failed components are the disk, blade, landing gear, bearing, and fastener. The frequently failed materials consist of steel, aluminum alloy, superalloy, and titanium alloy. Therefore, in order to assure the safety in aviation, more attention should be paid to the fatigue failures.

***Keywords*—**Aviation industry, failure analysis, failure component, fatigue.

I. Introduction

SINCE the first aircraft was invented in November, 1903, aviation industry has experienced significant growth over the past 115 years. And ever since the beginning of aviation, the first and most important issue for aviation industry is the flight safety. Aircraft is one of the most complex engineering systems that have been developed. Failure in any of the components could lead to property loss and casualties. Failure analysis has played a key role in the overall safety of aircraft systems, helping find the root causes of aircraft accidents and incidents [1], [2]. To improve the reliability of materials and systems, as well as increase the overall aircraft reliability effectively, it is important to learn from previous failure cases. And statistical analysis is an indispensable tool to summarize the failures that happened earlier and provide preventive measures.

Based on the failure cases, which were extracted from failure analysis journals, including Engineering Failure Analysis and Case studies in Engineering Failure Analysis, this study analyzes the failure information of aviation industry and summarizes some results on the basis of failed components, failed materials, and failure modes.

II. Potential Sources of Failures

The failures in aircraft components can be caused by varieties of reasons [3]-[5]. Analysis shows that the potential sources of failures can be related to one or more of the following errors:

1) Design: Inadequacies in design such as incorrect structure, notch, small transition radius, inappropriate fitting often result in failures in components, even if the component is made of the best materials. Sometimes even a carefully conceived and thoroughly evaluated design may still be deficient and contribute to early failure in service.
2) Material: For components used in specific conditions, suitable materials that have good mechanical properties and processing performance should be chosen to prevent the predictable failures. What is more, defects introduced in manufacturing process of raw material can cause failure of components.
3) Manufacture: Defects introduced during various manufacturing stages can have serious weakening on the properties of components. They can also become the nucleation of cracks that can then propagate with the load of fatigue and stretching, etc., leading to premature failures.
4) Assembly: With the best component design and choice of the best material, sometimes mistakes can happen during assembly. Deficiencies of this type are generally related to inaccurate, incomplete or ambiguous assembly specifications, but they can also occur as a consequence of human error or negligence.
5) Operation and maintenance: Improper operations also result in failure, which include over speeding, over heat, over loading, as well as inexperience, etc.

Service failure due to improper maintenance accounts for sizable fraction of total failures in aircraft industries. Inadequate attention in following the methodology/procedure and/or use of tools led to premature failure of components.

III. Results and Discussion

We investigated the research publications on failure cases in the period of 1990-2017 using the data from ScienceDirect and SpringerLink. 173 failure cases occurred in aviation industry were extracted from failure analysis journals, and analyzed the relation of failed components, failed materials, and failure modes.

Fig. 1 presents the failed parts distribution of 173 failure cases. The whole aircraft is mainly divided into three parts: engine system, airframe, and airborne equipment. It can be observed that 59 percent of failures concentrated on the engine system, especially the disk, blade, and bearing (as shown in Fig. 2). Then, failures of airframe, the bones of the aircraft, accounted for 36% of the total failures. As shown in Fig. 3, among all the airframe failures, landing gear failure and fastener failure covered a large proportion. In addition to the two main parts, engine system and airframe, airborne

W. Z. Wang is the professor of East China University of Science and Technology, Shanghai, SH 200237 China (corresponding author, phone: +86-21-64252819; fax: +86-21-64253513; e-mail: wangwz@ecust.edu.cn).

J. H. Lv and S.W. Liu are students of East China University of Science and Technology, Shanghai, SH 200237 China (e-mail: jiahuilv94@163.com, shaowuliu93@163.com).

equipment was a contributive cause for the failure as well.

