# STATISTIC APPROACH BASED ON "MONTE-CARLO SIMULATION" TO CALCULATE INSPECTION RELIABILITY FOR MULTIPLE SITE DAMAGE

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## INTRODUCTION

Changes in aircraft design concepts in recent years from "Safe-Life / Fail-Safe" to "Damage-Tolerance" have significantly increased the importance of the role of Non-destructive Inspections (NDI) and have placed a far greater importance on the effectiveness of NDI techniques and their ability to detect defects. To calculate inspection reliabilities based on probability of detection (POD) of the inspection method and "Multiple Site Damage" (MSD) (or "Widespread Fatigue Damage") assumptions for the defects, an approach to use a "Monte-Carlo Simulation" is described and results for crack inspection of aircraft lap joints are presented.

## AIRCRAFT DESIGN AND INSPECTION PHILOSOPHY

The damage tolerance concept accepts a structural damage in a component, and relies on the ability to detect this damage before it reaches critical dimensions. The damage-tolerant capability of a structural part relies on in-service NDI and therefore it is essential to define the inspection criterions

* inspection threshold (start of inspections) and
* inspection intervals .

The capability of inspection methodes is described by the

* probability of detection ( POD-curve ) .

A POD-curve, showing the probability to detect defects versus defect size, is only valid for one NDI technique applied on a defined inspection task. The POD data includes technical and human factors just as environmental conditions of the inspection. NDI methods applied for in service inspections should be able to detect small defects with high probability (POD = 90 %) at high confidence level (95 %) and have a low false alarm rate (p(FA) < 3 %), that means the risk to get defect indications from faultless areas should by low. Small defects are detectable using high sensivity for the inspection method. But decreasing the detectable defect size means increasing the false alarm rate.

To determine the inspection parameters inspection threshold and -interval it is necessary to know the defect growth during lifetime. The detectable defect size for a desired POD value is calculated from the POD-curve. Knowing the detectable defect size, the critical defect size and the defect growth behaviour, inspection threshold and "X-value" (time of defect growth from detectable to critical size) can be calculated. When safety-factors are applied to inspection threshold and "X-value", inspection start and inspection intervals are defined.

## LIMITATIONS OF THE METHOD

Until now calculations of the inspection parameters are based on a "single defect" assumption in the inspection area. This may be realistic in localised areas, but does not appear to be an realistic approach when applied to multi-fastener skin joints for the following reason:

> Fatigue cracks in multi-fastener joints do not usually exist in isolation (except in the early stages of fatigue initiation). It is suggested that a more realistic approach for multi-fastener skin joints would be to base the calculations on the assumption that in high life aircraft, before any single crack reaches a sigificant length, a multiple site damage (MSD) or widespread fatigue situation will exist.

## NDI RELIABILITY IN CASE OF MULTIPLE SITE DAMAGE (MSD)

To determine NDI reliability for MSD, it is assumed that in the inspection area there are N test positions, $N_0$ without defects and $N_d$ with defects of different sizes. On the basic of this scenario it is necessary to calculate the probabilities

$p(N_d,k_d)$ to get $k_d$ defect indications from $N_d$ defectiv positions (hits) and
$p(N_0,k_0)$ to get $k_0$ defect indications from $N_0$ defect free positions (false alarmes)

The probabilty p(n,k) to get k events out of n possible is given by the following formula :

$$p(n,k) = Fak(n,k) * q^k * (1 - q)^{n-k} \quad ; \quad q = \text{probability of the event}$$

with

$$Fak(n,k) = \frac{n * (n-1) * (n-2) * ... * (n-k+1)}{1 * 2 * 3 * .... * k} \quad ; k = 0, 1, 2, ... n$$

This formula is only applicable if the probability q is the same for all events, that means it is possible to calculate $p(N_0,k_0)$ the probability to get $k_0$ false alarms from the $N_0$ defect free inspection positions and $p(N_d,k_d)$ the probability to get $k_d$ defect indications from $N_d$ defective inspection positions if the POD for all defects is the same, that means all defects have the same size.

The assumption, that all defects in the inspection area are of the same size is not realistic. Therefore it was decided to do NDI "Monte-Carlo Simulation" to calculate the desired probabilties for a given POD and inspection scenario. To validate the model results of simulation and formula are compared for simple cases (false alarmes, all defects of same size).

