복합재 항공구조물의 손상허용평가를 위한 운항수명의 확률적 모델

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Probabilistic Model of Service Life to Evaluate Damage Tolerance of Composite Structure

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ABSTRACT

Modern aircraft composite structures are designed using a damage tolerance philosophy. This design philosophy envisions sufficient strength and structural integrity of the aircraft to sustain major damage and to avoid catastrophic failure. The only reasonable way to treat on the same basis all the conditions and uncertainties participating in the design of damage tolerant composite aircraft structures is to use the probability-based approach. Therefore, the model has been developed to assess the probability of structural failure (POSF) and associated risk taking into account the random mechanical loads, random temperature-humidity conditions, conditions causing damages, as well as structural strength variations due to intrinsic strength scatter, manufacturing defects, operational damages, temperature-humidity conditions. The model enables engineers to establish the relationship between static/residual strength safety margins, production quality control requirements, in-service inspection resolution and criteria, and POSF. This make possible to estimate the cost associated with the mentioned factors and to use this cost as overall criterion. The methodology has been programmed into software.

1. Introduction

The up-to-date deterministic design criteria used in aerospace industry do not give clear idea about structural risk. They only imply that if they are satisfied, the POSF for critical structural part is as low as $2x10^{-9}$ per flight hour. Sometimes the system of deterministic design criteria is not enough flexible to optimize the structure with respect to most powerful risk/cost criteria. In this concern, the ability to assess risk is becoming more and more important to designer as well as customer.

The problem of probability-based design of composite structures has attracted attention of many researchers. Methodology/software developed by NASA IPACS (Chamis [1]) including NESSUS, Northrop Grumman (Gary [2]), Rouchon [3] should be mentioned. Areas of their application and main focuses are noticeably different, but they may successfully complement each other. So, IPACS permits to find cumulative probability distribution of strength considering the mechanical and physical properties of material constituents, uncertainties of composite material synthesis, scatter of structural dimensions. These variables are used as input for laminate theory and then for finite element model. This way allows to avoid relatively expensive coupon tests. NGCAD uses the similar way but it starts with composite material properties, obtained by tests. Rouchon focused at operational damages and inspection scheduling.

Recently developed ProDeCompoS software[4],[5] assesses the POSF and the associated risk for critical subcomponents. ProDeCompoS formally starts with subcomponent data on strength scatter supported by

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quasi-deterministic structural analyses, which uses material properties. According to [5], subcomponent strength scatter is strongly influenced by the uncertainties of manufacturing process can not be obtained from only material constituents. ProDeCompoS focuses mainly at the proper description of external loads, subcomponent failure modes including the modes of damaged structure, manufacturing and operational damages, probability of damage detection (PODD) by different NDI, quality of repair. ProDeCompoS methodology requires a powerful database describing all the mentioned initial data.

The further advances in the development of ProDeCompoS model are outlined below. The model has been verified using the data of all-composite aircraft TwinBee, developed in KARI, S.Korea.

2. Probabilistic model

The Probabilistic model is Monte Carlo simulation of random residual strength histories for each aircraft. In ideal statement the task is a flight-by-flight numerical simulation of stressed state during its motion along the expected trajectories taking into account random environments. In each instant this state should be compared with critical strength state, which is also simulated depending on both initial state and its random variation in operation. Such comparison determines the local structural failure, which could be considered as the damage depending on consequences. If the analysis of global strength shows that this local failure results in global one, the failure is recorded. When n load histories and residual strength histories are simulated with m failures observed, the POSF per life is evaluated as m/n. The obtained POSF exhibits the scatter intrinsic to any sampling. It is possible to select n so that the error of estimation did not exceed the given value.

Changing the initial conditions of simulation (safety factor or margins of safety, frequency, and method of inspection, structural repair technique), user can select the rational parameters of structure and/or maintenance to satisfy the reliability/cost criteria. Really such simulation would take very long time, especially if parametric analysis is needed. In order to save time and reduce the initial data, we have introduced significant simplifications. The idea of these simplifications is the replacement of infinite continuous space of states of nature by finite countable set of states. Main sets are as follows (see Figure 1).

- Set of load/weights distributions over the airplane and the corresponding set of stressed states of structure;
- Set of states of structure, resulting from the impact damages;
- Set of inspection and repair procedures.

User can choose his own composition of each set that he wants to analyze.