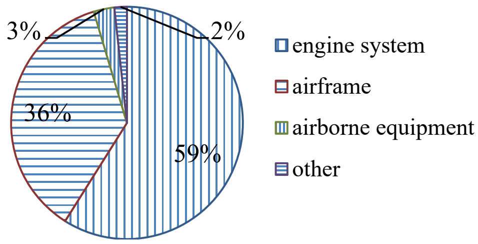

Fig. 1 Distribution of failed parts in aviation failure

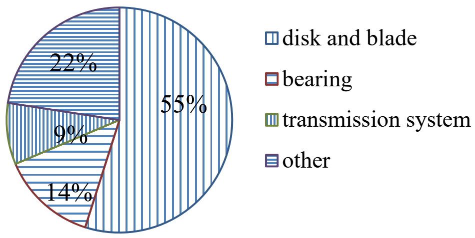

Fig. 2 Distribution of failed components in engine system

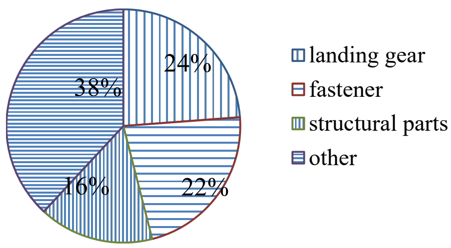

Fig. 3 Distribution of failed components in airframe

Fig. 4 shows the statistical result about failure modes. As one failure case may be caused by the combination of several failure modes, there is probably multiple counting of some failure cases when the percentage of the failure mode is calculated. It can be seen that fatigue cracking was the most common failure modes in aircraft, which accounted for 52% of the total failures. The second largest failures in the number of occurrence were corrosion failures, accounting for 17%, closely followed by abrasion with 12%.

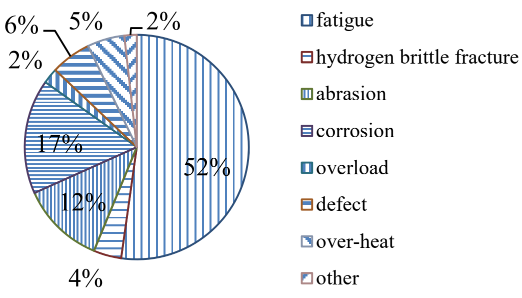

Fig. 4 Distribution of failure modes in aviation failure

Classified failures according to failed materials, they happen in order of steel, aluminum-magnesium, superalloy, titanium alloy, copper alloy and nonmetal materials, as shown in Fig. 5. It can be seen that steel, aluminum-magnesium alloy, superalloy, and titanium alloy were the four major failed materials, whose total ratio is 95%.

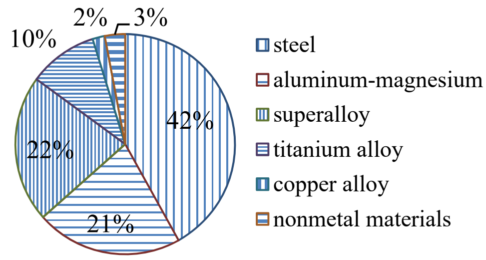

Fig. 5 Distribution of failed material in aviation failure

A. Statistical Results about Failure Cases in Engine System

As the heart of the aircraft, aero engine is a highly complex and precise system, providing driving force through conversion of thermal energy. With the improving requirements of engine performance and reliability, the key measure is to increase the thrust weight ratio by the applications of new materials, structures, advanced manufacture method, etc., and so the properties of materials are improved and working stress margins are reduced. At the same time, the operation condition of engine components becomes much more serious or deteriorative and its stress level is higher. Consequently, the failure of components in engine system accounts for most of the aircraft accidents.

1) Distribution of Failure Modes, Failure Causes, and Failed Materials in Disk and Blade

Aircraft engine disk and blade are the main components of the engine system and the key rotating parts, which is charged with the important task of energy conversion. Failure of the disk and blade can have catastrophic consequences, with resultant loss of lives and of the aircraft.

Classifying failure cases according to type of failure modes in disk and blade, the result is shown in Fig. 6. About 59% of the failures were caused by fatigue fracture. Over-heat and corrosion come in the second and third places with 16% percent and 11% percent of the total failures, respectively. In addition, foreign object damage was also an important cause of aircraft failures, reaching 9%.

