An Overview of the Applications of NDI/NDT in Engineering Design for Structural Integrity and Damage Tolerance in Aircraft Structures

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Abstract Most of the civilian commercial aircraft were designed in the past for at least 20–25 years and up to 90,000 flights. The aircraft design philosophy was based on safe life or fail-safe approaches. Many operators of commercial transport aircraft exceed these design service goals. Consequently, Non-destructive inspections (NDI) are mandatory for determining maintenance cycles, and as means for assessing damage and extent of the needed repair work. Presently, aircraft types are designed for the same service life, structural design according to fatigue and damage tolerance requirements. The ultimate purpose of the damage tolerance evaluation is the development of a recommended structural inspection program considering probable damage locations, crack initiation mechanisms, crack growth time histories and crack detectability, in the airframe structure and engine components to minimize the maintenance costs and to comply with the requirements of airworthiness regulations. The applications of damage tolerance requirements and the advances in light weight materials and composites lead to the need for defining structural integrity through NDI inspection program to ensure a high degree of reliability supported by evaluation tests for structural integrity. The damage tolerance principles, fatigue life assessment and new advances of NDI methodologies will be reviewed.

Keywords: NDI/NTD, Structural Integrity, Damage, Aircraft Structures.

1. Introduction

The current generation of civil transport aircraft were designed for at least 20–25 years and up to 90,000 flights. Many operators of jets and turboprops have exceeded these design service goals. Future aircraft types are designed for at least the same goals, but structure with higher fatigue life (endurance); higher damage tolerance capability and higher corrosion resistance are required to minimize the maintenance costs and enhanced airworthiness regulations. Ageing aircraft fleets are required to remain in service well beyond their original life expectancy. Life management tools range from those that may be employed during the initial design phase of new aircraft to those required to make technology insertion, repair and retain or-retire decisions.

Traditionally, fatigue has been the limiting factor in the determination of the economic life of aircraft fleets.

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Recent research has also identified interactions between corrosion and fatigue such that the presence of corrosion accelerates damage due to fatigue; thereby further reducing the total service life of an aircraft [1, 2].

The total economic service life of any aircraft fleet is determined by damage incurred as a result of fatigue and corrosion. The challenges to aircraft manufacturers, military and commercial users and technical community are: (a) identify and correct structural deterioration that could threaten aircraft safety; and (b) prevent or minimize structural deterioration that could become an excessive economic burden or affect the safety of the aircraft.

Non-destructive inspections (NDI) are significant means to monitor defects and assessment of repairs. The aim of this article is to review the aging of aircraft; current fatigue design approaches, and presents an overview of the role of non-destructive testing and evaluation within the application of damage tolerance and structural integrity approaches.

2. Fatigue damage in aging aircraft

One of the signs of aging in aircraft structures is the occurrence of multiple damages at adjacent locations, which influence each other. There are two types of damage that are likely to result from the interaction of dynamic loading conditions and environment. The first type is the multiple site fatigue damage (MSD in the same structural element. The second type is the multiple element damage (MED) in the form of fatigue cracking in similar adjacent structural elements. Widespread Fatigue Damage (WFD) is reached when the MSD or MED cracks are of sufficient size and density that the structure will no longer meets structural integrity and safety criteria. Recent research has also identified interactions between corrosion and fatigue at the fastener holes further reducing the total service life of an aging aircraft [3–5].

The USA Air Force has initiated the Aircraft Structural Integrity Program (ASIP) and durability studies and damage tolerance assessments of aging aircraft [6]. There is a requirement to develop new techniques and instrumentation to detect fatigue, corrosion-fatigue interactions, stress corrosion cracking, and nondestructive inspection of corrosion initiation at fastener holes, without prior removal of the fasteners [7, 8]. Proper application of NDE technology can offer significant improvements in diagnostic capabilities by monitoring fatigue cracking, and stress corrosion conditions that are, or could become, a flight-safety concern.

3. Fatigue design philosophies

Purely static loading is rarely observed in modern engineering components or structures. Fatigue, or metal fatigue, is the failure of a component as a result of cyclic stress.

