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Damage Tolerant Design and Nondestructive Inspection - Keys to Aircraft Airworthiness

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Abstract

Damage tolerant design and nondestructive inspection are key tasks for ensuring aircraft airworthiness. Damage tolerance is the ability to resist fracture from preexistent damage for a given period of time and is an essential attribute of components whose failure could result in catastrophic loss of life or property. Nondestructive inspections define the maximum size of life-limiting defects that could be present at a given time. Inspection requirements are determined by the anticipated service loads, the desired service life, and by the damage tolerance designed into the structure. This paper discusses how damage tolerance and nondestructive inspection work together to ensure airworthiness by preventing failure from undetected manufacturing and/or service-induced damage.

Keywords: Airworthiness, damage tolerance, nondestructive inspection, structural integrity, fatigue and fracture

1. Introduction

Although structural failures are rare, those that do occur are often related to preexistent manufacturing or service-induced damage (e.g., material anomalies or fatigue cracking). Two key elements for preventing such failures are nondestructive inspection and damage tolerant design [1]. Nondestructive inspection provides the first step toward structural integrity by identifying damaged components that must be repaired or discarded. Since all inspection techniques have limitations, however, some components will contain undetected cracks. Damage tolerant design then provides the second line of defense against

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premature fracture by incorporating structural configurations and materials that are resistant to subcritical crack growth and final fracture.

Damage tolerance is the ability of a structure to resist a specified amount of damage for a given period of service. The damage in question may result from initial manufacturing errors or service-induced degradation, whereas the time period of interest could represent the desired service life, the time between maintenance actions, or the period required to safely cease operation and remove all personnel from danger. Damage tolerance is the protection provided to unanticipated sources of impairment and is an essential attribute for structures and machines whose failure could result in catastrophic loss of life or property.

The keys to airworthiness are to discover all damage that could lead to failure by a rigorous inspection program, and to design structures that are resistant to damage through appropriate materials selection and structural design features. The influence of these two factors on component life are shown schematically in Figure 1, where longer crack growth lives are obtained by reducing the initial crack size through improved inspection and slowing crack growth rates through designs which incorporate more crack resistant materials and/or employ structural configurations which reduce stresses or provide crack arrestment mechanisms.

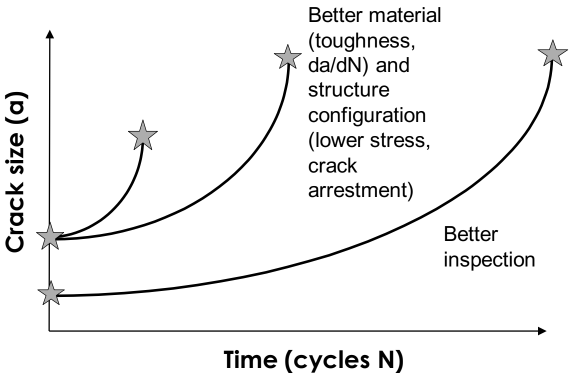

Fig. 1. Schematic improvement in life associated with better inspection (smaller initial crack) and more crack resistant material and/or structural configuration

Section 2 reviews structural failure modes and sets the context for the section 3 discussion of various types of manufacturing and service induced damage that could compromise airworthiness. Section 4 then overviews inspection methods and issues, while section 5 briefly describes fatigue design methodology. Section 6 summarizes various FAA requirements and procedures that incorporate these considerations for transport category aircraft.

2. 2 Structural failure modes

The paramount operational goal is to ensure that aircraft are retired or repaired before their structural life is exceeded. This objective requires that the designer explicitly specify life goals. The designer and operator must also anticipate worst case scenarios for the service loads and environment and must determine which forms of damage are likely to develop with use and when that damage could compromise airworthiness.

As background to this challenge, a brief review is given for the typical structural failure modes: elastic or inelastic deformation; creep; buckling; corrosion; fatigue and fracture [1]. When examining these failure mechanisms, it is important to distinguish between pristine structure that has been manufactured to "ideal" standards and components that have been subjected to wear and tear in service or those which could contain initial manufacturing damage. Indeed, the initial structural and material condition has a tremendous influence on which failure mode(s) will limit structural performance. Moreover, one must expect damage to develop and grow in service (i.e., by fatigue and/or corrosion) and that an initially "perfect" structure will likely develop some form of damage that could ultimately lead to failure.