As main load-carrying structures in aero engine, disk and blade work in severe conditions, bearing high-level working stress. Except for centrifugal force, bending moment, and axial load produced by rotor's rotation, the blade also suffers thermal stress for working in the high temperature. Under the influence of complicated stresses, fatigue failures dominate the distribution in aircraft. Because of the impact of sand, stone and other foreign objects ingested into engine, foreign object damage affects the fatigue life seriously.

As shown in Fig. 7, most of the failed disks and blades were made of superalloy.

Fig. 8 exhibits the failure causes distribution in the disk and blade failures. It can be found that causes related with material, manufacture and design, were responsible for around 57% of the failures, which indicates that the capacity of design, manufacture, and quality control is still inadequate. To meet the high requirements of engine performance and reliability, it is necessary to develop new materials, advanced structures, and new processing techniques. Human factors including assembly, operation and maintenance were responsible 31% of the failures. Consequently, inadequate operation, maintenance and assembly should be avoided to prevent the failure. With the increase of the turbine inlet temperature of high performance, aero engine day by day, coating technology has been widely used in the turbine blade. Some of the blade failures are directly related to the damage of coating, which accounted for 12%.

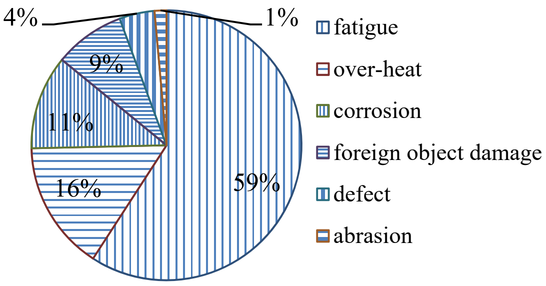

Fig. 6 Distribution of failure modes in disk and blade failure

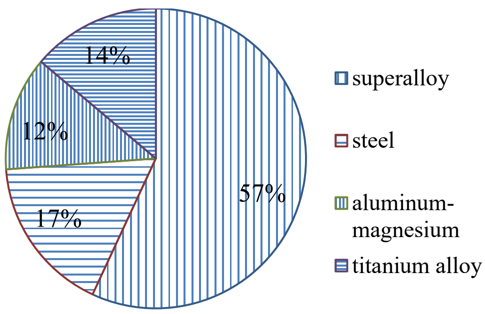

Fig. 7 Distribution of failed materials in disk and blade failure

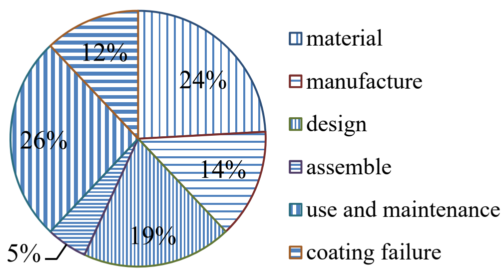

Fig. 8 Distribution of failure causes in disk and blade failure

2) Distribution of Failure Modes and Failure Causes in Bearing

The aircraft engine bearing is one of the important parts of the aircraft engine. Working under the condition of high speed, high load, and high temperature, their health status can directly affect the aircraft safety.

Classifying failure cases according to type of failure modes in bearing, the result is shown in Fig. 9. Failures of bearing were divided into four modes: contact fatigue, fracture (cage), fretting and abrasion, of which contact fatigue accounted for 57%. Fracture of cage and abrasion came in the second and third places with 22% percent and 14% percent of the total failures.

