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A PROBABILISTIC APPROACH TO AIRCRAFT TURBINE ROTOR MATERIAL DESIGN

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ABSTRACT

A probabilistic design code is being developed for high energy disks and rotors used in aircraft gas turbine engines. This code is intended to augment, not replace, the current safe-life approach to the design of these critical components. While the code will ultimately be applicable to a range of disk alloys, initial emphasis has been placed on titanium alloys containing hard alpha defects. The approach involves developing an enhanced defect distribution for hard alpha, obtaining crack initiation data for hard alpha and fatigue crack growth data for three titanium alloys, and integrating this information into a software code that is sufficiently efficient that it can be routinely used for design and life prediction.

INTRODUCTION

Current design practice for high energy aircraft gas turbine rotors is based on an approach called the "safe-life" method. This method assumes that all material and manufacturing conditions that may influence the fatigue life of a rotor have been accounted for in prior laboratory specimen and full-scale component testing. In addition, the final design is usually based on minimum properties. However, aircraft gas turbine industry experience has shown that the presence of certain material and manufacturing anomalies can potentially degrade the structural integrity of high energy rotors. These anomalies occur infrequently and, therefore, are generally not present, at least at critical locations, during the generation of laboratory-based specimen and component testing. Undetected material and manufacturing anomalies represent a departure from the assumed nominal conditions and have resulted in several incidents, including the loss of a DC-10 at Sioux City in 1989.

As a result of the Sioux City accident, the Federal Aviation Administration requested that industry, through the Aerospace Industries Association (AIA) Rotor Integrity Sub-Committee, review available techniques to see whether a damage tolerance approach could be introduced to produce a reduction in the rate of uncontained rotor events. The industry working group concluded that additional enhancements to the conventional rotor life management methodology could be established which explicitly address anomalous conditions. Damage tolerance could be structured to enforce design and life management adaptations which enhance rotor integrity under anomalous material or manufacturing conditions.

During the development of the Damage Tolerance Approach, it became apparent to the AIA Rotor Integrity Sub-Committee that the capabilities and effectiveness of this emerging technology could be significantly enhanced by further research and development. In early 1995, Southwest Research Institute, with guidance from the AIA Rotor Integrity Sub-Committee, proposed a three year program to address the shortfalls in data and technology. Southwest Research Institute, in collaboration with AlliedSignal, Allison, General Electric, and Pratt & Whitney, has initiated a program to develop a probabilistically-based damage tolerant design code for life management of commercial aircraft gas turbine rotors and disks. The design code is not intended to replace the current safe-life design methods but to provide an additional tool that the engine manufacturers can use for risk management. The program involves the integration of fracture mechanics, material properties, forging models, and advanced probabilistic methods and will incorporate NDE information generated in a companion program by the Engine Titanium Consortium. The software developed will be interfaced with the general purpose finite element codes used by the gas turbine manufacturers.

The structure of the design code will be sufficiently flexible that it will be able to handle titanium, nickel, and other disk alloys that are subject to the presence of anomalous conditions. In the first phase of the program, however, emphasis is being placed on the presence of certain melt related defects in titanium alloys. These defects are called hard alpha and represent small zones in the microstructure, Fig. 1, where the alpha phase has been stabilized by the presence of nitrogen that can be introduced at various stages in