Probability of failure assessment

The sampling is outlined in Figure 2. Initial strength S_I is sampled from continuous type distribution. The number of damages and their sizes are sampled from the distribution correspondent to damage size spectrum. The damage instants are sampled from uniform distribution over the life. Times Δt_i of damage existence are sampled in accordance with PODD and inspection interval. Then we sample the random maximum load L_i in each interval Δt_i. This load L_i in interval Δt_i is picked from *cdf* (cumulative distribution function)

$$cdf(L_i) = e^{-H_t(L_i)\Delta t_i}, \qquad (1)$$

where $H_t(L)$ is a cumulative exeedance curve. At the same time we generate random temperature and humidity and correspondent strength knockdown factor. Then we randomly sample the strength correspondent to the damage type damage size, temperature and humidity. Then we compare the resulting strength S_i with the load. If we record failure and stop considering this life (no replacements are assumed). If $L_i < S_i$, the strength of repaired structure is randomly generated and so on. If two or more intervals of damage existence are overlapped, we consider the minimum residual strength for each load case and damage type. We do not consider any mutual influence of damages.

When m failures were recorded per n lives, the $POSF=m/n$.

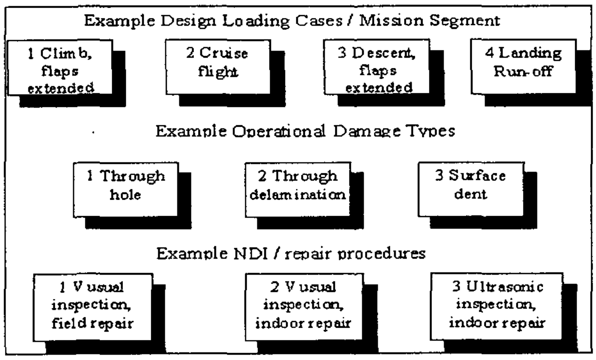

Figure 1

3. Structure of initial data

Probabilistic approach requires much more detailed data the deterministic one. In fact, instead of one fixed value we have to know the probability distribution function (PDF) and mutual correlation of different values.

At present time it seems possible to obtain enough information for reliability/risk prediction for some airplane structural components both on design phase and certification phase. The initial information, which can be really obtained for identification of probability model, is described below.

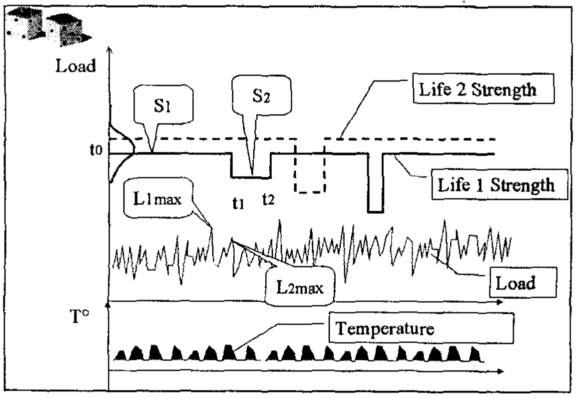

Figure 2

Stress-strain state of structure

The deterministic analysis of strength/rigidity of airplane is usually carried out for finite set of design loading cases: specified maneuvers, gust conditions, landing conditions, etc. It is also possible to establish the correspondence between such cases and flight mission segments, as is usually made for fatigue analysis. For each particular structure, only a few cases are critical for strength. They are used for structural sizing. Usually this set of design cases is selected by comparing the resulting loads and then is verified by using more accurate complicated methods and tests. The criteria of selection are the predicted static safety margin, and the margin for residual strength after damage.

The input data for POSF assessment are the residual strength *cdfs* depending on damage size, and temperature. Thermal stresses are not taken into account.

Description of loads/temperatures

The structural loads should be described in probabilistic manner, which should correspond to description of strength (for comparison), and should at least allow determining the maximum expected value of load for arbitrary time of operation.

Probabilistic description of all conceivable combinations of parameters determining the load and consequently all load distributions is scarcely possible because flight measurement data on the loads (stress) for all structural sites of interest are insufficient. In modern practice the load spectra are predicted by using probabilistic spectra of main flight parameters (maneuver load factor), gust intensity, sinking speed at landing, runway profiles, etc. The local stressed state of critical site is determined by the combination of flight parameters (load factor with speed, weight, Mach number, etc.). As far as here the continual space of stress-strain states is changed by a set of static cases, loads should be described in terms of these cases.

We describe the loads in a following way. All usage of aircraft is divided into specific missions. Each mission is divided into segments so that the load distribution during this segment is approximately constant and load occurrences can be described by one governing parameter. Usually the load distributions of static design cases are attributed (in conservative manner) to these mission segments. Initial data on loads are basically the exceedance curves for governing parameter, and the scale factor to convert this parameter into load comparable with strength. The linear relationship between the governing parameter and the stress level in the considered site is determined from static analysis made for appropriate design case. Applying some relevant strength criterion, the occurrence of failure load percentage can be obtained.

