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Damage tolerance analysis requires the capability to assess the damage, usually measured by incremental crack growth, accumulating in a given piece of structure under flight-by-flight spectrum loading. This requirement implies the need to process this damage accumulation over thousands of flights consisting of millions of load cycles. Many models have been developed to analyze the process of damage accumulation under spectrum loading. All these models have been computerized to permit timely cost-effective damage tolerance analyses to be performed. This recent book provides a detailed presentation of damage tolerance assessment and characterization methods for advanced composites, as well as an examination of the role of damage tolerance in the design of composites. Included are analytical models for different types of damage in different composite materials. Tables provide helpful reference The third volume of this six-volume compendium provides methodologies and lessons learned for the design, analysis, manufacture, and field support of fiber-reinforced, polymeric-matrix composite structures. It also provides guidance on material and process specifications and procedures for using the data that is presented in Volume 2. The information provided is consistent with the guidance provided in Volume 1, and is an extensive compilation of the current knowledge and experiences of engineers and scientists from industry, government, and academia who are active in composites. The Composite Materials Handbook, referred to by industry groups as CMH-17, is a six-volume engineering reference tool that contains over 1,000 records of the latest test data for polymer matrix, metal matrix, ceramic matrix, and structural sandwich composites. CMH-17 provides information and guidance necessary to design and fabricate end items from composite materials. It includes properties of composite materials that meet specific data requirements as well as guidelines for design, analysis, material selection, manufacturing, quality control, and repair. The primary purpose of the handbook is to standardize engineering methodologies related to testing, data reduction, and reporting of property data for current and emerging composite materials. It is used by engineers worldwide in designing and fabricating products made from composite materials. This thesis presents a new modeling framework and application methodology for the study of aircraft structures. The framework provides a 'cradle-to-grave' approach to structural analysis of a component, where structural integrity encompasses all phases of its lifespan. The methodology examines the holistic structural design of aircraft components by integrating fatigue and damage tolerance methodologies. It accomplishes this by marrying the load inputs from a fatigue analysis for new design, into a risk analysis for an existing design. The risk analysis incorporates the variability found from literature, including recorded defects, loadings, and material strength properties. The methodology is verified via formal conceptualization of the structures, which are demonstrated on an actual hydraulic accumulator and an engine nacelle inlet. The hydraulic accumulator is examined for structural integrity utilizing different base materials undergoing variable amplitude loading. Integrity is accomplished through a risk analysis by means of fault tree analysis. The engine nacelle inlet uses the damage tolerance philosophy for a sonic fatigue condition undergoing both constant amplitude loading and a theoretical flight design case. Residual strength changes are examined throughout crack growth, where structural integrity is accomplished through a risk analysis of component strength versus probability of failure. Both methodologies can be applied to nearly any structural application, not necessarily limited to aerospace. Most reliability problems are characterized by small Probabilities-of-Failure (POF) that typically require a large number of Limit-State Function (LSF) evaluations. In many cases, due to the high cost computational cost of each evaluation of an LSF, it is often desirable to limit the number of evaluations while keeping the accuracy of the POF as high as possible. The trade-off between the cost and accuracy is still a challenge. In this research, the applicability of the First-Order Reliability Method (FORM) and the Second-Order Reliability Method (SORM) was tested in a probabilistic damage tolerance analysis methodology with and without non-destructive inspections. The purposes of the research were to identify limitations and apply improvements to algorithms of these methods in order to make them more robust and efficient when an external crack growth code is to be used in realistic applications. An efficient method, called 'Varying Step Lengths Method', was introduced in this research that can obtain suitable step lengths for gradients of the LSF by the finite difference method. Also, the bisection method was applied to find the next search point in the optimization algorithm of FORM analyses. In addition, the suitability of SORM analyses after FORM analyses was tested in this context. To estimate the POF, FORM assumes a linearized Limit-State Surface (LSS) instead of the actual surface at the design point in the standard normal space. The method computes the shortest distance of the linearized LSS from the origin, and estimates