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Advanced design for lightweight structures: Review and prospects

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ABSTRACT

Current demand for fuel efficient aircraft has been pushing the aeronautical sector to develop ever more lightweight designs while keeping safe operation and required structural strength. Along with lightweighting, new structural design concepts have also been established in order to maintain the aircraft in service for longer periods of time, with high reliability levels. All these innovations and requirements have led to deeply optimized aeronautical structures contributing to more sustainable air transport.

This article reviews the major design philosophies which have been employed in aircraft structures, including safe-life, fail-safe and damage tolerance taking into account their impact on the structural design. A brief historical review is performed in order to analyse what led to the development of each philosophy. Material properties are related to each of the design philosophies.

Damage tolerant design has emerged as the main structural design philosophy in aeronautics, requiring deep knowledge on materials fatigue and corrosion strength, as well as potential failure modes and non-destructive inspection techniques, particularly minimum detectable defect and scan times.

A discussion on the implementation of structural health monitoring and self-healing structures within the current panorama of structures designed according to the damage tolerant philosophy is presented. This discussion is aided by a review of research on these two subjects. These two concepts show potential for further improving safety and durability of aircraft structures.

Contents

1. Introduction

Many definitions for structural design may be found in the literature. One holistic definition is given by the McGraw-Hill Concise Encyclopaedia of Engineering [1] stating that structural design is the science of “selection of materials and member type,

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Acronyms

ASIP	aircraft structural integrity programme
DCB	double cantilever beam
FBG	fibre Bragg grating
FSW	friction stir welding
IVHM	integrated vehicle health management
LBW	laser beam welding
MSD	multiple site damage
NDI	non-destructive inspection
POD	probability of detection
SHM	structural health monitoring
USAF	United States air force
WFD	widespread fatigue damage
WSPS	weapon system performance specification
X-FEM	extended finite elements method

size, and configuration to carry loads in a safe and serviceable fashion…”. Further, [1] states that structural design normally includes at least five distinct phases – project requirements, materials, structural scheme, analysis, and design, although in many structures one more stage may be required, which is testing. More complex structures, which make use of more state-of-art materials or concepts, regularly require proof of concept and demonstration of their capabilities and longevity. In summary, structural design may be described as the combination of several realms of engineering to the process of new product development. These realms include, mechanical, civil, and materials engineering among others.

Over the past few decades, structural design for aeronautical structures has been subjected to multiple pressures of different stakeholders in order to decrease their footprint and improve their safety for a more affordable and more competitive transportation of goods and people. This is summarized by “Quieter, Cleaner and Greener” or “More Affordable, Cleaner and Quieter” drivers which guide the development of the civil aeronautical industry [2]. One example of this effort is the reduction of emissions in this industry by the European Union Clean Sky initiative [3], which aims at reducing 50% CO_2 emissions and 80% NO_x emissions by 2020. Civil aircraft structures are one of the most efficient compared with other vehicles structures whilst at the same time presenting high safety records due to the constant innovation and the usage of advanced design principles.

The design principles employed to develop aeronautical structures explore all properties and failure modes of the materials in order to create optimal structures which tolerate inherent imperfections. Although these design concepts are regularly discussed, several experts present slightly different interpretations. The importance of using correct language for aeronautical fatigue is addressed in [4]. All the stakeholders that operate in this field are responsible for the eventual misunderstandings generated, from the different regulations issued by the airworthiness authorities and their application by aircraft manufacturers and airline operators, to the interpretation of maintenance plans by the aircraft operators.

This article focuses on the three main design philosophies applied to high performance structures, safe-life, fail-safe and damage tolerant design, highlighting the differences between them and their respective scope of application. Each philosophy is discussed in terms of material properties, highlighting the key material properties for each design methodology. Limitations of safe-life design methodology, leading to its replacement by damage tolerant design, are discussed. A final topic regarding the effect of newer concepts on design philosophy, such as structural health monitoring and self-healing structures are addressed. A review on these two concepts is presented and used to show their potential for improvement in maintaining continuous airworthiness of structures.

2. Historical background

In the early days of flight, aircrafts were designed solely on the basis of static strength. At the time this was sufficient, as airplanes were not able to perform long distance flights and had a short lifetime. Factors such as fatigue, corrosion, accidental damage, among others, were not taken into account. As initial aviation evolved from a mere hobby or technological demonstration to a serious mean of transportation or warfare, especially with requirements imposed by the two world wars, structural integrity became a relevant issue. The first implemented design approach was the safe-life or safety-by-retirement, where a structure is operated during a service life with a low probability of failure, being retired at the end of this safe life (which is the predicted safe-life plus an extra safety margin to take into account the uncertainty). As during war time aircrafts become obsolete before the safe life is over, this design methodology allowed for very safe structures.

Materials fatigue became a more prominent issue with the start of the jet age, as commercial airplanes aimed at longer distances and at higher altitudes, increasing the applied loads (e.g. cabin pressurization). The Havilland Comet crashes [5] have shown the limitations of this philosophy, as fatigue cracks occurred earlier than anticipated. The safe-life of the aircraft was determined through an experimental programme, but unaccounted phenomena have led to a non-conservative estimate.

The Comet crashes revealed limitations in the fatigue analyses, leading to the conclusion that safety could not be guaranteed on a safe-life basis without imposing uneconomically short service lives on major components of the structure. Fail-safe was put forward to address these limitations. This new concept involved designing a structure which could sustain a satisfactory life span without damage, but also allowed for inspectability and multiple load paths, in order to avoid complete structural failure within service. The last point is associated with the concept of residual strength which was introduced along with fail-safe design. Although this new design concept was applied to most of the aircraft structures, some remain designed under safe-life philosophy, such as the landing gears, as these are made from high-strength steels and are difficult to inspect for cracks in timely manner [5].

Military aviation maintained a safe-life approach verified by full-scale fatigue testing to several lifetimes, but the crash of the F-111 swing-wing fighter/bomber, on December 22, 1969, showed the limitations of this approach [6]. The failure occurred in the lower wing pivot plate, and was originated at a forging lap incorporated during the primary metal-working operation. Due to the proximity to a vertical reinforcement rib, it was not discovered in any of the production-level inspections. In 1974, the Military Specification – Airplane Damage Tolerance Requirements, MIL-A-83444 [7], was issued. This new approach differs from the fail-safe approach used after the Comet accidents in civil aviation, by including the assumption of initial damage and the possibility to have inspectable or non-inspectable structures during service life. With damage tolerant design, the concept of slow flaw growth was introduced which must characterize non-inspectable structures (initial damage must not grow to a critical size causing failure during the design service life) [8].

The Dan Air Boeing 707 crash in 1977 and the Aloha Airlines Boeing 737 accident of 1988 put the emphasis on inspectability in