Excessive deformation caused by applied loads can lead to unacceptable changes in component dimensions. Many materials behave in an elastic manner when forces are small and result in deflections that are readily predicted. These elastic deformations are controlled by the stiffness of the material and are recoverable when the component is unloaded (i.e., it returns to its original dimensions). Although elastic deformations are often not fatal by themselves, they can lead to situations where the structure fails to perform as intended.

If the applied forces exceed a given value for a particular material, the loaded member may continue to experience additional "inelastic" deformations. Although some of the total changes in dimensions may be recovered upon unloading, the member has permanently changed shape. The maximum load that can be applied without causing inelastic deformation is related to the material yield strength. Although most structures are designed to prevent yielding, inelastic deformations often provide an additional measure of safety before final failure occurs.

Creep is a time dependent failure mode that occurs when a member continues to deform under extended application of a static load. When the load is removed, some of the elongations may be recovered (elastic), whereas some deformations may remain at zero load (inelastic). These latter changes in dimension may be permanent or the member may gradually return to its original state after an additional period of time as these deformations continue to "relax." Creep is an important failure mode for metal components that operate for long periods at elevated temperatures and high loads (e.g., turbine engine blades). In addition, many polymers creep at room temperature.

Buckling failure is unique to slender members loaded in compression or shear. In this case, instability develops when the compression loading results in lateral deflections that, in turn, cause an additional bending moment that leads to further deflections and increased bending. Buckling can occur at very small elastic loads and is controlled by the material stiffness, edge support, the unsupported length, and the component cross-sectional moment of inertia. Buckling is an important failure mode for thin, compression-dominated structure (e.g., upper wing skins).

Corrosion is material degradation due to chemical attack and can occur in several forms – galvanic (dissimilar metal), pitting, exfoliation, intergranular attack, filiform, or, when combined with the presence of a tensile stress, stress corrosion cracking. This time dependent failure mechanism is highly dependent on the structural material and environment combination and is often accelerated by increasing temperature. Corrosion is a complex chemical phenomenon that can cause general thickness loss (and a corresponding increase in stress) as well as stress concentrations (i.e., pits and other localized areas of attack) that lead to fatigue cracking or fracture. Corrosion is difficult to predict, and its prevention requires careful materials selection, protective coatings, and periodic maintenance. Although corrosion can occur independent of applied loading (i.e., aircraft can continue to corrode without being flown), it frequently acts in conjunction with static or cyclic loading (e.g., stress corrosion or corrosion fatigue) to represent a particularly dangerous failure mode.

Cyclic fatigue is the failure mode associated with repeated loading and is one of the main factors that limits aircraft life. After repeated load cycles, small cracks will form, often at multiple locations in the structure. (This initial period of cycling is known as the crack nucleation life.) At the outset these cracks may be too small to cause fracture, but they do extend slowly after repeated cycling. Eventually some coalesce, leading to a dominant crack(s) that continues to grow in a stable manner. Finally, the dominant crack reaches a size that causes fracture, and the member fails in a sudden, catastrophic manner. Resisting fatigue failure is one of the main challenges to airworthiness, and is the subject of various design approaches discussed later.

Since fatigue can occur at relatively small cyclic loads and is so dependent on quality of construction, fatigue is a major consideration in the design and manufacture of many mechanical devices. Nondestructive inspection is essential to locate manufacturing anomalies that could lead to premature fatigue cracking and to detect cracks that do form before they grow to failure.

Final catastrophic fracture results when the member separates into two or more parts. Although fracture may occur in pristine structure that is subjected to overloads, it is frequently initiated at smaller loads by preexistent or by service-induced damage. Fracture can occur in a ductile manner that requires considerable expenditure of energy but can also happen suddenly with little warning. The fracture resistance of a structure is characterized by its material "toughness," and by geometric features such as crack stoppers or redundant structure.

The main focus of this paper deals with preventing damage-induced fracture, and is concerned with determining the fracture load as a function of crack size. Since cracks can grow in a subcritical manner by fatigue or stress corrosion cracking, the maximum load-carrying ability (i.e., residual strength) of the structure can decrease with time, as shown by the schematic "residual strength" diagram in Figure 2. Note here that there is an initial margin of safety provided by the fact that the stress needed to fracture the member (residual strength) exceeds the maximum applied load. This residual strength, however, decays with time (as small cracks form and grow by cyclic loading or as corrosion develops over time), until fracture occurs at the normal service load. At this time the component is no longer safe and must be retired or repaired. The following section discusses types of damage that could degrade residual strength during the operational life of the aircraft.