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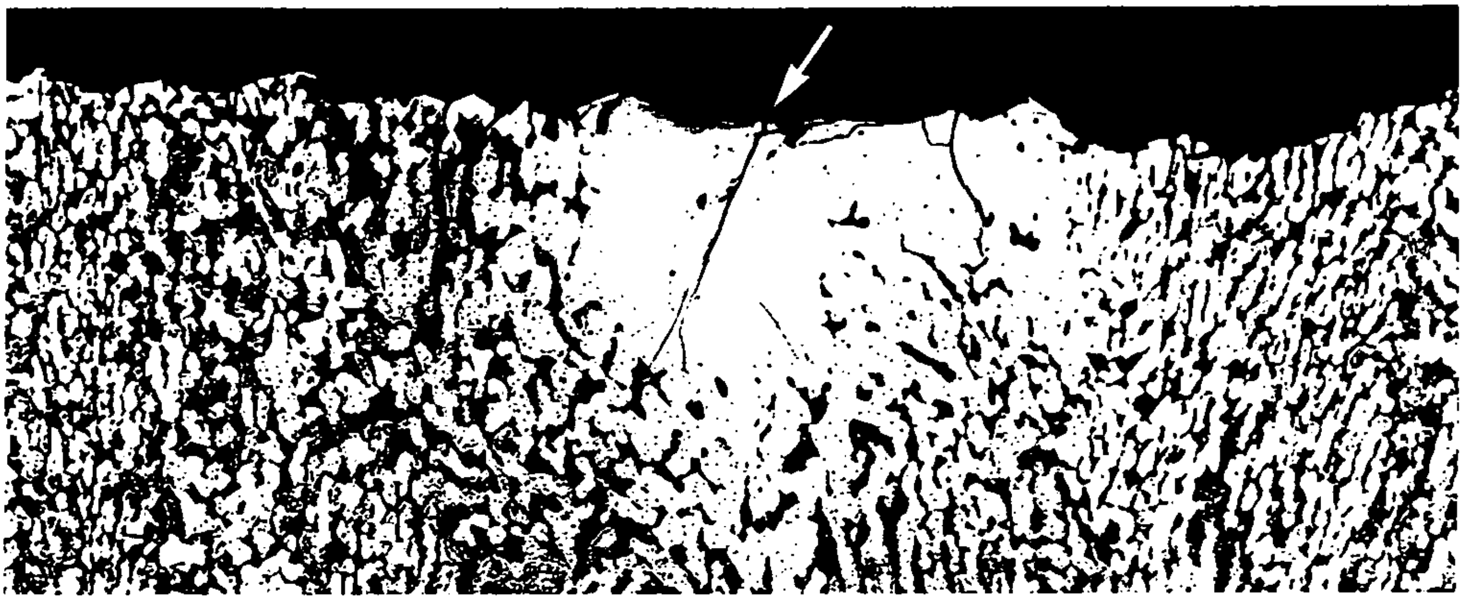

FIGURE 1. TYPICAL HARD ALPHA DEFECT (ARROW) IN AN ALPHA-BETA FORGED TITANIUM DISK ALLOY

the melting history[1]. These hard alpha zones are brittle, usually have cracks and voids associated with them, and have been responsible for the initiation of low-cycle fatigue cracks that resulted in uncontained disk failures.

The overall plan for this program was formulated to build upon a Federal Aviation Administration (FAA) report[2] that was prepared inresponse to the Sioux City incident that involved hard alpha, the recommendations of the AIA Rotor Integrity Subcommittee, and AGARD[3], NASA[4], Air Force[5], and Southwest Research Institute[6] experience and recommendations on damage tolerance concepts, advanced probabilistic methods and operational experience for gas turbine disks. The approach involves enhancement of the existing defect distribution for hard alpha, generating crack initiation strain data for hard alpha and fatigue crack growth data for three titanium disk alloys, and integrating this information into a software code (probabilistic tool) that is sufficiently efficient that it can be routinely used for design and life prediction. Development of the defect distribution for hard alpha includes the development of a deterministic forging code that predicts the change in shape and orientation of hard alpha defects during reduction from an ingot to a billet to a final disk geometry.

DEVELOPMENT OF DEFECT DISTRIBUTION FOR HARD ALPHA

Default Defect Distribution Developed by AIA Rotor Integrity Subcommittee

The AIA Rotor Integrity Subcommittee (RISC) has developed an engineering estimate of the titanium hard alpha default defect distribution in the form of an exceedance curve per volume of material. The exceedance curve gives the expected cumulative number of defects in a finished part greater than a certain inspection size for a given volume of material. The exceedance curve will be used to model the defect occurrence and size as a random variable. This random variable is a key ingredient in the rotor risk analysis.

