POLITECNICO
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Structural Reliability of aerospace components

Damage Tolerance Analysis for turbofan shaft

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Introduction to damage tolerance requirements

As said during the lesson, damage tolerance is a requisite according to regulations for aircraft components.

According to EASA:

EASA	CERTIFICATION MEMORANDUM
	EASA CM No.: EASA CM – PIFS – 007 Issue: 01 **Issue Date: 22nd of February 2013** **Issued by: Propulsion section** **Approved by: Head of Products Certification Department** **Regulatory Requirement(s): CS-E 515**

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Subject

Engine Critical Parts - Damage Tolerance Assessment

Manufacturing and Surface Induced Anomalies

A. Deterministic Approach:

A1. Deterministic Damage Tolerance Assessment

Demonstrate that the Surface Fracture Mechanics Life for all critical parts exceeds 3,000 cycles or 50 percent of the part certified life, whichever is less.

Assumptions:

(a) Analyses performed using Linear Elastic Fracture Mechanics;

(b) Initial anomaly size is one of the following:

- 0.762mm x 0.381mm (0.030 inches x 0.015 inches) for an assumed (semicircular) surface anomaly.
- 0.381mm x 0.381mm (0.015 inches x 0.015 inches) for an assumed (quarter-circular) corner anomaly.

(c) The assumptions used in this analysis (i.e. material properties, reference engine cycle, operating environment and its effect on the stress cycle etc.) should be declared.

(d) Anomalies should be treated as sharp propagating cracks from the first stress cycle.

A2. Service Damage Monitoring

The overall objective of Service Damage Monitoring is to review data obtained from field operation of the Type Design engine to determine if there are anomalous conditions which require corrective action. Appropriate action(s) may include assessment of the impact of damage observed on one part/location on other parts/locations.

Applicants should determine if surface damage that has been detected is consistent with the serviceable and repairable limits and determine if additional actions are required to prevent failure and rectify any potential unsafe condition which may be identified. Service damage monitoring consists of the following:

Introduction to damage tolerance requirements

$$P_f = Pr\left[a > a_{crit}\right]$$

B. Probabilistic Approach

B1. Probabilistic Damage Tolerance Assessment

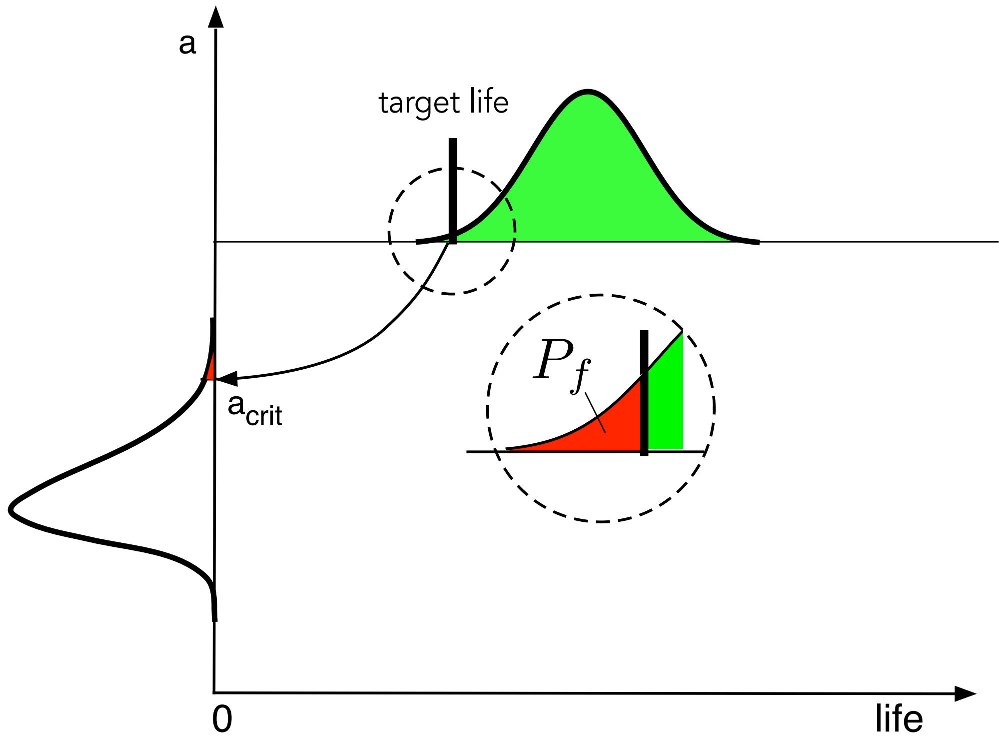
If an applicant chooses to pursue a probabilistic alternative to the deterministic approach detailed in paragraph 3.1.A. above, the applicant should provide and agree with the Agency such data that have an impact on the risk levels resulting from the analysis. These may include but are not limited to the following items as appropriate to the component:

- Anomaly size / frequency distribution
- Fleet utilisation
- Maintenance practices
- Production / Assembly processes
- Anomaly growth characteristics
- Inspection techniques and intervals
- Inspection Probability Of Detection (POD)

The process utilised to carry out the analysis needs to be agreed with the Agency.