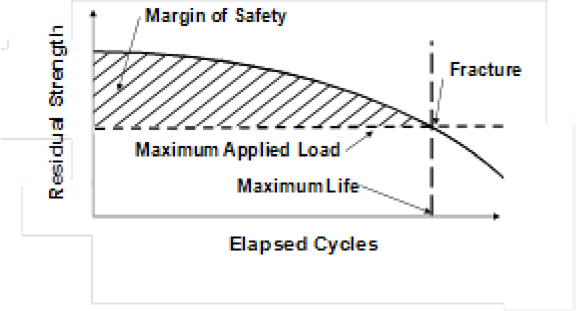

Fig. 2. Schematic residual strength diagram showing reduction in maximum load carrying ability of structure due to damage that develops over time

3. Manufacturing and service induced damage

Manufacturing errors that occur during material processing, machining, and structural assembly can lead to premature component failure. Examples of material flaws include porosity, constituent particles, inclusions, forging or casting defects, and improper thermal/mechanical treatment of the basic alloy. Machining problems include gouges and tears, rough surfaces, burrs and scratches at fastener holes or fillet locations, and other local material trauma caused by improper tool usage. Material surface condition plays an especially critical role in preventing fatigue crack formation. Final component assembly offers additional opportunity for damage in the form of “nicks and dings” from rough handling, improper welds, permanent deformations or cracking from force fits, as well as missing or damaged subcomponents. These machining and assembly errors are often accompanied by harmful residual stresses introduced during the manufacturing process.

In addition to normal wear and tear, service-induced damage includes several forms of corrosion, creep, or fatigue crack formation following cyclic loading. Overloads, thermal degradation, hydrogen embrittlement, fretting, or other forms of abuse suffered during service may also bring about permanent deformations and other detrimental changes in material properties. These damage mechanisms may also be aggravated by improper maintenance or repair during prior service. The possibility for foreign object damage (FOD) in the form of hail damage, bird strikes, accidental impacts, uncontained engine bursts, or battle damage in the case of military vehicles must also be considered. Again, these various forms of service-induced trauma are often accompanied by detrimental residual stresses that result from component abuse. Finally, development of corrosion and/or widespread fatigue damage (WFD) late in life must be given special attention. Although individual cracks may be relatively small, the fact that they occur in large numbers at multiple locations, makes WFD a particularly dangerous situation that can compromise damage tolerant attributes of older aircraft [2-3].

Thus, the challenge to continued airworthiness is to ensure that manufacturing or service induced damage does not cause an unacceptable reduction in residual strength and compromise structural integrity during the operating life of the structure. As discussed below, the first step in this procedure is to discover all damage that could lead to failure by a rigorous inspection program. Quantification of the largest damage that could exist following an inspection is paramount to determining the remaining air worthiness.

4. Nondestructive evaluation

Since fracture loads and component life are extremely sensitive to preexistent damage, nondestructive evaluation (NDE) plays a key role in preventing structural failures. Inspections of new structures are essential to detect manufacturing flaws that can cause immediate fracture or serve as sources for early fatigue cracking. As shown in Figure 3, the inspection goal is to find all damage (i.e. cracks > size a*) that could grow to failure in time t*. Here t* is the desired service life, or the time until the next inspection. When determining an appropriate inspection interval t* would be divided by a safety factor (often = 2), and would be based on fatigue crack growth analyses that consider anticipated loads, structural configuration, and material properties [1].

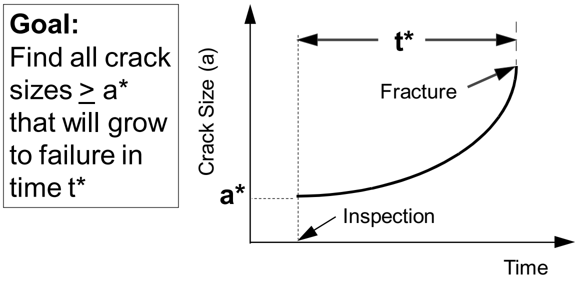

Fig. 3. Schematic crack growth curve defining inspection limit a* and time period t*

As shown schematically in Figure 4, selection of a particular inspection method for a given application involves a trade-off between performing a complex, time consuming inspection versus many repeated simpler inspections. Although the "difficult" inspection may reliably find small cracks, it may entail lengthy procedures and extensive down time for the aircraft. On the other hand, an "easy" NDE method (e.g., a simple visual inspection) may only locate "large" cracks to the desired degree of confidence, but if repeated often enough during service may also prevent final failure. In either case, it is necessary to specify an appropriate inspection period that will guarantee that all fatigue cracks, corrosion, FOD, or other forms of accidental damage will be located before they can grow to a size that compromises structural integrity.