Failure occurs in three phases: crack initiation, crack propagation, and catastrophic overload failure. The duration of each of these three phases depends on many factors including fundamental raw material characteristics, magnitude and orientation of applied stresses, processing history. Therefore, the design analysts must address the implications of repeated loads, fluctuating loads, and rapidly applied loads. As a result, fatigue analysis has become an early driver in the product development processes in the aerospace industry.

Fatigue failures are typically characterized as low-cycle or high cycle. Low cycle fatigue failures involve large cycles with significant localized plastic deformation and relatively short life. Most metals with a body centered cubic crystal structure have an endurance limit, a threshold stress limit below which fatigue cracks will not initiate within the first 2×10^6 cycles as shown in Fig. 1. Total lives are then reported as the sum of the initiation and propagation segments. Metals with a face center cubic crystal structure (e.g., aluminum, austenitic stainless steels, copper, etc.) do not typically have endurance limits. High-cycle fatigue failures occur where stresses and strains are largely confined to the elastic region. The Stress-Life (S-N) or Total Life (TL) method is widely used for high-cycle fatigue applications [9, 10].

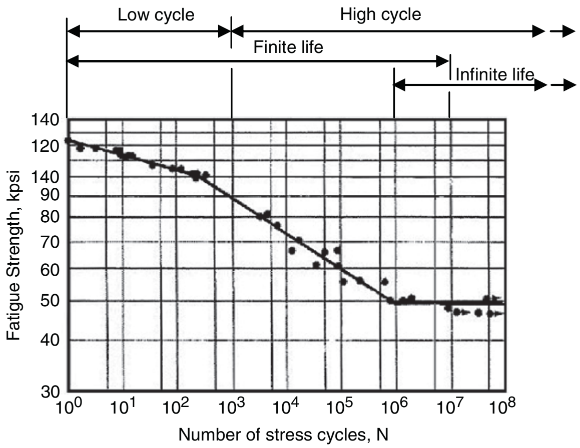

Fig. 1. An S-N diagram plotted from the results of completely reversed axial fatigue tests. Material: UNS G41300 steel normalized SMT = 1.16 kpsi, maximum SMT = 125 kpsi (data from NACA Technical Note 3866, December 1966)

4. Design principles

Two approaches are mainly used to design for establish the retirement life of parts considering the possibility of the presence of initial flaws or cracks of realistic size, and supplementing retirement lives by inspection plans based on testing and analysis.

4.1. Safe-Life

In aerospace, fatigue life evaluation has been specifically based on using a probabilistic approach for establishing the safety of their aircraft in the past on what is defined as safe-life design, whereby, the component/aircraft is virtually able to withstand its whole design-life without inspection. The “safe life” approach was introduced as the result of the Aircraft Structural Integrity Program (ASIP) to take into consideration the effects of cyclic loading on the airframe. The Safe- Life Design is based on Miner’s rule of linear cumulative damage. Miner’s Rule simply states that failure will occur when the summation of the damage caused by individual cycles exceeds unity [11]. Once a crack has occurred, or whenever the design life has expired, the component has to be removed. This highly conservative approach gives rise to very short inspection intervals that cannot be practically implemented by operators in an inspection program [10–12].

4.2. Damage tolerance

With the emergence of fracture mechanics, damage tolerance design principle was introduced to allow each individual component in an engineering structure to be used to the limit of its ability. Depending on the materials used in manufacture, many engineering components can tolerate the propagation of preexisting cracks, provided they do not exceed some critical size [13]. The critical size is the point at which the defect becomes unstable and very rapid crack growth to final failure may be expected [15, 16]. The point of instability is reached when the stress intensity at the crack tip (K) reaches the fracture toughness of the material (K_c), then the crack will run to failure at a catastrophic speed (Figs. 2 and 3). For values of (K) much lower than (K_c) slow and stable crack growth may be expected and the part may operate relatively safely [13–16]. Damage tolerance allows each individual part to be operated until a crack is detected by the best available NDT inspection method. If a crack is not detected then the part is returned to service. If no crack is found, then the same procedure is applied again, for the same inspection period.