The probabilities of Hazardous Engine Effects that must be met are defined in CS-E 510 (a)(3).

Note: When referring to CS-E 510(a)(3) an individual failure is considered to be a failure occurring anywhere in the engine as a result of a damage tolerance related cause and is not related to the failure of an individual component.



- Failure probability is the probability that the anomalies are larger than the critical defect size;
- probabilistic analyses need (as an input) a distribution of anomalies / flaws

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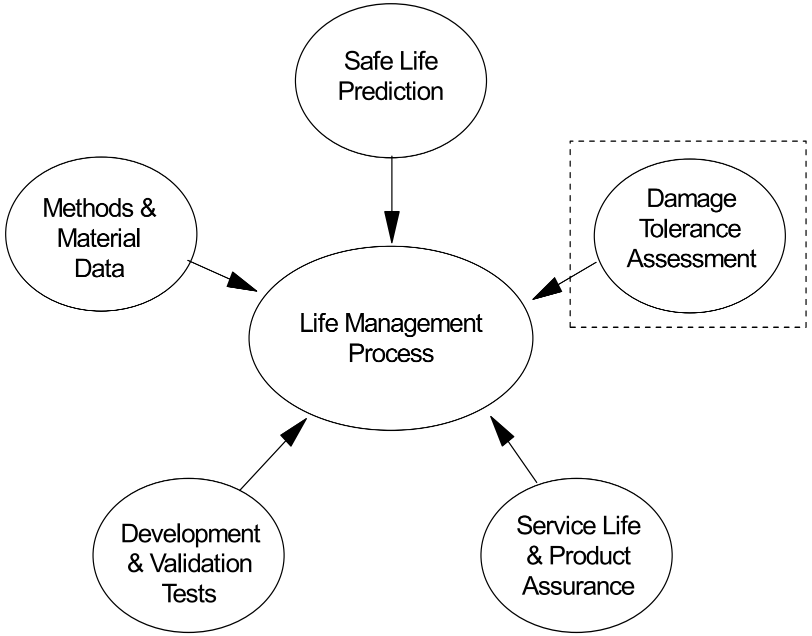
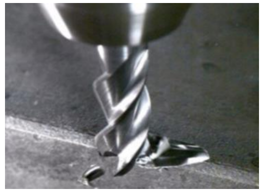
v. Probabilistic Risk Assessment. A fracture-mechanics based simulation procedure that uses statistical techniques to mathematically model and combine the influence of two or more variables to estimate the likelihood of various outcomes for a product. Since not all variables may be considered or may not be capable of being accurately quantified, the numerical predictions are used on a comparative basis to evaluate various options. Results from these analyses are typically used for design optimization to meet a predefined target or to conduct parametric studies. This type of procedure differs from an absolute risk analysis, which attempts to consider all significant variables and is used to quantify, on an absolute basis, the predicted number of future events with safety and reliability consequences.

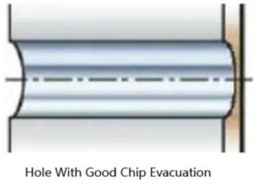
Figure 1-1: Enhanced Life Management Process

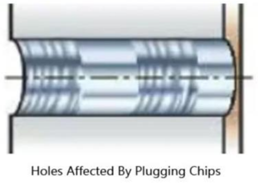


it covers typical anomalies due to machining of holes

Geometric Anomalies (Visual)

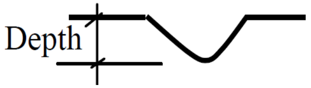


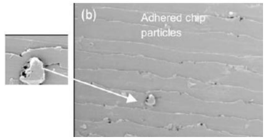




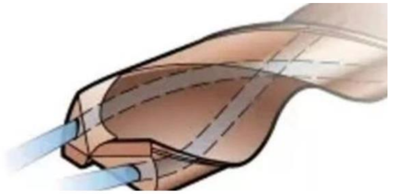
Tool Breakage, Chip Removal

Dents, Nicks, Scratches, Adhered chip particles, Burrs



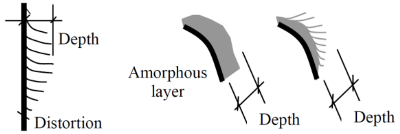


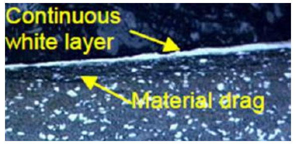
Non-Geometric Anomalies (Surface Integrity)



Lack of Lubrication, Tool Wear, Uncontrolled Machining

Distortion, Amorphous (white) Layer





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1. Approach.

a. As described in AC 33.70-1, Probabilistic Damage Tolerance Risk Assessments (PDTRA) is an acceptable method to assess the ability of a part to tolerate anomalies. The results of these assessments will provide the basis for evaluating the relative damage tolerance capabilities of candidate part designs and will also allow the engine manufacturer to balance its designs for both enhanced reliability and customer impact. The results will be compared against design target risk values (see paragraph 6, "Design Target Risk," in this chapter).