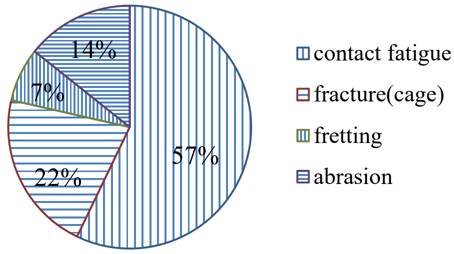

Fig. 9 Distribution of failure modes in bearing failure

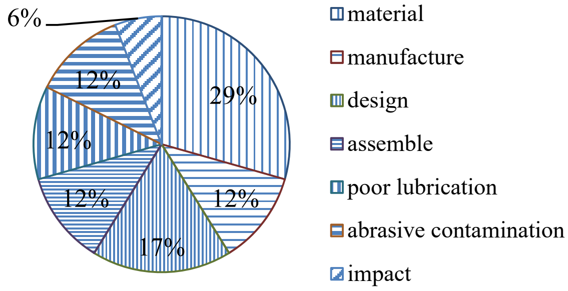

Fig. 10 Distribution of failure causes in bearing failure

Fig. 10 presents the failure causes distribution in the bearing failure. Defects in material ranked first with 29% among all the possible causes. Then, inadequate design came second with 17%. What is more, factors such as improper processing, impact, inadequate assembly, poor lubrication and abrasive contamination were contributed to bearing failures as well.

From further analysis of failures related to contact failure, it can be found that this failure mode mainly originates from metallurgical defects like non-metallic inclusions, coarse carbides, as well as machining defects, groove, notch and other stress concentration area. Under the effect of alternating stress, micro cracks initiate and expand to the rolling contact surface， resulting in spalling and causing the fatigue failure.

Abrasion is also a common failure mode, generally divided into abrasive wear and adhesive wear. And further analysis indicates that abrasion is mainly due to impurities and foreign hard particles introduced by working process, impure lubricant, and assembly.

From the statistics, failures induced by inadequate assembly and poor lubrication take a fairly large proportion. Behaviors against the operating procedures during assembly and disassembly may bring in abrasive, impact load, causing the early failure. And bad lubrication would cause quick temperature rising, leading to surface burn of raceway and rolling element.

B. Statistical Results about Failure Cases in Airframe

1) Distribution of Failure Modes and Failed Materials in Landing Gear

Fig. 11 presents the failed modes distribution of landing gears. It points out fatigue, stress corrosion and overload as the main failed modes in landing gears, of which fatigue accounted for 69%. Fig. 12 presents the failed materials distribution in landing gears. It can be seen that aluminum alloy and high strength steel have taken most of the failures.

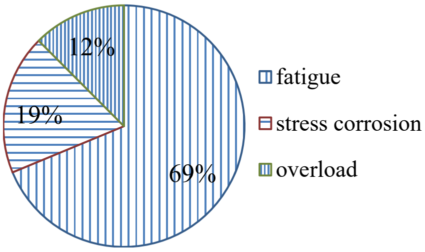

Fig. 11 Distribution of failure modes in landing gear failure

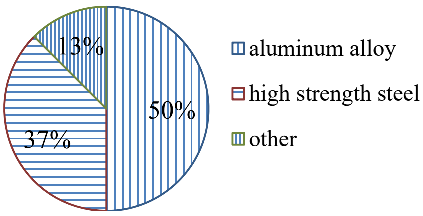

Fig. 12 Distribution of failed materials in landing gear failure

The landing gear of aircraft is one of the key parts for aircraft's flight safety, of which failure modes mostly behave as fatigue failure under alternating load condition. Unreasonable structural layout and design details, false material selection, high surface roughness, wounds, scratches, welding slag and void created during processing can easily become a fatigue source. From further analysis of failures related to fatigue failure, it can be found that corrosion pits were the main cause of fatigue initiation. Pits served as stress concentrators, then repeated stress cycles in take-off and landing initiated fatigue cracks. Landing gears are usually working in an open environment, subjected to severe environmental conditions, such as temperatures, climates. Therefore, corrosion is a contributive cause for the failure.

During all the failures correlated with corrosion, stress corrosion of high strength steel is especially dominant. High strength steel has been widely used in the manufacture of landing gear to achieve goals of structural weight-reduction. However, this sort of steel is sensitive to various of surface defects, such as notch, weld seam, defects caused by surface machining, and has low corrosion resistance.