the POF as the probability content outside the hyper-plane using an attractively low number of LSF evaluations. The accuracy of the POF obtained from the FORM analysis can be improved by subsequently applying the SORM analysis that takes the amount of curvature of the actual LSS into account and considers a hyperbolic LSS at the design point. The method estimates the POF as the probability content outside the hyper-paraboloid. In this research, the Augmented FORM algorithm was tested to estimate the POF with and without inspections. It was found that the algorithm can give much quicker estimate of the POF than other costly methods, e.g. Monte Carlo and numerical integration methods. Also, improvements were made to the algorithm for performing Fracture mechanics calculations using the NASA developed well-known Fracture mechanics and fatigue crack growth analysis software NASGRO. Three important random variables: Initial crack size, Load, and Paris crack growth constant C were considered. Subsequently, SORM was applied to improve the FORM results. The results were verified with those obtained from numerical integration and sampling methods used in the FAA-sponsored structural integrity software SMART|DT that also used NASGRO for crack growth calculation. The verification showed that the improved Augmented FORM can give efficient estimates of the POF with and without inspections using NASGRO. It was also revealed that in many cases SORM can improve the POF estimates. Discusses applications of failures and evaluation techniques to a variety of industries. * Presents a unified approach using two key elements of structural design. Most general aviation (GA) aircraft are designed for safe-life based upon a crack initiation type failure mechanism, e.g., Miner's rule. However, newer GA aircraft have a fatigue crack growth as a design option. In addition, it may be necessary to evaluate a field event such as a cracked structure to ascertain the remaining life. Therefore, a risk based probabilistic damage tolerance analysis (PDTA) program is needed in several aerospace situations. Many military aircraft fleets (e.g. US DoD (MIL-STD-820), UK MoD (ADRM), and Canadian Forces (TAM)) have adopted a risk management program/tool to ensure aircraft safety and airworthiness. Now more non-military agencies are adopting these practices to guarantee aircraft safety and maintain airworthiness. A comprehensive probabilistic damage tolerance method requires a combination of a deterministic crack growth model, inspection methods, probabilistic methods, and random variable modeling to provide a single probability-of-failure, cumulative probability-of-failure, and hazard rate with and without inspection. Today's crack growth simulations are strongly based on complex computer codes and numerical analyses, which can only provide discrete information about the underlying relationship. This complexity makes the crack growth analysis very expensive and consequently the single probability-of-failure, cumulative probability-of-failure, and hazard rate very expensive to compute. In this work, a general methodology to conduct probabilistic crack growth based damage tolerance methodology for small airplanes was developed and incorporated in computer software. The methodology overcomes the limitations from previous damage tolerance programs such as the number of random variables, extreme value distribution (EVD) loading generation, inspections/repair programs, and reduction on the computational time. Existing probabilistic damage tolerance methodologies have a limitation on the number of random variables (initial crack size, fracture toughness, and loading). In this work additional random variables were included in the model using Monte Carlo sampling (MCS), efficient numerical integration algorithms, and a surrogate model for crack growth modeling. Algorithms to determine the extreme value distribution from real aircraft loading, generated in this research as well, were developed and incorporated into the code. New efficient inspection and repair programs were studied, improved if necessary, and implemented into the code. The main contribution of this work includes the reduction of the computational time using an error based adaptive surrogate model; the surrogate model included a comprehensive number of random variables (e.g. initial crack size, fracture toughness, correlated Paris constants, yield and ultimate stress, etc.). The surrogate model was used as a substitution for the original crack growth model. Four different case studies are presented to demonstrate the different methodologies developed in this work. This document describes the technical details of the analysis methodology used in the static and damage tolerance analysis modules of the Repair Assessment Procedure and Integrated Design (RAPID) program. In this document, the static strength analysis method for repaired fuselage skin and skin modifications to antenna installation is first described. Next, a description of the damage tolerance method is provided. This document also includes descriptions of the methods developed for the damage tolerance analysis of common repairs including a repair near another repair and repairs at stiffeners. Flowcharts of static and damage tolerance analysis methods are provided. Among the principal causes of failure in structural dynamic systems are exceedance of maximum structural systems design limit and structural fatigue