2. Methodology.

a. Probabilistic risk assessments may be conducted using a variety of methods, such as Monte Carlo simulation or numerical integration techniques. When performing a PDTRA, use of the standardized inputs and default data presented in this AC will achieve consistent assessment results.

3. Anomaly Distributions.

a. A key input distribution associated with PDTRA assessments is the size and rate of occurrence of the anomalies. This type of information is statistical in nature and can be presented in a form that specifies the number of anomalies that exceed a particular size in a given amount of surface area.

b. Manufacturing-Induced Anomaly Distributions.

(1) Manufacturing-induced anomaly distributions that apply to circular hole features in disks have been developed to characterize the size (depth) distribution and frequency of said anomalies (see Appendix 2). The distributions apply to circular holes machined in titanium, steel, nickel, or powder nickel rotor components.

(2) The anomaly distributions contained in Appendix 2 may be used to determine compliance with paragraph 6 ("Design Target Risk") of this chapter. The background pertaining to the development of these distributions is contained in the technical paper "Development of Anomaly Distributions for Machined Holes in Aircraft Engine Rotors." The distributions were developed by modeling crack sizes detected during component/engine testing or through in-service experience using an EIFS (Effective Initial Flaw Size) approach. The final distributions were validated based on OEM field experience. This process resulted in a probability of exceedance curve (see figure A2-1) that can be used to determine a relative risk reduction but not an absolute level of risk.

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6. Design Target Risk.

a. The DTR is a benchmark relative risk level selected to enhance the overall safety of high-energy rotating components. Since no machine or device is 100-percent reliable, it is inappropriate to require a level that is technologically unachievable. Nevertheless, the goal is to achieve a significant and distinct improvement over and above current rotor designs.

b. For manufacturing-induced anomaly assessments, designs must meet the specified feature DTR to be considered acceptable. (Note: Only circular hole feature assessments and DTR's are currently available.)

c. Design Target Risk values are specified in Table 2-1 below:

Table 2-1. Allowable Risk for Circular Holes

Component Feature	Design Target Risk (feature events per component published service lifetime)
Circular Holes	2.0 E-05

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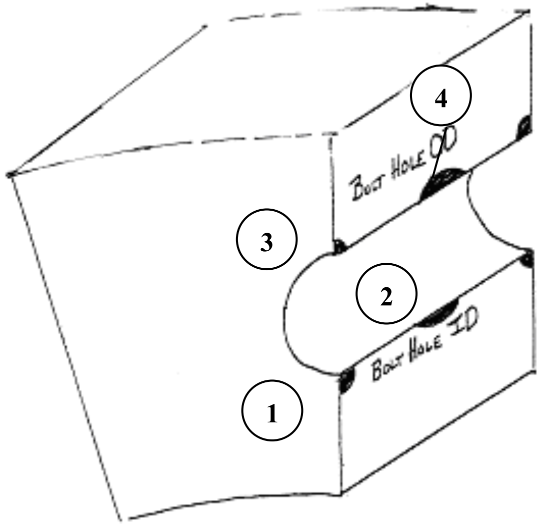
a. Stress analysis,
b. Hole set definition including surface area and number of holes,
c. Crack growth model definition,
d. Crack growth calculations, and
e. Relative risk calculation.

Figure A1-2



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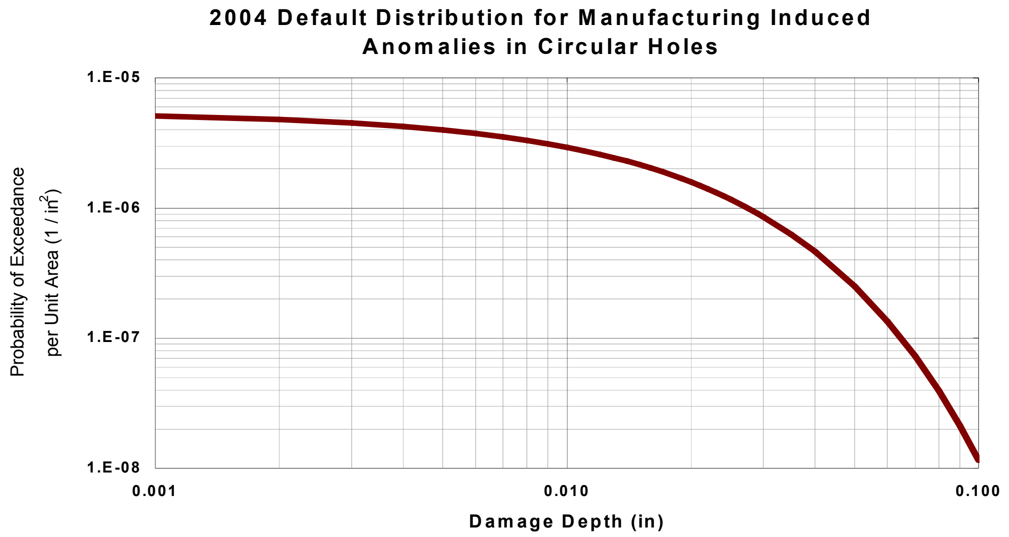
$\nu = 1.0$ for any $L/D > 1.3$
$\nu = 0.04$ for any $L/D < 1.0$