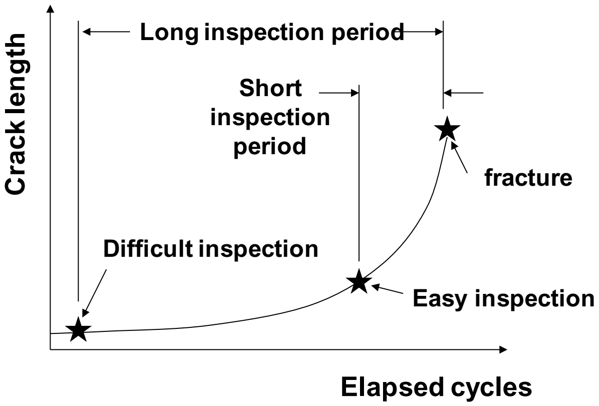

Fig. 4. Trade-off between inspection period and initial crack size

Successful NDE depends on many factors, including selection of the correct technique for the given application, proper calibration and operation of test equipment, surface preparation, flaw shape and orientation, and a host of human factors (e.g., inspector training, experience, alertness, confidence, expectations). When employing nondestructive inspection methods, it is important to keep in mind that all NDE techniques have limits regarding the size of the anomaly that can be reliably detected. While extremely small cracks can often be located under ideal conditions, it is unfortunately possible to miss much larger cracks during field-level inspections. Thus, when evaluating the results of an inspection, it is important to focus on determining the largest flaw that can be missed rather than emphasizing the smallest crack that can be found. To this end various statistical methods have been developed to establish probability-of-detection (POD) limits for a given inspection application [4].

Although many inspection methods are possible, the main NDE techniques employed in practice are visual, radiography, ultrasonic, eddy current, magnetic particle, and dye penetrant methods [1]. Although limited to relatively large anomalies, visual inspection is the most common method for locating surface damage, especially when employed with magnification and lighting aids. Internal flaws not visible to the human eye can often be found by X-rays or gamma rays (radiography) or by use of high-frequency sound waves (ultrasonics) that penetrate deep into the interior of the structure. Small surface or near-surface cracks can be readily found in electrically conductive materials by examining changes in small eddy currents generated near the component surface by an alternating magnetic field. Surface cracks in ferromagnetic materials may also be located by magnetizing the component and then allowing small magnetic particles to migrate to interruptions in the normal magnetic field caused by cracking. Brightly colored fluids may also be used to seep between crack faces and locate surface-breaking cracks by the popular dye penetrant inspection method.

Thus, the key challenge here is to select and properly apply the best inspection method for the particular case of interest. This decision rests not only on the capabilities of the particular inspection method, but also on the ability to determine an appropriate inspection interval that guarantees all damage is found before growing to a size that causes fracture. Determination of the safe inspection interval often entails fracture mechanics based life prediction methods that consider the applied loads, initial crack size and shape, structural geometry, and material properties [1].

5. Overview of fatigue design criteria

Having noted that limitations in inspection methods result in the possibility that structures contain small, undetected cracks that can grow by fatigue, now consider a “big picture” view of various design strategies to prevent component failure. Whereas there are several approaches to structural integrity, the general keys to long-life designs are proper materials selection, setting low stress levels, providing multiple load path and crack-arresting features, and implementation of rigorous inspection programs. Development of fracture mechanics techniques during the 1960s and 1970s led to sophisticated methods to explicitly treat initial damage as a design variable when evaluating residual strength and fatigue life. The present discussion is intended to help set the context for current air worthiness requirements for structural integrity employed by the FAA and other agencies.

Infinite-Life Design Early designers treated fatigue by attempting to keep component stresses below the endurance limit for the material of interest. The endurance limit is the maximum constant-amplitude stress that can be applied to a pristine specimen without ever causing a fatigue failure (i.e., infinite life). Although the endurance limit concept was useful for solving fatigue problems that originally plagued railroad equipment and other machines that made the industrial revolution possible, this approach has many serious limitations. The endurance limit is extremely sensitive to the condition of the test specimen. Notches, small scratches, or other “nicks and dings” serve as stress concentrations that quickly cause localized fatigue cracking and greatly reduce the endurance limit so that little, if any, damage tolerance can be achieved by this approach. Moreover, residual stresses introduced by manufacturing or by localized yielding during variable-amplitude loading often have deleterious effects. Since it is impractical, if not impossible, to design high-performance structures for “infinite” lives by the simple endurance limit methodology, it is now accepted that most structures will have a finite fatigue life. The objective of the designer, then, is to determine what that service life should be and then to ensure that the actual component exceeds that goal.