The limited data used to determine the defect distribution consisted of the following:

- Metallurgical three-dimensional analysis of hard alpha defects

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[1] C. E. Shamblen and G. B. Hunter, Proc. Vacuum Metallurgy Conf., pp. 3-11, 1989.

[2] "Titanium Rotating Components Review Team Report," Federal Aviation Administration, December 14, 1990.

[3] "Damage Tolerance Concepts for Critical Engine Components," AGARD Conf. Proc. No. 393, 1985.

[4] J. C. Newman, Jr., "Contribution from NASA Langley Research Center on the AGARD Engine Disc Programme," private correspondence.

[5] P. G. Roth, "Probabilistic Rotor Design System (PRDS) Phase I," AFWAL Report WL-TR-92-2011, May, 1992; also, J. D. Adamson, E. P. Fox, and J. E. Malone, "Probabilistic Design System-Phase I and II Interim Report, Contract F33615-92-C-2219, December, 1995.

[6] S. J. Hudak, et.al., "Growth of Small Cracks in Aeroengine Disc Materials," AFWAL TR-88-4090, 1988.

contained in the JETQC[7] industry database. The metallurgical data contains the dimensions of the defect core size, diffusion zone size, and chemical content (nitrogen, oxygen, and carbon).

- The number of hard alpha defects per one million pounds of titanium based on the JETQC database.
- The number of in-service events recorded by each RISC company based on in-service experience of their titanium components.
- Representative probability of detection curves for bar and billet.

The influence of frequency of part inspection, hard alpha finds and part removal were accounted for by mathematically simulating the inspection procedure using the before-inspection exceedance curve and the probability of detection curve.

The 1990-1993 exceedance curve is shown in Fig. 2. The curve shows the expected cumulative number of hard alpha defects greater than a given inspection area in a finished part using a triple melt titanium processing procedure and a #3 FBH probability of detection curve for the inspection of the billet and forging.

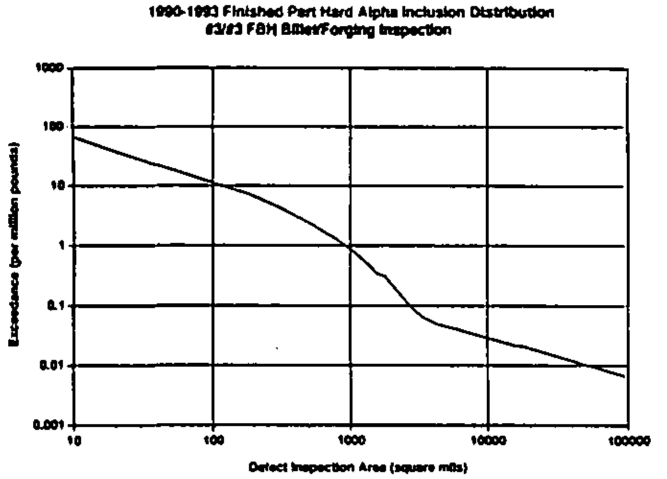

FIGURE 2. 1990-1993 FINISHED PART HARD ALPHA INCLUSION DISTRIBUTION #3/#3 FBH BILLET/FORGING INSPECTION

Development of Improved Defect Distribution

There are several activities in progress which will be used to improve the defect distribution. Some of the tasks are listed below:

Stress/volume/cycle component histories. The engine manufacturers are to supply information on stress/volume/cycle histories of components. Further analysis of this information may remove some of the uncertainty with the final positioning of the defect distribution and improve correlation of the defect distribution with in-service experience.

Improved fracture mechanics data and calculations. Significant enhancements to the fracture mechanics material properties are being developed. This information can be used to develop an improved analysis when correlating the defect distribution with the expected number of failures of in-service components based on probabilistic fracture mechanics analysis. Specifically, enhancements are:

- fatigue crack growth rates in vacuum for three titanium alloys, (see next section)
- crack nucleation models,
- stochastic fatigue crack growth data,

Improved POD curves from the Engine Titanium Consortium project. An important ingredient of the defect distribution formulation is the simulation of the inspection processes. The FAA sponsored Engine Titanium Consortium project is developing improved multizone inspection techniques for the detection of hard alpha defects in titanium. Improved probability of detection curves can be used during the development of the defect distribution for future parts.