Figure A2-1



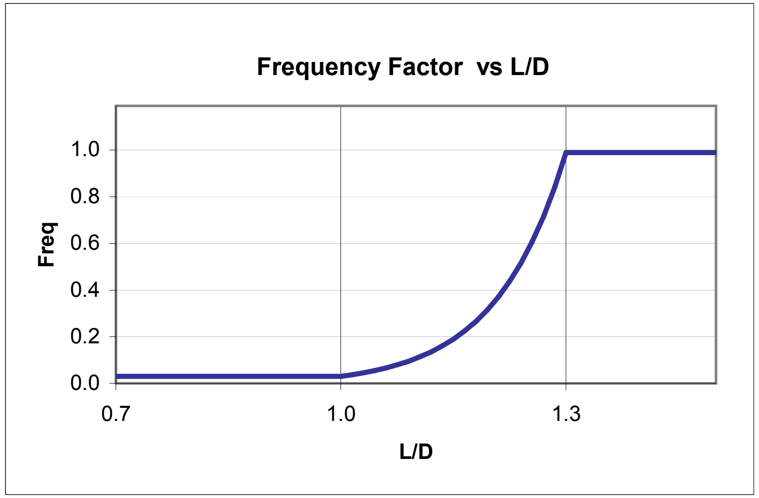
Equation for the default hole anomaly exceedance curve:

Equation A2-1

$$F(x) = \nu * 5.42E\text{-}06 * EXP(-61.546*(x))$$

where x is anomaly depth in inches, and F(x) is exceedance probability per unit area ($1/in^2$).

Figure A2-2. Frequency Reduction Factor



Equation for the L/D frequency reduction factor as a function of L/D is:

Equation A2-2

$$\nu = 0.04 * EXP[10.7296 * (L/D - 1)]$$

where L/D is a ratio of the hole length L over diameter D, and the dimensionless frequency factor ν should be used as a multiplication coefficient for the right-hand-side of the equation Eq. A2-1 for cases where $1 < L/D < 1.3$.

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Fig. A7-1 : Surface Damage Risk Assessment Workflow