failure. These processes are analyzed in this volume, and require sophisticated methods such as stochastic processes and their interactions with a structure as applied forces with stochastic description, finite element techniques, and other processes. Once these aspects are understood and applied, approaches to enhancing the reliability and damage tolerance of structural systems can be examined and applied to specific structural dynamic systems. This volume offers a comprehensive treatment of the issues and the sophisticated techniques involved and includes numerous illustrative examples. A summary of research conducted during the first year is presented. The research objectives were sought by conducting two tasks: (1) investigation of probabilistic design techniques for reliability-based design of composite sandwich panels, and (2) examination of strain energy density failure criterion in conjunction with response surface methodology for global-local design of damage tolerant helicopter fuselage structures. This report primarily discusses the efforts surrounding the first task and provides a discussion of some preliminary work involving the second task. Rais-Rohani, Masoud Langley Research Center In this report, an approach to damage-tolerant aircraft structural design is proposed based on the concept of an equivalent "Level of Safety" that incorporates past service experience in the design of new structures. The discrete "Level of Safety" for a single inspection event is defined as the compliment of the probability that a single flaw size larger than the critical flaw size for residual strength of the structure exists, and that the flaw will not be detected. The cumulative 'Level of Safety" for the entire structure is the product of the discrete "Level of Safety" values for each flaw of each damage type present at each location in the structure. Based on the definition of "Level of Safety", a design procedure was identified and demonstrated on a composite sandwich panel for various damage types, with results showing the sensitivity of the structural sizing parameters to the relative safety of the design. The "Level of Safety" approach has broad potential application to damage-tolerant aircraft sturctural design with uncertainty. This report describes a simplified procedure for the development of stress histories for use in the analysis of aircraft repairs. This report concentrates on stress histories for fuselage skin repairs. A description of typical fuselage loadings is provided, and basic fuselage stress histories are described. A method for development of an exceedance diagram for analysis of fuselage skin repairs is detailed. Subsequently, a methodology for generating detailed stress histories is reviewed. Some of the key features are (1) the inclusion of a range of flights of different severities, (2) the inclusion of deterministic loads where they occur, e.g., ground-air-ground cycles, (3) the use of a near-optimum number of stress levels (10-16 positive and negative), (4) the combination of positive and negative excursions of equal frequency, and (5) matching of the total number of flights and cycles with the total exceedance diagram. Two methods of estimating fuselage skin stresses are presented, the first based on static equilibrium requirements and the second based on a limit load analysis. A comparison of the proposed history generation scheme with that of an airframe manufacturer for the KC-135 is also presented. The predicted fatigue crack growth patterns for a hypothetical through crack at a fastener hole are compared for the two history generation schemes at three areas within a fuselage. The majority of aircraft structures are designed to be damage-tolerant such that safe operation can continue in the presence of minor damage. It is necessary to schedule inspections so that minor damage can be found and repaired. It is generally not possible to perform structural inspections prior to every flight. The scheduling is traditionally accomplished through a deterministic set of methods referred to as Damage Tolerance Analysis (DTA). DTA has proven to produce safe aircraft but does not provide estimates of the probability of failure of future flights or the probability of repair of future inspections. Without these estimates maintenance costs cannot be accurately predicted. Also, estimation of failure probabilities is now a regulatory requirement for some aircraft. The set of methods concerned with the probabilistic formulation of this problem are collectively referred to as Probabilistic Damage Tolerance Analysis (PDTA). The goal of PDTA is to control the failure probability while holding maintenance costs to a reasonable level. This work focuses specifically on PDTA for fatigue cracking of metallic aircraft structures. The growth of a crack (or cracks) must be modeled using all available data and engineering knowledge. The length of a crack can be assessed only indirectly through evidence such as non-destructive inspection results, failures or lack of failures, and the observed severity of usage of the structure. The current set of industry PDTA tools are lacking in several ways: they may in some cases yield poor estimates of failure probabilities, they cannot realistically represent the variety of possible failure and maintenance scenarios, and they do not allow for model updates which incorporate observed evidence. A PDTA modeling methodology must be flexible enough to estimate