Including other random variables. The risk evaluation procedure was performed using only the defect distribution as random; all other parameters were deterministic. While it is expected that the defect distribution will be an important random variable, perhaps dominant, other random variables such as crack growth rate may also be important. Once the probabilistic rotor code is completed, it will be straightforward to include other random variables.

Improved deformation model. The present methodology assumes a simplified deformation process of the hard alpha defect from ingot to billet to forging. The deformation computer code MAAP (see below), will provide a vehicle to perform numerical studies of defect deformation during the deformation processes and, thus, develop an improved deformation model.

In order to make realistic assessments of the effects of forging on the defect distribution an accurate deterministic model is needed to describe the physical state of the inclusion. A finite element model of the inclusion, called MAAP (Micromodel Analysis of Anomaly Presentation), has been developed that calculates the time evolution of the stress and strain in a control volume that extends several diameters beyond the edge of the inclusion. This "micromodel" of the defect has the advantage of isolating the calculation to a region where the presence of the defect has the most influence, and thus minimizes the computational effort required. The tacit assumption is made that beyond the edge of this microvolume, the presence of the defect has a negligible effect on the stress and strain distribution in the aggregate forging. Thus, the model is limited to the analysis of very small defects (with, say, characteristic dimensions <100X the characteristic dimensions of the forging) where this assumption is expected to hold.

The boundary conditions needed to run the micromodel analysis must be provided by a "macromodel", which calculates the evolution of the aggregate forging. Position, velocity, strain rate and temperature data are provided to MAAP from tracer particle data generated by the "macrocode". The assumption is made that the position of these tracer particles coincides with the position of the inclusion throughout the forging history, which is also consistent with the assumption that the defects are very small in size.

The uniqueness of MAAP lies in its constitutive models. MAAP

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[7] Jet Engine Titanium Quality Committe, proprietary database.

was specifically formulated to calculate the evolution of the voids and cracks that can occur when a brittle inclusion is subjected to 300- 400% strains that are typically seen in a rotary disk forging.

A series of experiments is being performed to validate the results generated from MAAP. Experiments were designed so that they would more rigorously test the veracity of the code predictions. For example, the first test involves the deformation of a high density inclusion that remains essentially rigid through the forging process, and MAAP will be used to predict the change in orientation of the defect. Later experiments involve defects that change shape as well as orientation, and the final set of experiments will be performed on actual disk forgings containing natural and synthetic inclusions.

CRACK INITIATION AND GROWTH DATA

Crack Initiation

Large hard alpha defects are often extensively voided and cracked in the final forged configuration. Current life prediction methodologies commonly assume that an initial crack with size equal to the size of the HA defect is present at the beginning of life, and that the crack will begin growing as a normal fatigue crack from the first cycle. This assumption could be overly conservative, however, for smaller HA defects which are less likely to be extensively cracked and voided. These smaller defects may play a significant role in the probabilistic risk assessment, because the smaller defects are harder to find by NDE, and because a relatively larger number of the smaller defects are postulated to exist in the initial defect distributions. Therefore, it is useful to assess the cracking tendencies of the HA defects, in order to determine if it is possible to take credit for some nonzero crack initiation life in the life prediction methodology.

The tendencies of the HA defects to form cracks are being evaluated with two different experimental measures. First, the monotonic fracture strain (i.e., the strain at first fracture of the HA during a single tensile loading excursion) is being determined. These results will help to determine when cracks are formed during the forging process and also the allowable location for HA on specific disk designs. Second, the number of cycles required to initiate a growing crack during fatigue cycling is being determined, along with some characterization of the growth rate of this crack as it grows in and near the diffusion zone. These results will directly impact life modeling of the rotor in service.

