FATIGUE AND DAMAGE TOLERANCE ASSESSMENT OF AIRCRAFT STRUCTURES IN PRESENCE OF MULTIPLE DAMAGE.

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1. Abstract.

Following the Aloha accident, the aeronautical community has decided a strong voluntary effort for reevaluating all the issues surrounding the aging fleet.
The Aloha accident highlighted that one of the main results of the airplane's aging process is the increased susceptibility to multiple site or multiple element damage (MSD/MED).
A lot of concerns are generally expressed when considering MSD/MED.
Typical and simple calculation methods and ideas are developed here, in order to show that MSD/MED can be assessed with a better confidence level than previously thought.
The results concur to show that in most situations, MSD/MED can be accounted for by slightly modifying the current methodology.

2. Background.

In 1988, a major accident occurred on a Boeing 737 of Aloha airlines (1). A large part of the forward fuselage separated from the aircraft during the flight. Fatigue and debonding of a lap joint were identified as the main cause of the failure. The aircraft had accumulated about 90000 flights.
Following this accident, the first international conference on aging airplanes took place. Major deficiencies related to the safety of aging airplanes were highlighted.
The number of older airplanes increased drastically over the past years, raising new structural issues.
Technical knowledge, airworthiness and maintenance systems were judged inadequate to ensure timely detection of the new issues and to address them correctly.
Following this severe report, a strong voluntary effort was decided by the aeronautical community.The Airworthiness Assurance Working Group (AAWG) was created.
This organization coordinates a panel of working groups whose tasks are to propose corrective actions to improve aging airplanes safety.
The major objectives (see Fig 1) were to:

- . identify and perform urgent actions needed on older airplanes,
- . improve fatigue analysis quality,
- . identify the necessary research to be done,
- . improve communication between manufacturers, airworthiness authorities and operators.
- . understand and decrease human factor influence.

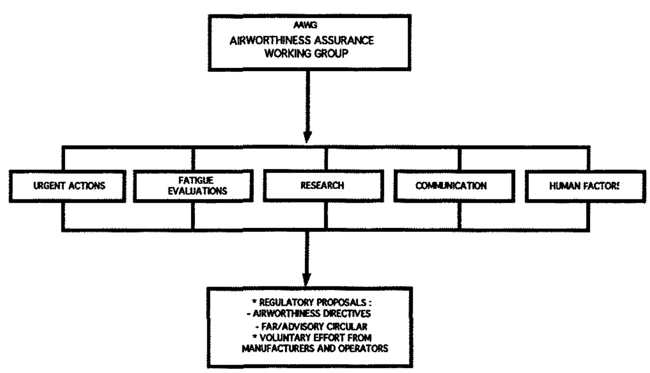

Figure 1 : AAWG. Field of action.

This paper is about fatigue analysis of aging aircraft and more specifically about multiple damage, one of the main causes of the Aloha accident.
The aim is to focus on industrial assessment basis rather than research activity.

3. Widespread fatigue damage.

The fatigue behaviour of an aircraft structure is assessed and demonstrated by analysis and test through all industrial stages : design, certification, maintenance programme and product support activities, as presented on Fig 2.

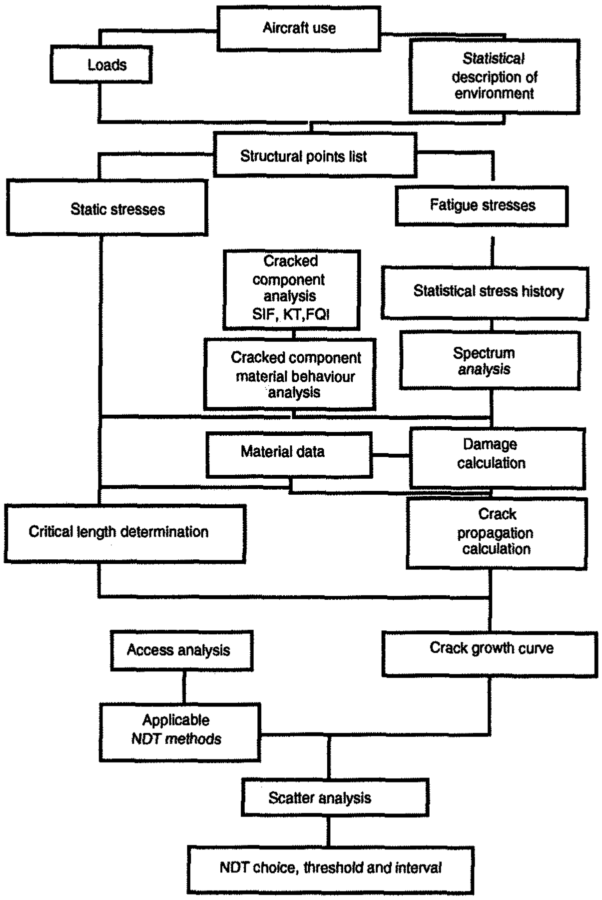

Figure 2 : Steps of fatigue behaviour control.