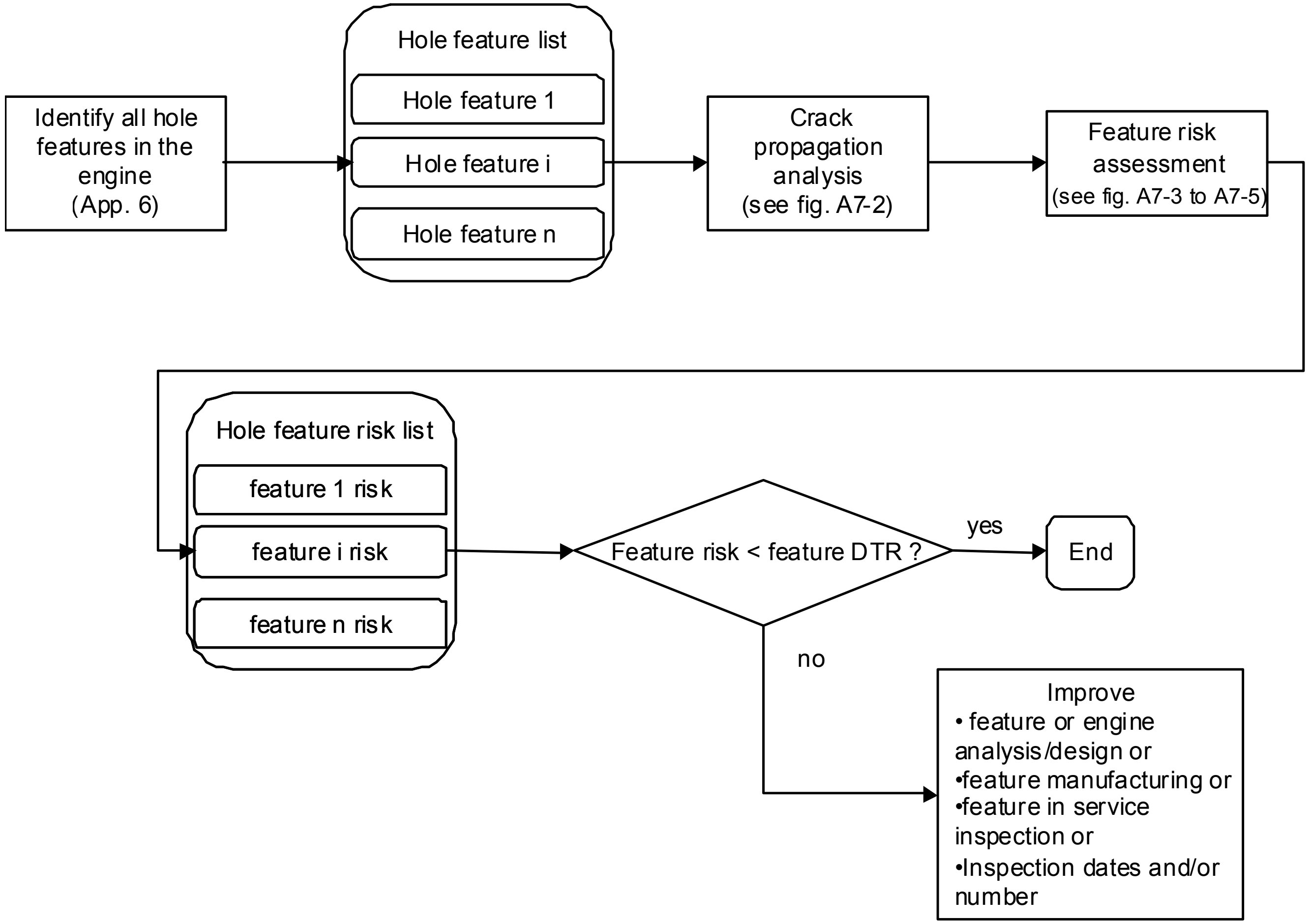

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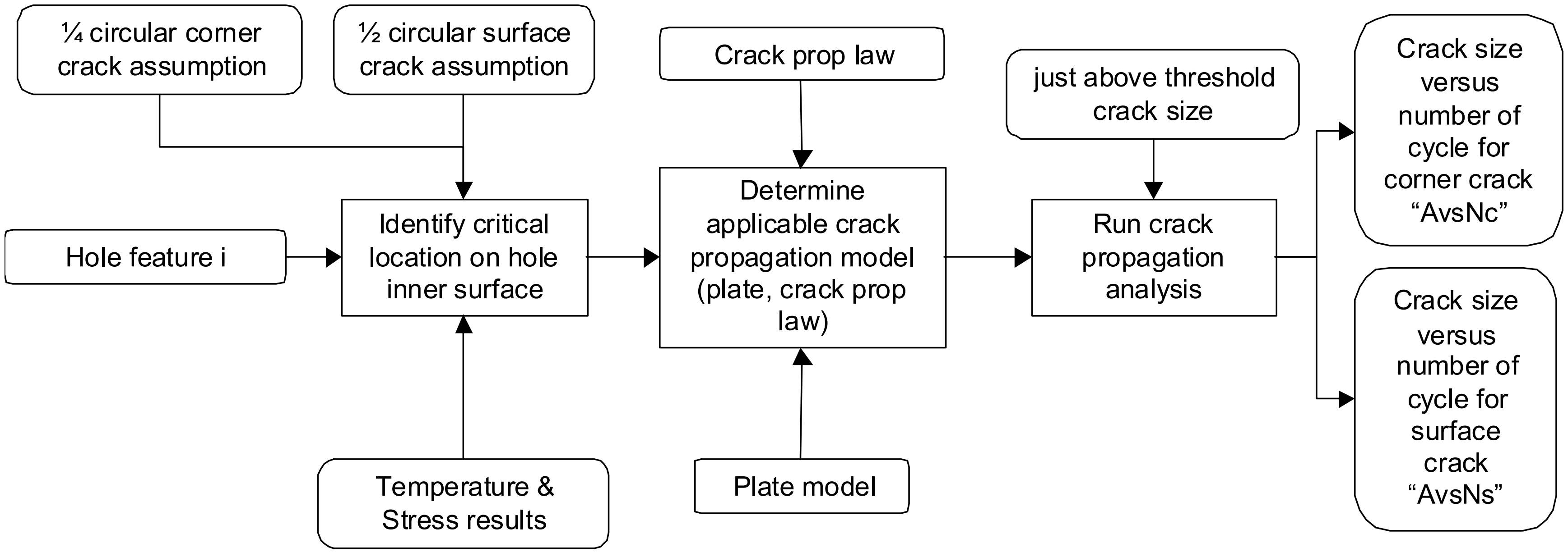
Figure A7-2: Crack Propagation Analysis