Structural temperature is assumed to be independent on mechanic load for each design case/segment. But the more segments/cases we consider, the better correlation of load and temperature is taken into account. Temperature is characterized by the exceedance curve similar to that for load.

Description of damages

Available statistical data, as well as relevant mathematical models, derived on the basis of these data can be used for probabilistic description of damages (e.g. Stewart[4]). This information should be compressed similar to load information by introduction of finite set of damage types as it is shown in Figure 1. The list of damage types should be related to the availability of methods for predicting the residual strength depending on damage size. The choice of types depends also on the type of load realized in considered site. E.g. if only tension takes place, a primary attention should be paid to through damages, but delaminations are of minor importance. The damage size spectra are derived for each chosen type of damage. They are represented by the exceedance curves similar to those for load.

Description of inspections

The efficiency of inspection should be described by the PODD the damage of definite type and size. Only a few attempts to identify this probability function are known from literature. As a rule, the special tests are needed to obtain this probability. Representative experts should inspect different sites of structure having the damages of different size and type. The PODD is determined as the ratio of a number of successful inspections to their total number. It is also possible to determine the PODD by indirect way, comparing the empirical probability function of detected damages with theoretical one and assuming that their difference is stipulated by various PODD for various damage sizes (e.g. Stewart[4]).

Description of repairs

There may be a lot of decisions if the damage is detected. At present the simplest algorithm is realized in a model. If the damage is detected, is should be repaired at once. The method of repair is directly determined by type of inspection which has resulted in the detection of damage (see figure 2). The degree of strength restorations after repair is determined by the method of repair corresponding to inspection. It was found that this logic does not strongly influence the final result. However it is possible to devise the logic which considerably influences the POSF.

4. Verification

The model has been verified by comparison with exact solutions for invariable strength, invariable load. Several practical examples have been solved including main wing box of SU29 aerobatic aircraft, Lear Fan all-composite aircraft, TwinBee all-composite aircraft. Parametric analysis showed the expected relations between the model parameters and POSF. The main risk drivers are revealed

5. Parametric Study

In order to understand what are the main parameters influencing the POSF (risk drivers), some parametric study has been carried out. The model has not so many parameters, but this study has revealed that almost all of them should be considered as essential risk drivers in domains of their uncertainty. Figure 3 bring a rough idea about the weight of some risk drivers. The frequency and extent of operational damage, characteristics of repair are presently the most uncertain factors.

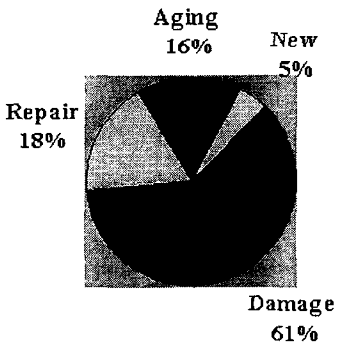

Figure 3

For existent aircraft fleet, the damage detection capability and inspection intervals are the only parameters we can change in order to control the POSF. Figure 4 shows the POSF vs. the inspection interval for one type if NDI.

6. Aging

Structural aging may be considered as accumulation of undetectable damages. In fact, the damage accumulation is peculiar to the present model. Since the damage exceedance curve is quite uncertain in a domain of undetectable damages, we have some freedom to manipulate this curve in order to obtain the desirable mean strength degradation pattern. Figure 5 shows the example curve obtained using the model.

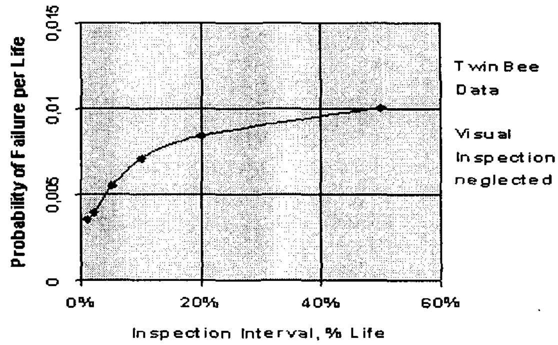

Figure 4

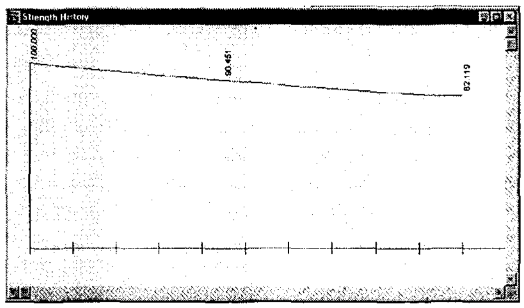

Figure 5

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