## NDI "MONTE-CARLO SIMULATION" MODEL

Input data for the NDI "Monte-Carlo Simulation" (example see fig.1) are

* the POD data of the inspection method and
* defect scenario at the inspection time $T_i$ .

Output data are probabilities for the possible NDI recordings, which are in the language of signal detection theory are the following :

TN = true negative indication (no defect ; no defect indication)
FN = false negative indication (defect ; no defect indication / missed defects)
FP = false positive indication (no defect ; defect indication / false alarm)
TP = true positive indication (defect ; defect indication / hit)

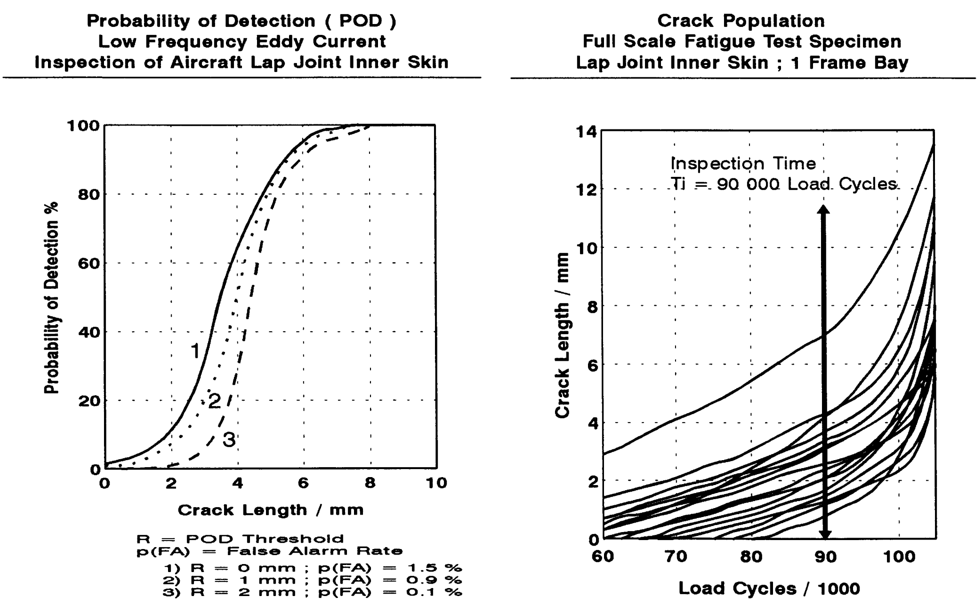


Figure 1. Example of input data for "Monte-Carlo Simulation" of nondestructive inspection methods

To determine which recording case is valid for each inspection position $j = 1 \ldots N$ with defect of size $l(j)$ the following rules are applied :

A random number $p_R$ and the probability $POD[l(j)]$ to detect a defect of size $l(j)$ are compared. (In case of defects size $l(j) = 0$ , $POD[0]$ is the false alarm rate).
If $p_R > POD[l(j)]$ the NDI recording is negative (no defect indicated at position j) and if $p_R <= POD[l(j)]$ the NDI recording is positive (defect indicated at position j).

Looking at the defect size $l(j)$ it can be decided whether the NDI recording is true or false. The reporting of nondestructive inspection is true if the result of the inspection is in agreement with the defect size and false if not. For each inspection position the model gives a probable recording case and at the end of the loop for the N inspection positions we get a possible inspection result of

$a_{TN}$ recordings true negative
$a_{FN}$ recordings false negative = number missed defects
$a_{FP}$ recordings false negative = number of false alarms $a_{FA}$
$a_{TP}$ recordings true positive = number of hits

where $a_{DI} = a_{TP}+a_{FP}$ is the total number of defect indications.

To calulate the probability for the different recording cases, the simulation model includes three loops,

* the inner for the N positions of the inspection area,
* the middle for M inspections (This lopp is necessary to get a statistic of possible inspection recordings) and
* the outer for varying the time of inspection.

Runing M inspection loops with the model we get M different inspection recordings and it is possible to calculate the probabilities for interesting recording cases, fore example :

$p(a_{FA})$ = probability to get $a_{FA}$ false alarms and
$p(a_{DI})$ = probability to get $a_{DI}$ defect indications (false alarms + hits)

## EXAMPLE OF MODELING AND VALIDATION

The Monte-Carlo Simulation model was used to calculate reliabilities for non-destructive inspections of an aircraft lap joint. The inspection method was low frequency Eddy Current and the inspection area, one frame bay of the lap joint (25 rivets with 50 inspection positions left and right of the rivet). Probability of detection and defect population are shown in fig. 1 and a possible defect scenario at inspection time $T_i$ = 90 000 load cycles is shown in fig.2. (The defect population used is the result of microfractografic investigation of a full scale fatigue test specimen.)