Test specimens contain individual synthetic HA defects[8], inserted at known locations into forged, rotor-grade Ti-6-4 parent material and then HIP'd. The defects have a cylindrical shape and include a concentric cylindrical simulated diffusion zone. Test variables include the nominal nitrogen content of the defect core (2 or 6 percent), the nominal defect size (2/64" or 5/64" diameter cores), and the defect location in the test specimen (embedded or surface-breaking). The test specimen is a simple flat plate with reduced gage section 0.5-in. thick by 1.0-in. wide. Both visual and nonvisual (acoustic emission, ultrasonic) means of crack detection are being employed as appropriate to the defect location. Since the cracking behavior of the synthetic HA is not necessarily identical to that of naturally occurring HA, a limited number of additional initiation tests are planned using available Ti-6-4 material (from the ETC contaminated billet study) that contains naturally occurring HA defects.

If the crack initiation and early growth period is found to be a significant fraction of the total life, then simple analytical models will be developed to predict initiation life as a function of important physical defect characteristics (e.g., size, nitrogen content). These initiation life models will interface with probabilistic descriptions of initial defect distributions (see above) in order to develop probabilistic predictions of cycles to form a growing fatigue crack.

Fatigue Crack Propagation

Since HA defects typically occur at subsurface locations, the resulting fatigue cracks will be embedded and hence isolated from the engine atmosphere for at least some of their life. Eventually these cracks may break through to the surface and continue growing as surface cracks. Other cracks may initiate from HA defects at surface locations. The growth rates of these embedded and surface fatigue cracks may be different, even at the same ΔK value, due to environmental effects. Fatigue crack growth (FCG) rates of titanium rotor alloys are likely to be significantly slower in vacuum compared to air, and the embedded cracks are growing in a vacuum-like environment. However, these differences have not been characterized for current rotor alloys to a level of detail adequate for design and certification purposes.

Vacuum fatigue crack growth tests are being conducted to generate these needed data for Ti-6-4 and Ti-6-2-4-2, with additional limited testing of Ti-17. Test specimens are machined from disk forgings. Near-threshold data are being generated with a single edge notch button head specimen, while Paris regime tests employ a so-called Kb bar specimen with a semi-elliptical surface crack. The DC electric potential drop method is being used for all crack length measurements. Further details of the general test technique are available elsewhere[9]. The test matrix for the vacuum FCG tests covers stress ratios from $R = 0$ to 0.75 and temperatures from 70°F to 400°F (for Ti-6-4) or to 1000°F (for Ti-6-2-4-2).

Extensive FCG data in air environments are available in the proprietary databases of the engine companies and in the public domain (e.g.[10]). These data show, as for nearly all FCG data, appreciable scatter in FCG rates associated with scatter in total crack growth life. This scatter is a potential source of uncertainty in predicted rotor lives. Other sources of FCG life scatter include inaccuracies or unknowns in modeling of residual stresses, elastic-plastic stress fields, stress intensity factors, etc. However, the significance of this scatter in comparison to other sources of variability in hardware reliability, such as initial defect

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[8] M. F. X. Gigliotti, L. C. Perocchi, E. J. Nieters, and R. S. Gilmore, "Design and Fabrication of Forged Ti-6Al-4V Blocks with Synthetic Ti-N Inclusions for Estimation of Detectability by Ultrasonic Signal-to-Noise," *Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 14, Plenum Press, 1995, pp. 2089-2096.

[9] R. H. VanStone and T. L. Richardson, "Potential-Drop Monitoring of Cracks in Surface-Flawed Specimens," *Automated Test Methods for Fracture and Fatigue Crack Growth, ASTM STP 877*, 1985, pp. 148-166.