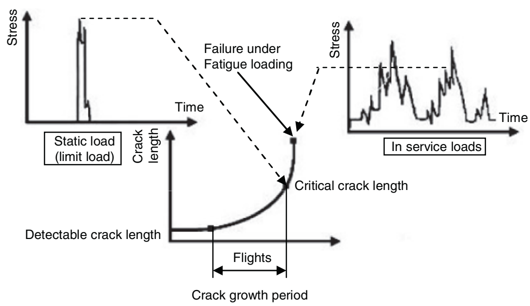

Fig. 2. Principle of damage tolerance investigation [3]

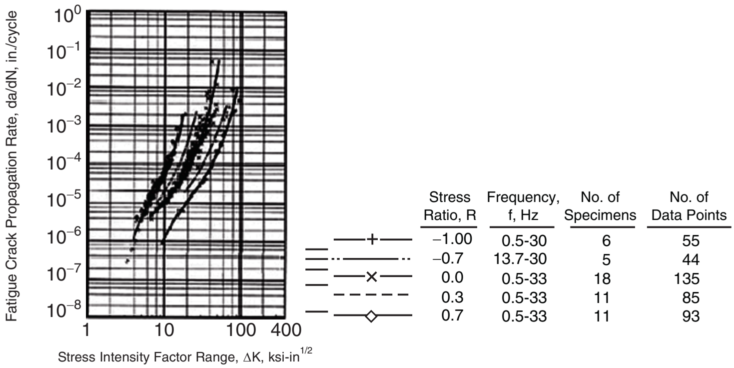

Fig. 3. A sample display of fatigue crack propagation rate [5]

Once a crack is determined, it has to be clearly quantified with respect to its dimensions. This approach requires knowledge of crack growth rate, and critical crack sizes to allow for a limited continuation of the aircraft's operation as long as the crack cannot reach the maximum allowable crack length. Thus, more flexible maintenance schedules (Fig. 4) could be implemented based on the development of NDT structural inspection program [11–14].

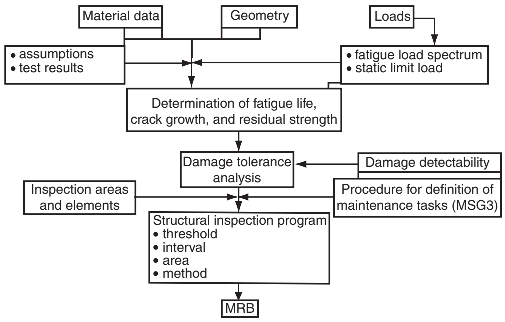

Fig. 4. Development of structure inspection program [3]

4.3. Holistic structural integrity program (HOLSIP)

The total economic service life of any aircraft fleet is determined by damage incurred as a result of fatigue and corrosion. Traditionally, fatigue has been the limiting factor in the determination of the economic life of aircraft fleets. Corrosion was not included in the current life prediction paradigms namely, safe-life and/or damage tolerance. Therefore, any corrosion damage that is discovered had to be repaired immediately, resulting in significant aircraft maintenance costs and reduced aircraft availability [15, 16].