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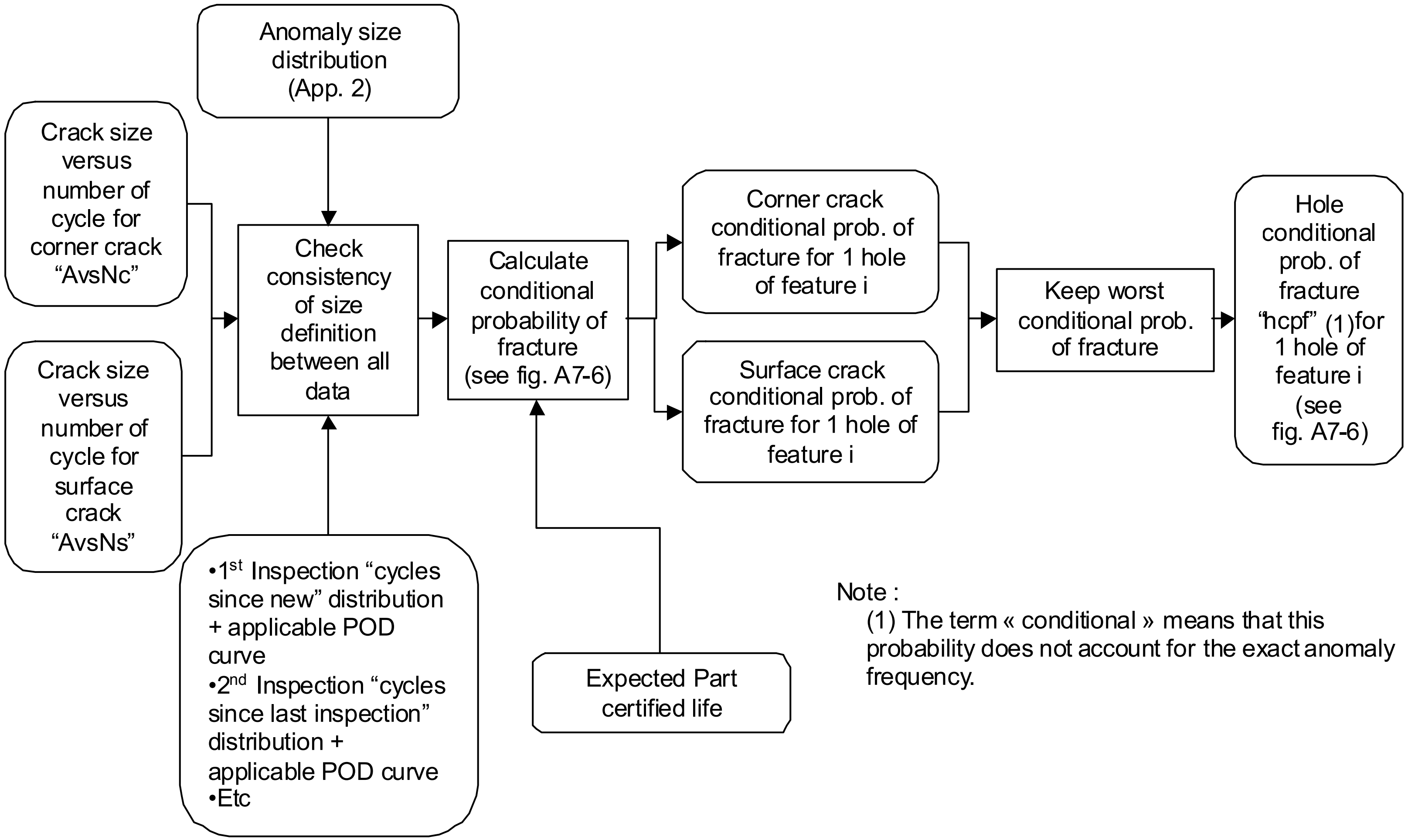
Appendix 7

Figure A7-3 : Feature Risk Assessment (1/3)

1st step : consider only one hole of the hole feature i and calculate the conditional probability of fracture for this hole.



Note :

(1) The term « conditional » means that this probability does not account for the exact anomaly frequency.

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Figure A7-4: Feature Risk Assessment (2/3)

2nd step : Calculate the probability of fracture for one hole by combining the conditional probability of fracture for one hole with the hole actual inner surface area, the applicable manufacturing credits and anomaly frequency correction factor.