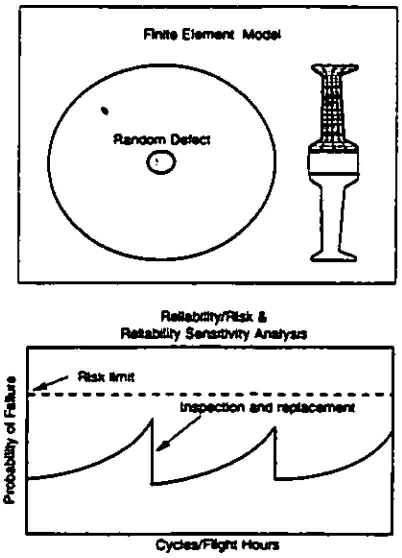
[10] A. J. A. Mom and M. D. Raizenne, *AGARD Engine Disc Cooperative Test Programme*, AGARD-R-766, 1988.

Random Variables

- Defect occurrence
- Defect distribution
  - Size, shape, orientation
  - Built in defaults, user-defined
- Fracture toughness
- Fatigue crack growth parameters
- Shop visit time
- Mission variations
- Geometrical variations
- Expandable to others
- Distribution library built in, expandable by user

Probabilistic Methods

- System reliability approach
  - Define approx. iso-risk zones
  - Sum risks from all zones
- Monte Carlo simulation
  - Restart capability
  - User-specified confidence/error
- Tailored, more efficient method
  - Limit state approach coupled with adaptive life approximation method and adaptive importance sampling method



Failure Modes

- Fatigue and fracture due to hard alpha defects in titanium
- Expandable to others

Crack Growth

- Surface and subsurface
- Interface with NASGRO or user supplied code or tabular a vs. N input
- Stress gradient effects

Stress Analysis

- Finite element analysis
- Axisymmetric models
- 3D stress effects through stress modification (e.g., stress concentration factors)
- Neutral file for other FE codes
- Overspeed

Inspection Features

- Different POD's for different regions
- Different POD's for initial and field inspection
- POD library built in, expandable by user
- Multiple inspection schedules

Computer Dperation

- Graphical user interface
- Text input file interface
- HP Unix-based workstations

FIGURE 3. SUMMARY OF THE PROBABILISTIC ROTOR DESIGN COMPUTER CODE

distributions or NDE probability of detection, is not yet known.

The scatter in FCG life will be treated in the probabilistic rotor design system at a level of sophistication appropriate to the relative significance of the scatter. A preliminary approach will consider a simple life scatter factor derived from FCG coupon and feature test results. If a more detailed approach is warranted, the available FCG data for air and vacuum will be analyzed with appropriate statistical models. The variability in the FCG equation constants will be characterized in a manner that yields an accurate description of variability in total life (e.g.[11]). This method will also be chosen to facilitate efficient inclusion in the overall framework of the probabilistic design system.

INTEGRATED PROBABILISTIC DESIGN CODE

Description of Plan and Framework

A probabilistic rotor design code to analyze the joint probabilistic effects of hard alpha defects, inspection, and other significant uncertainties will be developed and distributed to the aircraft engine manufacturing industry. The specifications of the code have been developed in conjunction with the participating engine companies to ensure that the product will address all the significant and practical design issues common to the industry. Based on the specifications, a code framework has been developed and coding has begun.

A summary of the computer code is presented in Fig. 3. The probabilistic variables include defect occurrence and distribution (size, shape, and orientation), PODs, inspection schedules, material properties, and mission and geometrical variations. Several probabilistic methods will be implemented, including a Monte Carlo-based approach and more efficient, tailored methods. The code will interface with finite element codes by using neutral (ASCII format) finite element result files. The code will include 3D stress effects through stress modification (e.g., stress concentration factors). The primary fracture mechanics analysis tool will be the NASGRO code. The user will have the option of using a user-supplied fracture mechanics code or a tabular a-N (i.e., defect size versus cycles) input. The code will allow the user to define multiple PODs and multiple inspection times based on geometrical locations (zones). The output of the code will include risk and defect size distribution as a function of cycles/flight hours. This information can be used to design new disks and rotors, to perform fleet risk analysis, and to assist in fleet risk management through inspection planning.