accurately the failure and repair probabilities under a variety of maintenance scenarios, and be capable of incorporating observed evidence as it becomes available. This dissertation describes and develops new PDTA methodologies that directly address the deficiencies of the currently used tools. The new methods are implemented as a free, publicly licensed and open source R software package that can be downloaded from the Comprehensive R Archive Network. The tools consist of two main components. First, an explicit (and expensive) Monte Carlo approach is presented which simulates the life of an aircraft structural component flight-by-flight. This straightforward MC routine can be used to provide defensible estimates of the failure probabilities for future flights and repair probabilities for future inspections under a variety of failure and maintenance scenarios. This routine is intended to provide baseline estimates against which to compare the results of other, more efficient approaches. Second, an original approach is described which models the fatigue process and future scheduled inspections as a hidden Markov model. This model is solved using a particle-based approximation and the sequential importance sampling algorithm, which provides an efficient solution to the PDTA problem. Sequential importance sampling is an extension of importance sampling to a Markov process, allowing for efficient Bayesian updating of model parameters. This model updating capability, the benefit of which is demonstrated, is lacking in other PDTA approaches. The results of this approach are shown to agree with the results of the explicit Monte Carlo routine for a number of PDTA problems. Extensions to the typical PDTA problem, which cannot be solved using currently available tools, are presented and solved in this work. These extensions include incorporating observed evidence (such as non-destructive inspection results), more realistic treatment of possible future repairs, and the modeling of failure involving more than one crack (the so-called continuing damage problem). The described hidden Markov model / sequential importance sampling approach to PDTA has the potential to improve aerospace structural safety and reduce maintenance costs by providing a more accurate assessment of the risk of failure and the likelihood of repairs throughout the life of an aircraft. Aerospace vehicles are designed to be durable and damage tolerant. Durability is largely an economic life-cycle design consideration whereas damage tolerance directly addresses the structural airworthiness (safety) of the vehicle. However, both durability and damage tolerance design methodologies must address the deleterious effects of changes in material properties and the initiation and growth of microstructural damage that may occur during the service lifetime of the vehicle. Durability and damage tolerance design and certification requirements are addressed for commercial transport aircraft and NASA manned spacecraft systems. The state-of-the-art in advanced design and analysis methods is illustrated by discussing the results of several recently completed NASA technology development programs. These programs include the NASA Advanced Subsonic Technology Program demonstrating technologies for large transport aircraft and the X-33 hypersonic test vehicle demonstrating technologies for a single-stage-to-orbit space launch vehicle.Harris, Charles E. and Starnes, James H., Jr. and Shuart, Mark J.Langley Research CenterAIRCRAFT RELIABILITY; DAMAGE; DESIGN ANALYSIS; MICROSTRUCTURE; LIFE (DURABILITY); AEROSPACE VEHICLES; CERTIFICATION; COMMERCIAL AIRCRAFT; ECONOMICS; HYPERSONIC VEHICLES; X-33 REUSABLE LAUNCH VEHICLE... The Manual presents a methodology for integrating projectile impact damage tolerance into aircraft structural design. The information is presented in three sections: (1) Description of Projectile Threats; (2) Analysis Methods for Predicting Structural Response to Projectile Impact; and (3) Design Guidelines for Impact Tolerance. This report has been prepared at the request of the Structures and Materials Panel of AGARD. This book consists of a collection of lectures prepared for a short course on "Fracture Mechanics Methodology" sponsored by the Advisory Group for Aerospace Research and Development (AGARD), part of the North Atlantic Treaty Organization (NATO). The course was organized jointly by Professor George C. Sih of the Institute of Fracture and Solid Mechanics at Lehigh University in the United States and Professor Luciano Faria from Centro de Mecanica e de Materiais das Universidade de Lisboa in Portugal. It was held in Lisbon from June 1 to 4, 1981. Dr. Robert Badaliance from the McDonnell Aircraft Company in St. Louis and Dr. Oscar Orringer from the Depart ment of Transportation in Cambridge are the other US lecturers while Professor Carlos Moura Branco from Portugal also lectured. The audience consisted of engineers from the Portuguese industry with a large portion from the aeronautical sector and others who are particularly interested to apply the fracture mechanics discipline for analyzing the integrity of structural components and fracture control methods. Particular. emphases were given to the fundamentals of fracture mechanics as applied to aircraft structures. An improved certification methodology for composite structures was developed. The methodology permits certification of bonded and concurred composite structures with