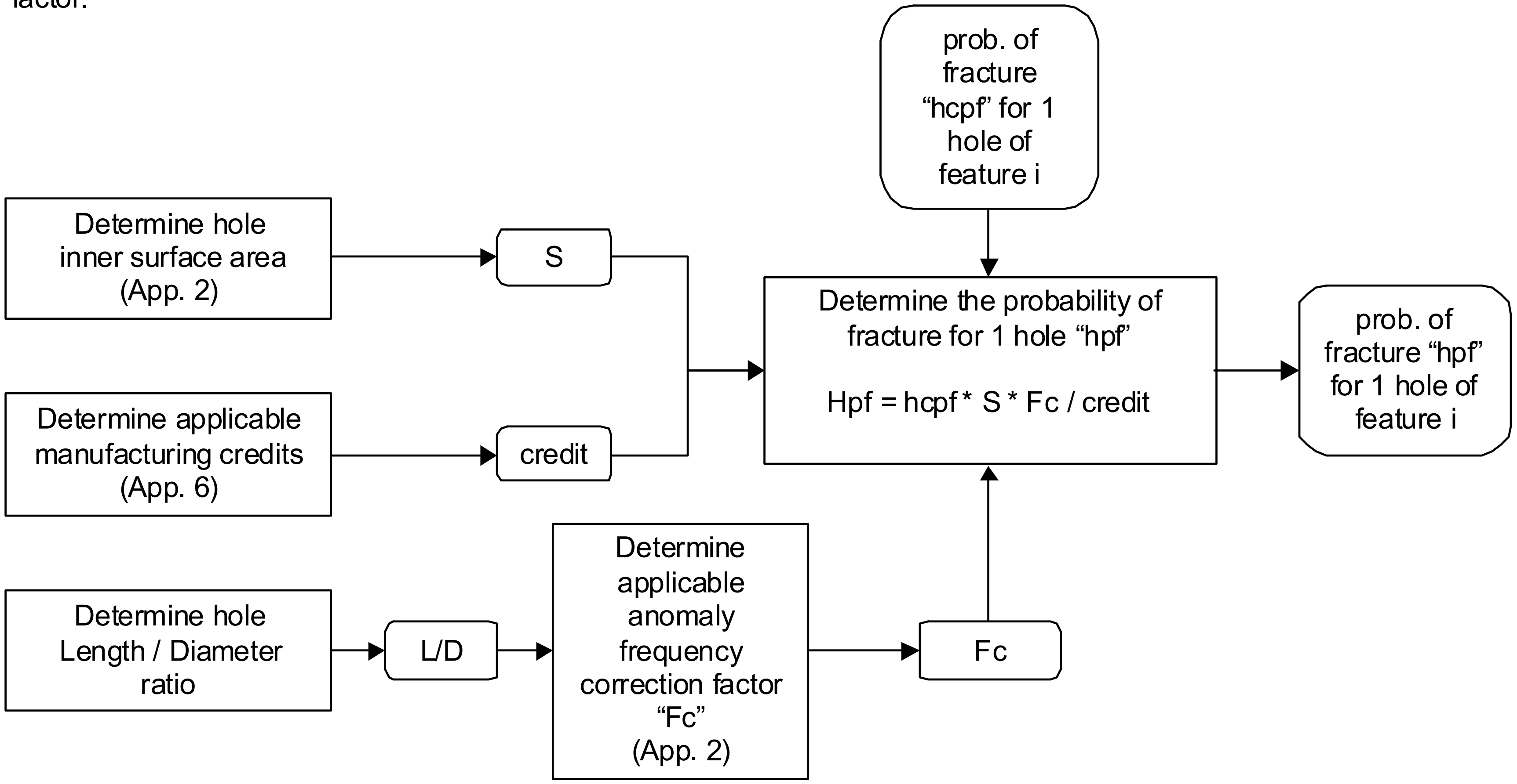

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Figure A7-5: Feature Risk Assessment (3/3)

3rd step : Calculate the risk of fracture for the feature i from the probability of fracture for one hole.