Safe-Life Design The safe-life approach treats fatigue as a crack nucleation process and does not explicitly consider the possibility for crack growth (failure is assumed when cracks are first formed). Since fatigue tests often demonstrate considerable "scatter," extensive testing is needed to determine the expected mean life for the desired service loading. The mean life is then divided by a safety factor (often 4) to determine the maximum allowable service life that provides a low probability for fatigue failure. The safe-life approach led to several inadequate aircraft designs in the 1960s, however, and its current use is discouraged, although aircraft landing gear and many helicopter components are still designed to safe-life criteria. The Achilles heel for the safe-life approach is that the presence of unanticipated structural or material damage greatly reduces the crack nucleation portion of the fatigue process. Thus, the safety factor may not account for the reduction in fatigue life caused by the undetected initial damage in particular aircraft.

In order to overcome this shortcoming of the safe-life approach, damage tolerant design methods were developed that assume the structure contains initial cracks. The initial crack size is usually based on inspection limits and is expected to be a conservative assumption. There are two general approaches, with variations, that may be followed to guarantee that the structure (with its assumed cracks) does not fail in service: slow crack growth and fail-safe design.

Slow Crack Growth The slow crack growth (or safe crack growth) design criterion selects component materials and sets stress levels so that the assumed preexistent crack will not grow to failure during service (see Figure 5) and is the normal approach for single load path structure. For increased safety, the allowed service life is usually obtained by dividing the total crack growth period by a factor of 2. The component would have to be retired or inspected at this time before continued operation would be permitted.

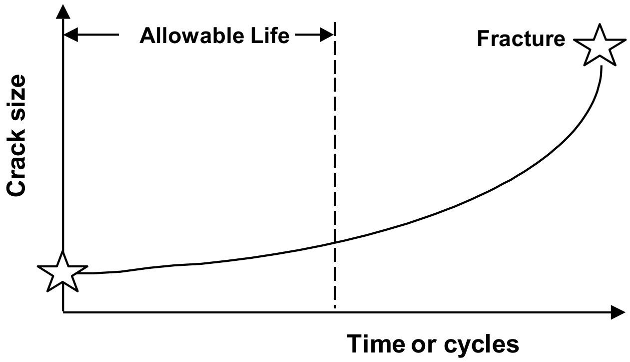

Fig. 5. Schematic representation of slow crack growth approach to fatigue resistant design

Fail-Safe Design The fail-safe approach is another technique for achieving damage tolerance. The goal here is to employ multiple load paths and/or crack arrest features so that a single component failure does not lead to immediate loss of the entire structure. As shown schematically in Figure 6, for example, a large panel is comprised of several individual components loaded in parallel rather than a single continuous member. If one of the individual components fails, its load is immediately picked up by adjacent structure and total fracture is avoided. It is essential, however, that the original failure be detected and promptly repaired, because the extra load carried by remaining components will shorten their fatigue lives. This possibility was vividly demonstrated by the 1977 loss of an older Boeing 707 transport aircraft that flew for an additional 100 flights after an undetected spar fracture in the horizontal stabilizer. Although the original fracture was contained as planned, the remaining "fail-safe" structure was required to carry additional load, and eventually developed fatigue cracks that resulted in complete loss of the aircraft. This accident led to changes in certification procedures that require the use of fracture mechanics methods to develop supplementary inspection documents (SID's) for continued operation of older aircraft [2,3].

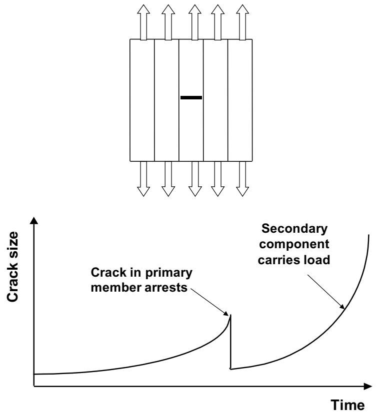

Fig. 6. Schematic representation of multi-load path structure showing crack arrestment when a single member fails and the subsequent load is taken up by other members