the same level of confidence as bolted structures. This methodology also ensures that the threat of in service low velocity impact is adequately addressed. The methodology was demonstrated on actual composite aircraft structures to evaluate the damage tolerance capability of these structures. The F/A-18A upper wing skin was used for methodology demonstration. Sensitivity studies were conducted to determine the influence of impact damage threat scenarios and damage tolerance design requirements on the reliability of composite structures. This book provides a state-of-the-art review of the fail-safe and damage tolerance approaches, allowing weight savings and increasing aircraft reliability and structural integrity. The application of the damage tolerance approach requires extensive know-how of the fatigue and fracture properties, corrosion strength, potential failure modes and non-destructive inspection techniques, particularly minimum detectable defect and inspection intervals. In parallel, engineering practice involving damage tolerance requires numerical techniques for stress analysis of cracked structures. These evolved from basic mode I evaluations using rough finite element approaches, to current 3D modeling based on energetic approaches as the VCCT, or simulation of joining processes. This book provides a concise introduction to this subject. Aviation rules mandate the need for an aircraft structure to meet damage tolerance requirements. The damaged structure must maintain adequate residual strength in order to maintain its integrity and this is accomplished through a continuous inspection program. The multifold objective of this work is to present a methodology based on a direct Monte Carlo simulation (MCS) process to assess the reliability of an aircraft structure. Initially, the structure is modeled as a parallel system with active redundancy comprised of elements with uncorrelated strengths. Closed form expressions for the system capacity cumulative distribution function are expanded from three elements in the current literature up to six elements. The second objective is to compute the probability of failure of a fuselage skin lap joint under static load conditions by examining the residual strength of the fasteners when subjected to various load distributions initially and following subsequent fastener sequential failures. The last objective is to present a MCS methodology for computing the non-periodic inspections required in order to maintain a prescribed minimum reliability level. A critical evaluation of three analytical approaches is made to determine their applicability and/or potential for analytically assuring airframe durability during the design stage. A suitable analytical format for quantifying durability damage is developed based on U.S. Air Force durability design specifications and durability analysis needs. Air Force durability requirements are briefly reviewed and discussed. Three potential approaches for durability damage analysis are conceptually evaluated and discussed: (1) Conventional Fatigue Analysis (Palmgren-Miner Rule); (2) Deterministic Crack Growth Approach; and (3) Probabilistic Crack Growth Approach. The resulting evaluation provides the prerequisite work needed to develop a durability analysis methodology. The probabilistic crack growth approach is found to be the most promising for developing the durability analysis methodology under Phase 1. A daring, original approach to understanding and predicting the mechanical behavior of materials "Damage is an abstraction . . . Strength is an observable, an independent variable that can be measured, with clear and familiar engineering definitions." -from the Preface to Damage Tolerance and Durability of Material Systems Long-term behavior is one of the most challenging and important aspects of material engineering. There is a great need for a useful conceptual or operational framework for measuring long-term behavior. As much a revolution in philosophy as an engineering text, Damage Tolerance and Durability of Material Systems postulates a new mechanistic philosophy and methodology for predicting the remaining strength and life of engineering material. This philosophy associates the local physical changes in material states and stress states caused by time-variable applied environments with global properties and performance. There are three fundamental issues associated with the mechanical behavior of engineering materials and structures: their stiffness, strength, and life. Treating these issues from the standpoint of technical difficulty, time, and cost for characterization, and relationship to safety, reliability, liability, and economy, the authors explore such topics as: * Damage tolerance and failure modes * Factors that determine composite strength * Micromechanical models of composite stiffness and strength * Stiffness evolution * Strength evolution during damage accumulation * Non-uniform stress states * Lifetime prediction With a robust selection of example applications and case studies, this book takes a step toward the fulfillment of a vision of a future in which the prediction of physical properties from first principles will make possible the creation and application of new materials and material systems at a remarkable cost savings. This book gathers contributions addressing issues related to the analysis of composite structures, whose most relevant common thread is augmented numerical