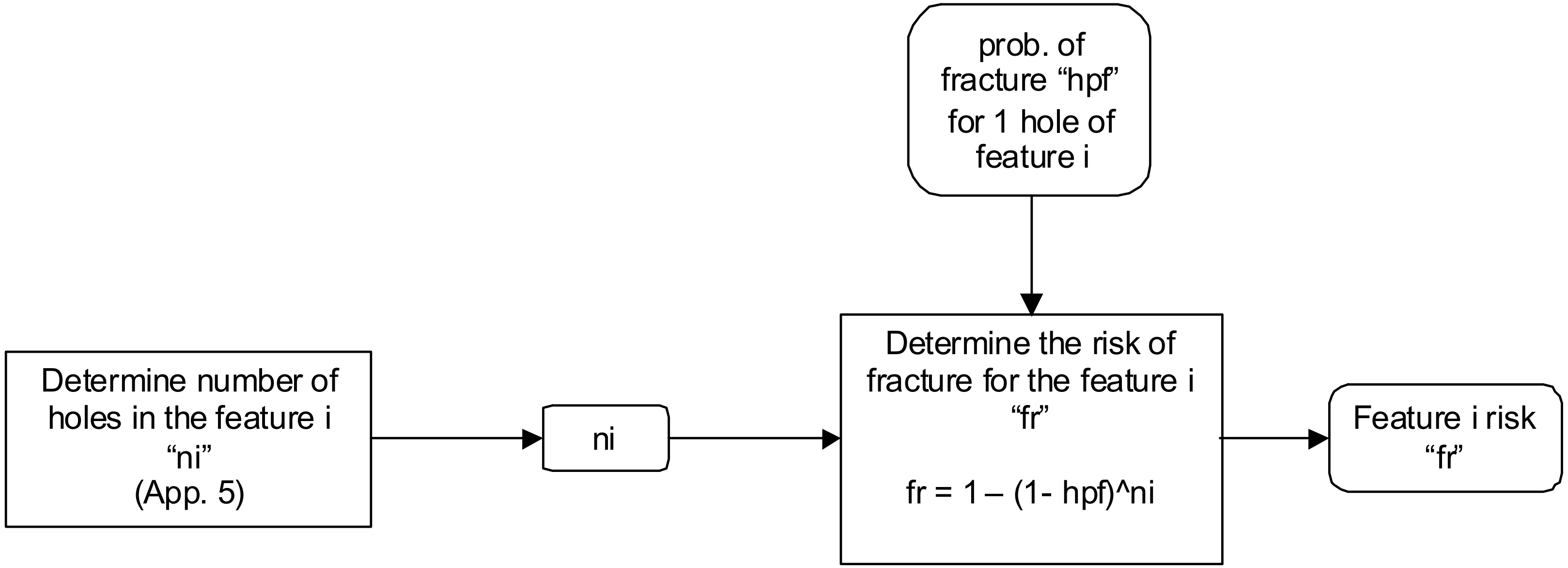

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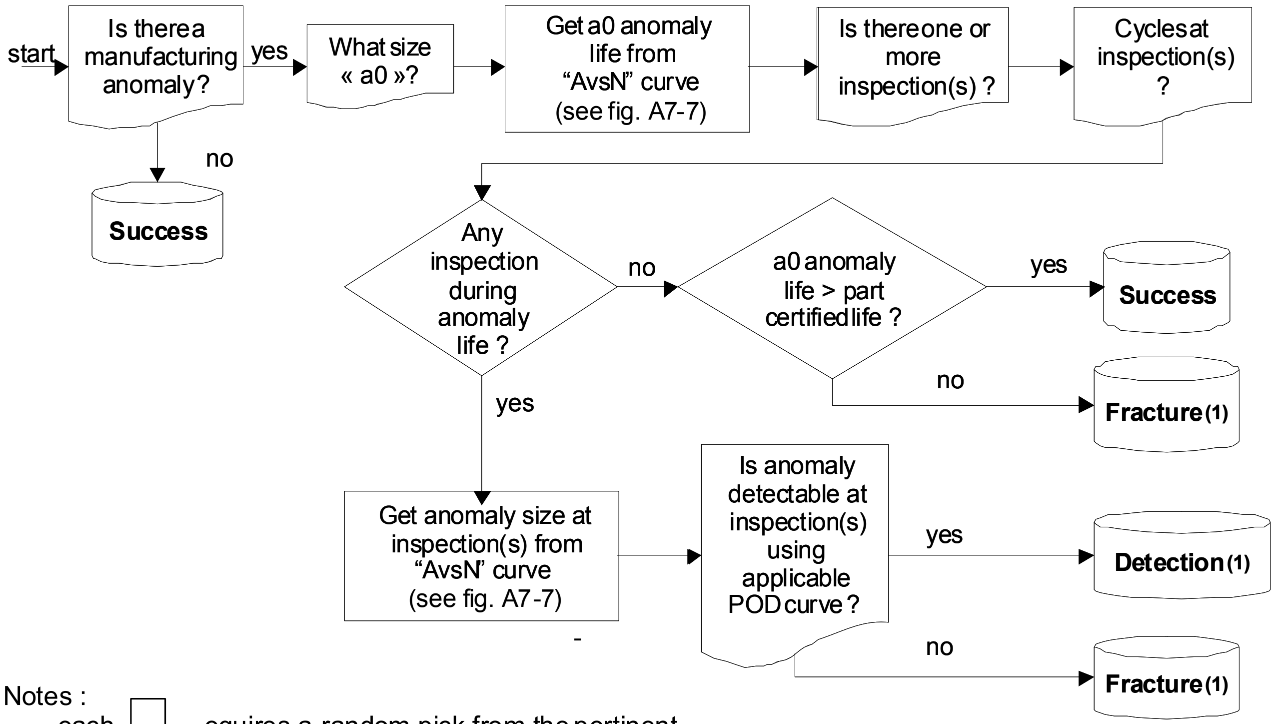
Figure A7-6: Conditional Probability of Fracture Calculation

The POF calculation is described here following a Monte Carlo simulation process. A large sample of holes should be simulated (see App. 1, 3 (e)). Each hole simulation in the sample follows the flowchart below to determine if it : fractures before part certified life / succeeds to reach part certified life / is detected with a crack.



Notes :

- each ▢ requires a random pick from the pertinent random variable distribution
- (1) record the number of cycles at fracture or detection for each hole

$$\boxed{\text{Conditional prob. of fracture before N cycles} = \frac{\text{number of fractured holes before N cycles}}{\text{total sample size}}}$$

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Figure A7-7: a0 Anomaly Life & Anomaly Size at Inspection(s) Calculations

from "AvsN"Curve