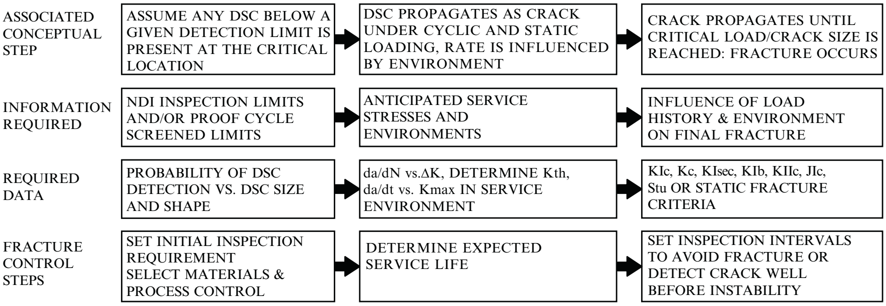

Fig. 5. Conceptual diagram of the HOLSIP program

The Holistic Structural integrity program (HOLSIP) was proposed to address the synergistic effects of cyclic loading and environmental exposure to ensure structural integrity of aging aircraft and accurate determination of proactive planned maintenance cycles (Fig. 5). The success of this new program depends on the development of novel NDI/NDT methods and techniques for detecting wide spread fatigue (WFD) and Wide Spread Corrosion Damage wide spread damage (WSCD) in fasteners, as well as detecting delamination in composites.

5. Role of NDT in structural integrity and fatigue management

Non-destructive testing (NDT) are noninvasive techniques to determine the integrity of a material, component or structure or quantitatively measure some characteristic of an object. The reliability and sensitivity of an NDT method is an essential issue. By use of artificial flaws, the threshold of the sensitivity of a testing system has to be determined. If the sensitivity is to low defective test objects are not always recognized. If the sensitivity is too high parts with smaller flaws are rejected which would have been of no consequence to the serviceability of the component [16–18]. The Aircraft inspection involves multiple inspection solutions and diversification of inspection equipment to optimize the cost-effectiveness of the system. The most common NDT Methods are: Ultrasonic Testing (UT), Radiographic Testing (RT), and Eddy Current (EC). Other methods include guided wave inspection techniques (GW), Edge-Of-Light EOL, conventional ultrasonic pulse-echo (UT) and eddy current techniques (ET) for corrosion detection in aircraft structures [19, 20].

6. Evolving DNT methods

Computed Tomography is a radiographic NDT-method to locate and size planar volumetric details in three dimensions.

A CT-scanner generates X-ray attenuation measurements that are used to produce computed reconstructed images of defects in composite structure with their effects to the fatigue and the damage behavior of the test specimen [19–22]. Ultrasonic inspection using C-Scan (Fig. 6) is widely used in aircraft inspection for the detection of delimitations in composite structures, detection of crushed core, de-bonds in honeycomb structures, impact damage, and exfoliation corrosion. Ultrasonic inspection is usually performed with two techniques: (a) Reflection (Pulse echo) technique and (b) through transmission technique. Pulse echo' technique is most widely used in estimating location and size of the defect in testing metallic, nonmetallic, magnetic or nonmagnetic materials. Ultrasonic energy data (transmitted or reflected) are displayed or recorded and presented in two dimensional graphical presentations that could be digitized, stored for post processing [20–23].

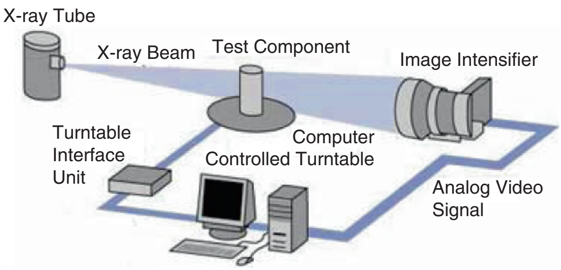

Fig. 6. A schematic sketch of a CT-scan

6. Conclusions

1. The "safe-life" approach was introduced as the result of the Aircraft Structural Integrity Program (ASIP). It involves rigorous fatigue testing of a representative of crack free airframe and certain components for 40,000 h "ensuring" a safe life of 10,000 h.
2. The damage tolerance design principle accommodates the presence of preexisting cracks in aerospace structures. Fracture mechanics provides the concepts to predict the propagation of these cracks based on a rigorous NDT inspection program.
3. The holistic approach was developed to incorporate corrosion and fretting into ASIP program.
4. New inspection techniques such as computer tomography and Acoustic emission, thermography are being developed to monitor structural integrity of engineering structures containing composites and newly developed lightweight materials.
5. There is a requirement to develop new techniques and instrumentation to detect corrosion initiation at fastener holes, without prior removal of the fastener, and to quantify the detectability of corrosion damage.

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