Retirement for Cause As nondestructive inspection and crack growth analysis methods have matured, it has become possible to employ a "retirement for cause" or "safety by inspection" strategy to extend the lives of existing hardware that have reached their theoretical life limits. Although the initial design life may have been based on crack formation concepts (i.e., safe-life design), the actual current damage state is established through rigorous nondestructive evaluation. Fracture mechanics concepts then determine the remaining additional service life (if any) that can be safely exploited for individual components. The retirement-for-cause approach is shown schematically in Figure 7, where periodic inspections locate damaged components that are then repaired or replaced. The structures are subsequently returned to service for another specified period, when the inspection/repair process is repeated. This process can be repeated indefinitely until the costs of inspection and repair become prohibitive (many cracks would be expected to develop after long lifetimes). The basis for this procedure is to reliably determine the maximum crack size that could exist following an inspection and repair cycle, and then determine the remaining operational life of a component with this potential crack.

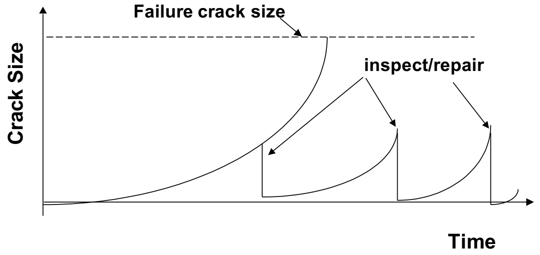

Fig. 7. Schematic representation of the retirement for cause approach showing how repeated inspections can be used to extend fatigue life

6. Summary of civil transport airworthiness requirements

Mr. R. G. Eastin, Chief Scientific and Technical Advisor for Fatigue and Damage Tolerance with the USA Federal Aviation Administration (FAA), has written a series of papers that discuss the details and philosophy of the FAA approaches to ensuring structural integrity of aircraft [2-3, 5-6]. Separate regulations apply to “normal, utility, aerobatic, and commuter category” airplanes (Part 23), transport category aircraft (Part 25), normal category rotorcraft (Part 27), and transport category rotorcraft (Part 29). While it is not possible to review all of that discussion, some key points are briefly reviewed here with regard to commercial air worthiness requirements for fatigue and damage tolerance.

For the Part 25 transport category aircraft, the safe-life approach is generally prohibited except for landing gear and other components where damage tolerance is shown to be impractical. Since it has been FAA policy not to dictate particular design approaches, both single (i.e., slow crack growth) and multi-load path (i.e., fail-safe) damage tolerant procedures are permitted.

There is special concern for older aircraft where widespread fatigue damage (WFD) could be an issue. As indicated by the well known 1988 “Aloha Airlines” incident [6], it is possible for multiple small undetected cracks to suddenly link up and compromise the damage tolerance built into the aircraft. Thus, special amendment 25-96 was issued in 1998 for the WFD problem [3,6]. That document states in part: “Special consideration for widespread fatigue damage must be included where the design is such that this type of damage could occur. It must be demonstrated with full scale fatigue test evidence that widespread fatigue damage will not occur within the design service goal of the airplane.”

As discussed in [6], damage tolerance requirements for commercial aircraft have developed steadily during the past several decades to a mature approach with a remarkable safety record for ensuring airworthiness. Although the relative emphasizes on inspection and damage tolerance continues to evolve, these two tasks are the keys to success.

7. Conclusions

The objective of this paper has been to introduce the challenges facing the engineer who seeks to design, build, and maintain safe structures. Ensuring structural integrity requires anticipation of all possible failure mechanisms and then providing adequate resistance to these various threats. Whereas every effort is made to ensure high-quality construction, experience has shown that it is impossible to build complex mechanical devices that are free of initial manufacturing or material flaws. Moreover, accidental damage may occur during use, along with fatigue, corrosion, or other forms of material degradation. Thus, nondestructive evaluation, both before and during service, is an essential step for achieving structural reliability. Damage tolerant designs provide additional protection against such trauma by keeping stress levels small, employing damage resistant materials, and providing crack-arresting structural features.

The foundations for structural integrity have been compared with the stability provided by a "three-legged stool." One leg is a rigorous inspection program that locates manufacturing or service-induced damage before it can lead to failure. Another leg is superior residual strength that ensures the catastrophic fracture load always exceeds the largest applied service load. The third leg of the damage tolerance stool is a long subcritical crack growth life that gives many opportunities to locate and repair any damage that does develop before it grows to a size that causes final fracture. These three legs must work together to ensure continued structural airworthiness.

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