Two intermediate versions and a final version of the code will be developed. Several examples will be developed to verify the correctness of the coding and validate the methodology against field experience. A design sensitivity study will be conducted using the final version to provide design guidelines. To transfer the technology to industry, a workshop will be conducted at the end of the project.

Probabilistic Tools and Approach

The current activity focuses primarily on titanium disks with hard alpha anomalies as the single critical source of disk failures. The rareness of the defects lends itself to simplifications in probabilistic modeling. The framework of the code, however, has considered potential future extension to other materials such as nickel-based alloys

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[11] D. F. Ostergaard and B. M. Hillberry, "Characterization of the Variability in Fatigue Crack Propagation Data," *Probabilistic Fracture Mechanics and Fatigue Methods: Applications for Structural Design and Maintenance, ASTM STP 798*, 1983, pp. 97-115.

with a high density of material defects and other low cycle fatigue failure modes such as those associated with porosity and machining-induced surface anomalies.

A common approach to a disk risk calculation is to divide the volume into a small number (typically less than 100) of approximately equal-risk zones. If we define A as the event of failure given the initial defects in zone i (i from 1 to m), then the risk of a disk failure is defined as:

$$\textit{Prob. of failure in a single disk} = \mathbf{P}\ [\mathbf{A}_1 \cup \mathbf{A}_2 \cup \mathbf{A}_3 \ldots \cup \mathbf{A}_m]$$

If the failure events are independent (a reasonable assumption), the above equation can be simplified as:

$$\textit{Prob. of failure in a single disk} = 1 - \prod (1 - \mathbf{P}\ [\mathbf{A}_i])$$

which is approximately equal to the sum of $\mathbf{P}\ [\mathbf{A}_i]$ for small $\mathbf{P}\ [\mathbf{A}_i]$.

The average rate of defect occurrences and size distribution is defined using a defect size exceedance curve on a volumetric basis (e.g., per million pounds), see the section on Development of Defect Distribution for Hard Alpha. The occurrence rate can be modeled as a discrete random variable, for example, a Poisson variable. When the defect occurrence rate per disk is very low, as is the case for hard alpha defects, the probability of having more than two defects (of significant size) in a zone would be negligible. In such a case, the probability of failure in each zone is the product of the probability of having a defect (a user input) and the probability of fracture given a defect. However, the framework of the code will be such that it can be extended, without a major change in the code structure, for a multiple number of defects in a zone.

Given a random defect in a zone with a calculated probability of occurrence, the probabilistic analysis task is to compute the probability of fracture given all the probabilistic variables mentioned above. There are two basic approaches to be included in the code. One is Monte Carlo random simulation, which is known to be time consuming but is the most robust and easy to implement. There are several options on how a Monte Carlo simulation can be devised. For examples, PODs can be simulated randomly or applied analytically to define post-inspection defect size distribution; the location of a defect can be generated randomly within a zone, or can be analytically determined based on worst case or other considerations.

The tailored probabilistic methods will include the limit state approach used extensively in the field of structural reliability. By searching for most likely failure regions quickly, this approach allows the time consuming analysis to be concentrated in a small variable space[12]. This approach will be combined with the adaptive importance sampling concept, which allows selective sampling in the suspected failure regions[13]. Other approaches under consideration include the use of regression analysis to construct approximate a-N functions, the tracking of the defect size population through inspections[14] and the inclusion of additional random variables by integrating the probability of failure conditioned on these random variables[5].

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[12] Y.-T. Wu, H.R. Millwater, and T.A. Cruse, "An Advanced Probabilistic Structural Analysis Method for Implicit Performance Functions" *AIAA Journal*, Vol. 28, No. 9, pp. 1663-1669, September 1990.

[13] Y.-T. Wu,"Computational Methods for Efficient Structural Reliability and Reliability Sensitivity Analysis" *AIAA Journal*, Vol. 32, No. 8, pp. 1717-1723, August 1994.

[14] A.P. Berens, P.W. Hovey, and D.A. Skinn, "Risk Analysis for Aging Aircraft Fleets," Wright Laboratory, WL-TR-91-3066, October 1991.