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Structural Design Methodology Based on Concepts of Uncertainty

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FOREWORD

This report summarizes the work accomplished during the period of May 16, 1998 – September 30, 1999, under the NASA Langley Research Center Grant No. NAG-1-2055. The principal investigator of this program was Dr. K. Y. Lin. David Rusk was the graduate research assistant. Dr. Jiaji Du, a visiting scientist from West Virginia University, was the researcher for this project. Dr. Bjorn Backman of the Boeing Company also contributed to this project. The NASA project manager is Dr. W. Jefferson Stroud. Invaluable discussions and support of this research from Dr. Jeff Stroud of NASA, Dr. Bjorn Backman of Boeing, Dr. Larry Ilcewicz and Dr. Dave Swartz of the FAA are greatly appreciated.

ABSTRACT

The principal goal of this research program is to develop a design process for damage tolerant aircraft structures using a definition of structural "Level of Safety" that incorporates past service experience. The design process is based on the concept of an equivalent "Level of Safety" for a given structure. 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.

The design method derived from the above definition consists of the following steps: collecting in-service damage data from existing aircraft, establishing the baseline safety level for an existing structural component, conducting damage tolerance analyses for residual strength of the new structural design, and determining structural configuration for a given load and the required safety level (sizing). The design method was 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 structural design with uncertainty.

EXECUTIVE SUMMARY

There are at least two fundamental shortcomings to traditional aircraft design procedures using factors of safety and knockdown factors. First, these procedures may be difficult to apply to aircraft that have unconventional configurations, use new material systems, and contain novel structural concepts. Second, levels of safety and reliability cannot be easily measured for a structural component. As a result, it is not possible to determine the relative importance of various design options on the safety of the aircraft. In addition, with no measure of safety it is unlikely that there is a consistent level of safety and efficiency throughout the aircraft. The principal goal of this research program is to develop a design process for damage tolerant aircraft structures using a definition of structural "Level of Safety" that incorporates past service experience.

In this report, an approach to damage-tolerant aircraft structural design based on the concept of an equivalent "Level of Safety" is studied. 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.

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To demonstrate the design methodology on a new structure, a composite sandwich panel was analyzed for residual strength as a function of damage size for disbond, delamination and notch damage. A two-step analysis model was used to determine post-buckling residual strength for each damage type. The residual strength vs. damage size results were used to demonstrate application of the “Level of Safety” design processes using two example problems. The influence of the structural sizing parameters on the overall “Level of Safety” was also demonstrated in the examples. Bayesian statistical tools are incorporated into the design method to quantify the uncertainty in the probability data, and to allow post-design damage data to be used to update the “Level of Safety” values for the structure. Some methods of obtaining in-service damage data for the current aircraft fleet have been suggested. Concerns regarding the calculation of “Level of Safety” values for existing aircraft components have also been discussed.

The definition of structural “Level of Safety”, and the design methodology derived from it, is an extension of reliability theory and statistical analysis tools to the design and maintenance of damage-tolerant aircraft structures. The method presents a unified approach to damage tolerance that allows a direct comparison of relative safety between aircraft components using different materials, construction techniques, loading or operational conditions. It incorporates planning for the service inspection program into the design process. The use of Bayesian statistical tools in the “Level of Safety” method provides a mechanism for validating the damage assumptions made during the design process, and for reducing the level of uncertainty and risk over the life-cycle of the structure.

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1 INTRODUCTION

1.1 Background

Traditional design procedures for aircraft structures are based on a combination of factors of safety for the loads and knockdown factors for the strength. Both the factors of safety and knockdown factors have been obtained from the past five decades of design for metal aircraft.

There are at least two fundamental shortcomings to these traditional design procedures. First, because the procedures were developed for conventional configurations, metallic materials, and familiar structural concepts, these traditional procedures may be difficult to apply to aircraft that have unconventional configurations, use new material systems, and contain novel structural concepts. Consider, for example, the case of composite materials. Adaptations of traditional design procedures to account for larger scatter in composite properties and the sensitivity of composite structures to environmental effects and to damage have led to a very conservative approach for designing composite structures. This approach, in essence, assumes that a “worst case scenario” occurs simultaneously for each design condition – temperature, moisture, damage, loading, etc. This results in substantial and unnecessary weight penalties.