Simulation results for this defect scenario and three different POD threshold levels are shown in fig 3. The inspection area includes 31 positions without defect an 19 with cracks (one crack of 7 mm and 18 with crack lengths between 0,5 and 4.5 mm). The output data (histograms) show the probabilities $p(a_{FA})$ for the recording case false alarm and $p(a_{DI})$ for the case defect indication versus number of events.

**Liste of Defects**
**Full Scale Fatigue Test Specimen**
**Inspection Time Ti = 90 000 Load Cycles**

| Test Position | Crack Length |
|---|---|
| Pos. 15 | 1.00 mm |
| Pos. 16 | 0.40 mm |
| Pos. 17 | 0.80 mm |
| Pos. 18 | 1.70 mm |
| Pos. 19 | 1.20 mm |
| Pos. 20 | 2.60 mm |
| Pos. 21 | 3.70 mm |
| Pos. 22 | 3.40 mm |
| Pos. 23 | 2.10 mm |
| Pos. 24 | 7.00 mm |
| Pos. 26 | 2.10 mm |
| Pos. 27 | 1.50 mm |
| Pos. 28 | 4.20 mm |
| Pos. 29 | 1.10 mm |
| Pos. 30 | 4.30 mm |
| Pos. 31 | 1.30 mm |
| Pos. 32 | 2.40 mm |
| Pos. 33 | 3.20 mm |
| Pos. 34 | 3.10 mm |

**Statitics of Defects**
**Full Scale Fatigue Test Specimen**
**Inspection Time Ti = 90 000 Load Cycles**

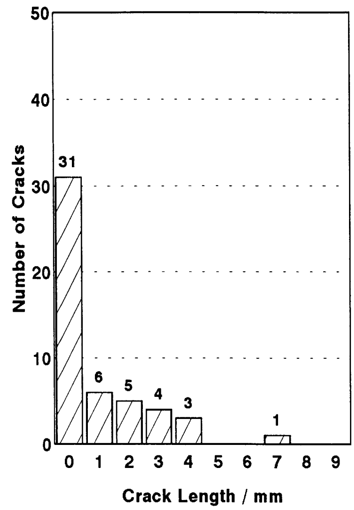


Figure 2. Example of defect scenario for NDI "Monte-Carlo Simulation"

Increasing the POD threshold R (less inspection sensitivity) means decreasing the probability of false alarms and defect indications. At threshold R=0 and R=1 the probability to get false alarms is greater than 20 %. Even if there is only 1 crack with high POD values and 5 ( 3.5 mm to 4.5 mm) with moderate, the probability to get 2 and more defects indications is high.

To validate the "Monte-Carlo Simulation" the probabilties of false alarms are compared with the results of the formula. Fig 4. shows the probability of false alarms versus load cycles for the defect population of fig 1. The lines are the results of the simulation and the dashed line of the formula for different numbers of false alarms. This validation test shows a good agreement of modeling and formula.