2) Distribution of Failure Modes and Failed Materials in Fastener

Classifying failure cases according to type of failure modes in fastener, the result is shown in Fig. 13, of which fatigue (43%) and hydrogen brittle fracture (36%) account for most of the failure. Fig. 14 presents failed materials distribution in the fastener failure. Titanium alloy and high strength steel are the two main failed materials.

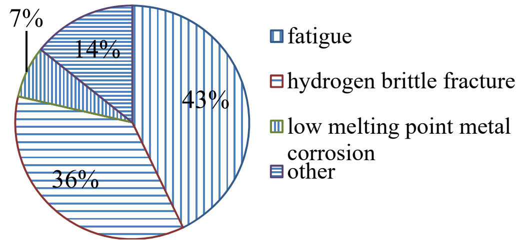

Fig. 13 Distribution of failure modes in fastener failure

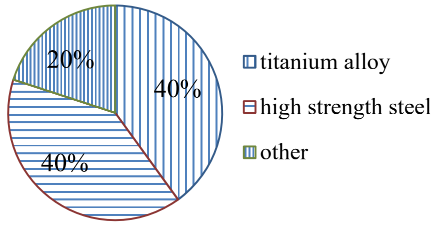

Fig. 14 Distribution of failed materials in fastener failure

From the statistics, hydrogen brittle fracture of titanium alloy and high strength steel is especially dominant. Because of the high specific strength and attractive mechanical properties, materials such as titanium alloy and high strength steel have been widely used in aerial fasteners. However, both the materials are sensitive to hydrogen, and it is important to reduce the hydrogen content both in manufacture and use. Remarkably, there are several cases, which were caused by low melting point metal. Under tensile stress and temperature effect, the low melting element caused the intergranular corrosion damage.

IV. Conclusion

In this study, statistical analysis is carried out to investigate the distribution of failure modes, type of components, and materials on failure cases occurred in aerospace, which are extracted from failure analysis journals. Through the analysis, the conclusions are as follows:

1) Classifying the ratio of failure occurrence on the basis of failed components, failed materials as well as failure modes, the results indicate that:
- More than half of failures concentrated on the engine system, especially the disks, blades, and bearings. Then, among the second largest proportion of the failures, airframe, landing gears failure and fasteners failure account for 46%.
- The fatigue cracking is the most common failure modes in aircraft.
- Steel, aluminum-magnesium alloy, superalloy, and titanium alloy are the four major failed materials.

2) In failures of aircraft engine disk and blade:
- 59% of the failures were caused by fatigue. What is more, over-heat, corrosion and foreign object damage were important factors resulting failures as well.

- Analyzing from the failure causes, factors related with material, manufacture and design, are responsible for around 57% of the failures. Inadequate maintenance and assembly are also important causes resulting failure.
- The most failed material in the failure cases is mainly super alloy, accounting for 57% of the total failure cases.

3) In failures of aircraft engine bearing:

- Contact fatigue accounts for 57% of the bearing failures, and fatigue fracture of cage comes second with 22 percent.
- Defects in material rank first with 29% among all the possible causes, followed by inadequate design with 17%.
- Impurities and foreign hard particles introduced by working process, impure lubricant as well as assembly should be avoided to prevent abrasion failure.

4) In failures of landing gear:

- Fatigue failure ranks first by a wild margin, with 69% putting it more than 50% ahead of stress corrosion failure.
- The most failed materials in landing gear failures are aluminum alloy (50%) and high strength steel (37%), accounting for 87% of the total failures.
- Most of the fatigue failures were caused by corrosion pits. Severe working conditions and properties of material make corrosion, especially stress corrosion of high strength steel, become the great threat to the landing gear.

5) In failures of fastener:

- Fatigue failure takes the first place with 43%, closely followed by hydrogen brittle fracture with 17%.
- Titanium alloy (40%) and high strength steel (40%) are the two main failed materials.
- The corrosion damage due to low melting point metal is remarkable.

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