A second shortcoming of traditional design procedures is that measures of safety and reliability are not available. As a result, it is not possible to determine (with any precision) the relative importance of various design options on the safety of the aircraft. In addition, with no measure of safety it is unlikely that there is a consistent level of safety and efficiency throughout the aircraft. That situation can lead to excessive weight with no corresponding improvement in overall safety.

New structural design procedures based on the concept of “design under uncertainty” help to overcome many of these problems. In particular, measures of safety and reliability are available during the design process and for the final design. This information allows the designer to produce a consistent level of safety and efficiency throughout the aircraft – no unnecessary over-designs in some areas. As a result, designers can save weight while maintaining safety. In addition, in design under uncertainty it is possible to determine the sensitivity of safety to design changes that can be linked to changes in cost. For the same cost, aircraft can be made safer than with traditional design approaches, or, for the same safety and reliability, the aircraft can be made at a lower cost. Design under uncertainty also has application to the flight certification process, as it allows the uncertainty inherent in any new design to be quantified. Thus, flight certification criteria can be established which define the safety margins necessary for compliance based on the level of uncertainty associated with the design.

Based on the above consideration, a research program was established by the University of Washington to study the feasibility of developing a design procedure based on concepts of uncertainty and of applying this procedure to the design of airframe structures for commercial transport. The program is being sponsored by NASA Langley Research Center. The new design procedure is based on the fact that design data such as loading, material properties, damage, etc. are of statistical character. Design procedures based on uncertainty have the potential for reducing the weight and cost of airframe structures while maintaining prescribed level of safety. These procedures could also help reduce the design cycle time, particularly for unconventional aircraft that use new materials and novel structural concepts.

1.2 Review of existing technologies

The non-deterministic design approach is one of the current research emphases in various disciplines of engineering (Ref.1, 2, 3, 4). This design methodology has been applied to civil, mechanical and electronics engineering applications for decades. In recent years, there have been applications to aerospace composite structures as well. Chamis developed a probabilistic design procedure for composite structures (Ref. 5). The research has generated the Integrated Probabilistic Analysis of Composite Structures (IPACS). The procedure combines physics, mechanics, specific structure, system concepts and manufacturing. In IPACS, fiber mechanical and physical properties, resin properties, and the fiber placement techniques are the input data and all of these data are considered random variables. A probabilistic lamination theory is then established using a micromechanics approach. This is followed by a probabilistic finite element analysis based on structural mechanics. The output of IPACS includes structural sizing, failure prediction and load limiting application. IPACS does not include operational lifetime considerations such as material degradation and random damage processes during service.

Kan, et al., proposed a probabilistic methodology for composite airframe certification. The original work focused on probabilistic models to characterize data scatter in composite static strength and fatigue-life tests (Ref. 6). The goal was to evaluate structural testing requirements to achieve B-basis allowables for flight certification. Their methods were extended to include data scatter in bonded and cocured structures, and to assess impact damage requirements for certification (Ref. 7). The impact threat to aircraft was characterized using a Weibull distribution of impact energy. A damage detection threshold of Barely Visible Impact Damage (BVID) was set for a dent depth ≥ 0.05 in. in thin laminates. A method was presented for predicting post-impact residual strength of built-up structures which incorporates a statistical analysis of data scatter from compression test specimens with the impact threat distribution, to give an integrated probabilistic reliability analysis procedure. This model was then modified to reduce the number of empirical coefficients and test data points needed for an analysis (Ref. 8).

Rouchon (Ref. 9) has also contributed to composite structural design, primarily in two major areas: 1) certification and compliance philosophy; 2) probabilistic inspection for fleet reliability. Rouchon's efforts in the area of certification and compliance philosophy address second source material qualification, conditions to simulate environmental effects, and damage tolerance demonstration for accidental impact damage. His work on probabilistic inspection is focused on the need to detect impact damage in composite structures before the critical load level for catastrophic failure is reached (Ref. 10). A simplified probabilistic approach was presented for damage tolerance evaluation, where post-impact residual strength data are combined with probabilistic assessments of impact damage threats and flight load factors to set inspection intervals for maintaining failure probabilities below a threshold