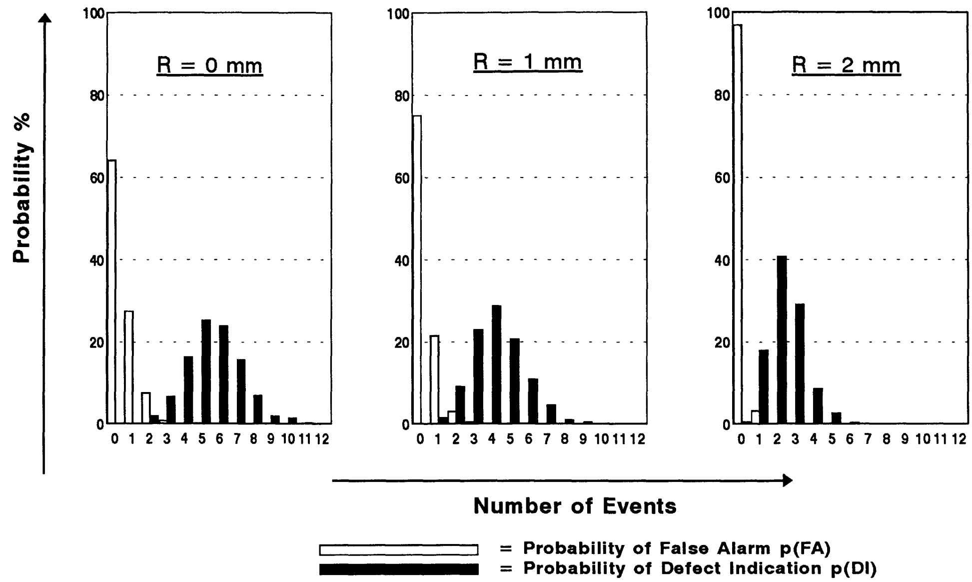


Figure 3 . Result of NDI "Monte-Carlo Simulation" for various POD threshold levels R for low frequency Eddy Current inspection of Aircraft lap joint inner skin.

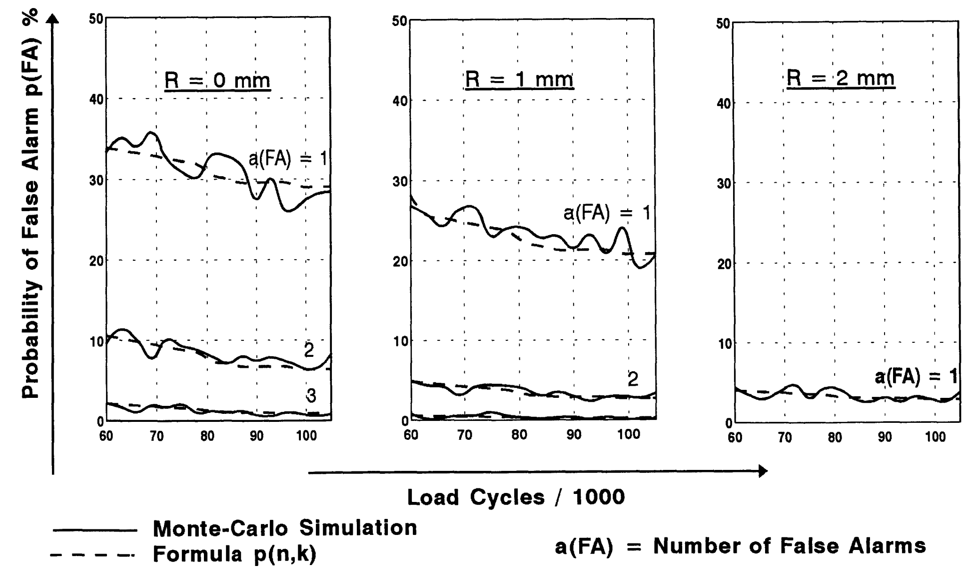


Figure 4. Validation of NDI "Monte-Carlo Simulation".
Probability of false alarms p(FA) for various POD threshold levels R.

## NDI "MONTE-CARLO SIMULATION" DURING LIFETIME

The described NDI "Monte-Carlo Simulation" has been applied with the defect population and the POD curves of fig. 1. The resultes, cumulative probability of defect indication $P(a_{DI})$ versus load cycles for various numbers of indications $a_{DI}$ and different POD threshold values R are shown in fig 5. The dotted lines are those with high probability of false alarms. There is a strong influence of the POD threshold level on the probability of defect indication even the POD curves show only less influence of the threshold for high POD values (see fig. 1).

Asking for a probability of defect indication $P(a_{DI})$ = 90 % and cutting of the area of probable false alarmes, the different thresholds lead nearly to the same inspection threshold of 90 000 load cycles. The fig. 6 shows the inspection "X-values" calculated with the data of fig 5., compared with the calculation based on single defect assumption (defects are only detected if their size is larger than the detectable defect size). The "X-values" decrease with increasing POD threshold and the gap between multiple site damage and single defect assumption becomes smaler.

The simulation results show an advantage of high sensitive NDI methods for multiple site damage. But for high sensitive methods a certain number of false alarms has to be considered. The MSD situation is indicated by certain number of defect indications which is higher than the number of possible false alarmes. For the low frequency Eddy Current inspection (POD threshold R = 0 ) of an aircraft lap joint inner skin, MSD is indicated by 4 and more defects recorded.