efficiency, which is more accurate for given computational costs than existing methods and methodologies. It first presents structural theories to deal with the anisotropy of composites and to embed multifield and nonlinear effects to extend design capabilities and provide methods of augmenting the fidelity of structural theories and lowering computational costs, including the finite element method. The second part of the book focuses on damage analysis; the multiscale and multicomponent nature of composites leads to extremely complex failure mechanisms, and predictive tools require physics-based models to reduce the need for fitting and tuning based on costly and lengthy experiments, and to lower computational costs; furthermore the correct monitoring of in-service damage is decisive in the context of damage tolerance. The third part then presents recent advances in embedding characterization and manufacturing effects in virtual testing. The book summarizes the outcomes of the FULLCOMP (FULLy integrated analysis, design, manufacturing, and health-monitoring of COMPosite structures) research project. The effect of localized impact damage on the general reliability of composite constructions is of concern in a variety of contexts. The advantages of using instrumented impact test procedures and enhanced data acquisition techniques to quantify the level of damage are illustrated for some specific applications. Using this approach the extent of the damage can then be characterized for controlled and reproducible impact conditions. The procedures outlined and the flexibility they offer in imparting damage to materials or components provide the basis for a constructive damage tolerance methodology. Comprehensively covers new and existing methods for the design and analysis of composites structures with damage present Provides efficient and accurate approaches for analysing structures with holes and impact damage Introduces a new methodology for fatigue analysis of composites Provides design guidelines, and step by step descriptions of how to apply the methods, along with evaluation of their accuracy and applicability Includes problems and exercises Accompanied by a website hosting lecture slides and solutions This recent book provides a detailed presentation of damage tolerance assessment and characterization methods for advanced composites, as well as an examination of the role of damage tolerance in the design of composites. Included are analytical models for different types of damage in different composite materials. Tables provide helpful reference

- Composite Structures Damage Tolerance Analysis Methodologies
- Advanced Durability And Damage Tolerance Design And Analysis Methods For Composite Structures Lessons Learned From NASA Technology Development Programs
- Advanced Durability And Damage Tolerance Design And Analysis Methods For Composite Structures
- Damage Tolerance Of Metallic Aircraft Structures
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- Fatigue And Damage Tolerance Assessment Of Aircraft Structure Under Uncertainty
- Damage Accumulation Techniques In Damage Tolerance Analysis
- Assessment Of Damage Tolerance Requirements And Analyses Analytical Methods
- Design Manual For Impact Damage Tolerant Aircraft Structure
- Techniques For Optimisation And Analysis Of Composite Structures For Damage Tolerance And Buckling Stiffness
- Probabilistic Damage Tolerance Analyses With Inspections Using The First And Second order Reliability Analysis Methods
- Monte Carlo Simulation Methodology For The Reliability Of Aircraft Structures Under Damage Tolerance Considerations
- Development Of A Fatigue life Methodology For Composite Structures Subjected To Out of plane Load Components
- Damage Tolerance And Durability Of Material Systems
- Design Of Composite Structures For Reliability And Damage Tolerance
- Structural Dynamic Systems Computational Techniques And Optimization
- Damage Tolerance Assessment Procedures For Composite Materials And Components
- Reliability based Methods Applied To The Design Of Damage Tolerant Aircraft Structures
- Fundamentals Of Structural Integrity
- Enhancement To Repair Assessment Procedure And Integrated Design RAPID Analysis Methods Enhancements
- Advanced Certification Methodology For Composite Structures
- Estimation Of Probability Of Failure For Damage Tolerant Aerospace Structures
- Fracture Mechanics Methodology
- Review Of Damage Tolerance For Composite Sandwich Airframe Structures
- Approaches To Assessment Of Damage Tolerance Levels In FRP Structures
- Structural Design Methodology Based On Concepts Of Uncertainty
- Damage Tolerance In Advanced Composites
- Durability Methods Development
- Modeling The Effect Of Damage In Composite Structures
- Generation Of Spectra And Stress Histories For Fatigue And Damage Tolerance Analysis Of Fuselage Repairs
- Monte Carlo Simulation Methodology For The Reliability Of Aircraft Structures
- Damage tolerance And Fatigue Evaluation Of Structure
- Polymer Matrix Composites Materials Usage Design And Analysis
- Advances In Predictive Models And Methodologies For Numerically Efficient Linear And Nonlinear Analysis Of Composites
- Scientific And Technical Aerospace Reports
- FAA NASA International Symposium On Advanced Structural Integrity Methods For Airframe Durability And Damage Tolerance Part 2
- FAA NASA International Symposium On Advanced Structural Integrity Methods For Airframe Durability And Damage Tolerance