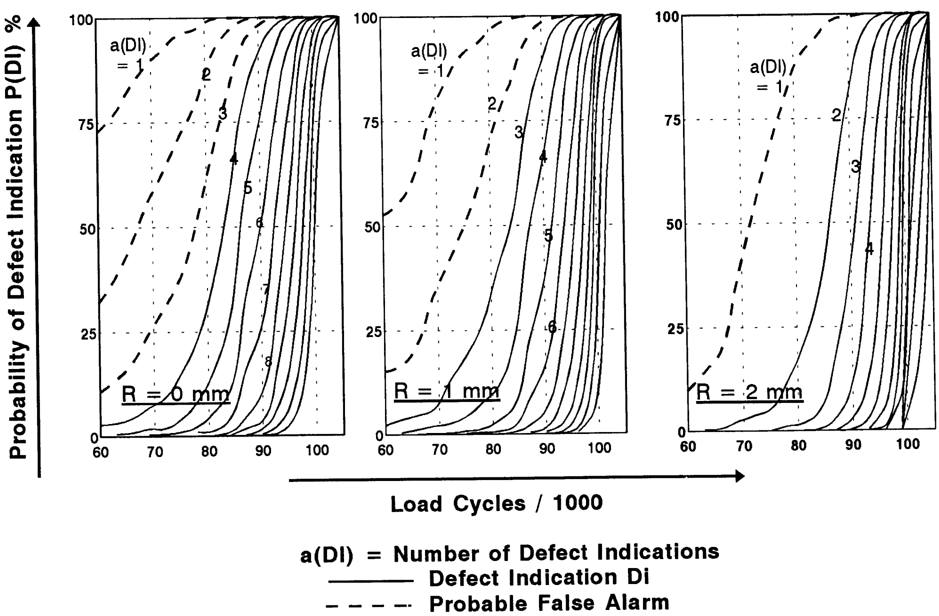


Figure 5. Cumulative probability of defect indication P(DI) (false alarms and hits)

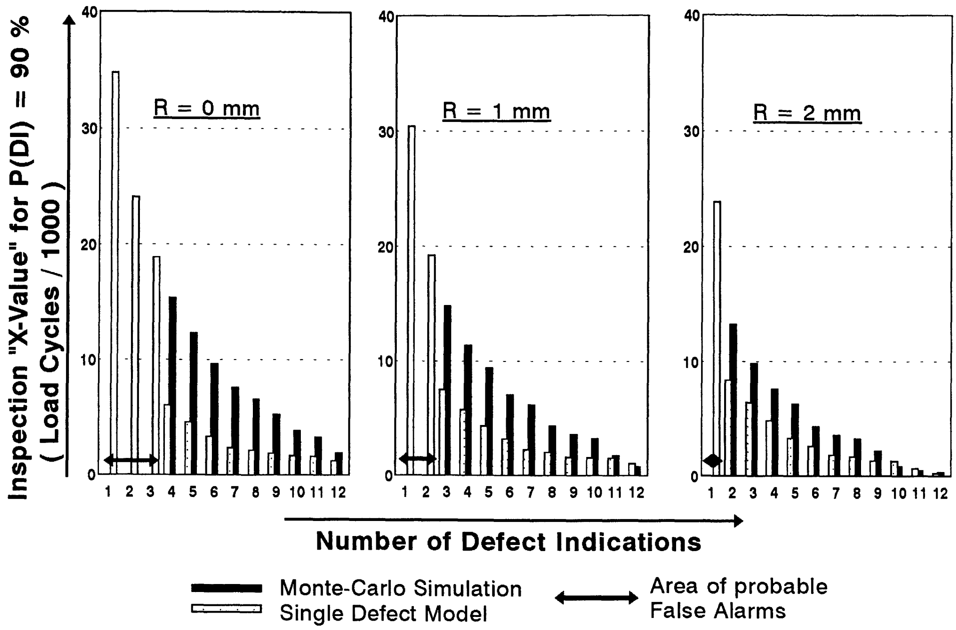


Figure 6. Inspection "X-values" as result of NDI "Monte-Carlos Simulation" ( Probability of defect indication P(DI) = 90 % ).

## CONCLUSIONS

The method to apply a "Monte-Carlo Simulation" model for nondestructive inspections on the basic of defect population and POD-curve of the inspection method can help to understand the recordings of NDT inspections and to validate then. The model is helpfull to study the influence of the POD on the inspection results and to optimize inspection strategies.

## REFERENCES


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