3.1 Fatigue quality assessment.

Fatigue quality is a function of design, stress levels and material properties. This quality is assessed by analysis supported by extensive full scale testing and tear down investigations.
This procedure ensures the detection of defects coming from causes such as unexpected high loads or bad design, in an early stage of the aircraft life. Modifications and improved maintenance programs are proposed when significant damage is discovered.
However, this assessment is initially conducted only up to the planned operational life of the aircraft.
After this time, the probability of fatigue damage increases as it is an age related problem. It is also clear that the initial knowledge of fatigue quality may not be sufficient to deal properly with safety, without further design or maintenance corrective actions. This is the basic link between fatigue and aging aircraft issues.

3.2 Multiple damage.

In addition to highly loaded or high stress concentration areas, a lot of multiple design features, such as frames, panel joints, exist on an aircraft. These structures are assembled with an important number of fasteners, introducing moderate stress concentrations.

The life of such components is generally longer than the initial life objective, as demonstrated by initial analysis and tests. However, as an important number of similar details exist, several cracks may initiate in the same component. This kind of cracking, called multiple damage, is typical for aging aircraft structures. When numerous small cracks are of sufficient density whereby the required residual strength of the structure is not sustained, the damage is called widespread. The point in time where this event happens is the occurrence of widespread fatigue damage.

Two kinds of multiple damage may be found :

- multiple site damage (MSD) is a source of widespread fatigue damage characterized by the simultaneous presence of fatigue cracks in the same structural element (e.g. fatigue cracks may coalesce with or without other damage leading to a loss of required residual strength).

- multiple element damage (MED) is a source of widespread fatigue damage characterized by the simultaneous presence of fatigue cracks in similar adjacent structural elements.

Concerns generally expressed regarding MSD/MED compared to single site damage are important :

- the cracks may interact. This can be seen for instance in Fig 3, leading to an increase in the stress intensity factor and then crack propagation rate compared to single site damage.

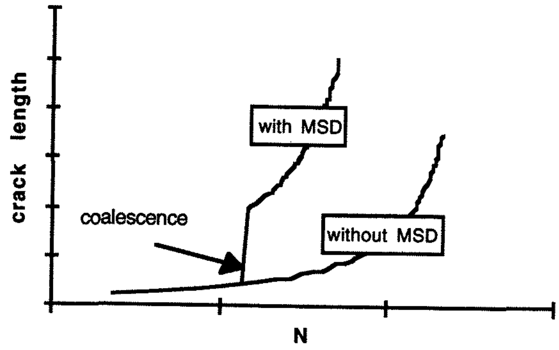

Figure 3 : Crack propagation comparison.

- residual strength may be suddenly and drastically reduced, even for small cracks.

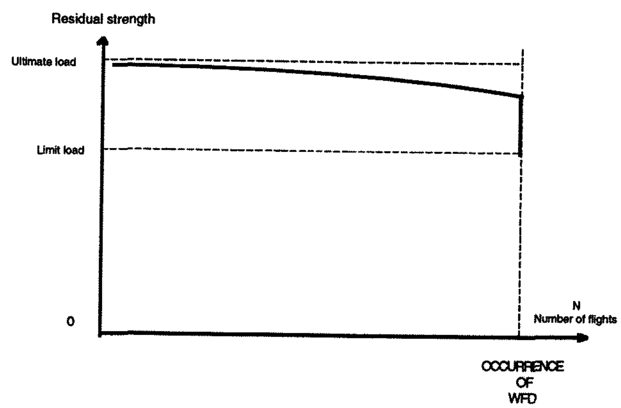

Figure 4 : Residual strength reduction.

- detectability by maintenance inspection is estimated difficult if it is necessary to find very small cracks.

In short, multiple damage is typical of aging aircraft structures, may lead to increased crack growth rate, reduced residual strength and may be not detectable by inspection.
At all steps, damage tolerance may be unadequate to handle widespread fatigue damage.
If additionaly we consider the fact that some cases of widespread fatigue damage cannot be properly modelled at the present time, owing to the lack of scientific knowledge, it is easy to understand that WFD is a major concern for the safe use of aging airplanes.

4. Basis for modelling multiple damage.

The aim of this main section is to highlight the author's engineering judgment on the concerns expressed above. At each step, simple calculations are used to assess the importance of these issues and to provide ideas and basis for multiple damage modelling.

4.1 Initiation.

MSD susceptible structures include repetitive similar details.
The first step of the analysis is to study the fatigue behaviour of a single site damage.

4.1.1 Single site damage.

In this field, major manufacturers have developed satisfactory tools and test background.

For instance, in the case of a double shear joint, see Fig 5; the main parameters are well known :

- sheet thicknesses,
- fastener type, diameter, clamping,
- assembly type,
- material,
- fretting conditions,
- secondary bendings,
- surface condition.

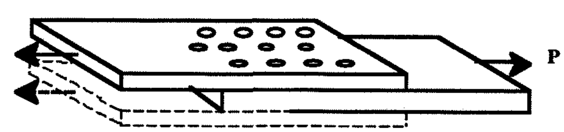

Figure 5 : Double shear joint.

The fatigue quality of the joint is modelled through a function of these parameters.

The knowledge of stress history allows an initiation life estimate to be made. This estimate and the natural fatigue scatter may be approached by conventional statistical distributions such as log normal law, whose parameters are (log N0, σ), where :

N0 is the mean life,
σ is the standard deviation.

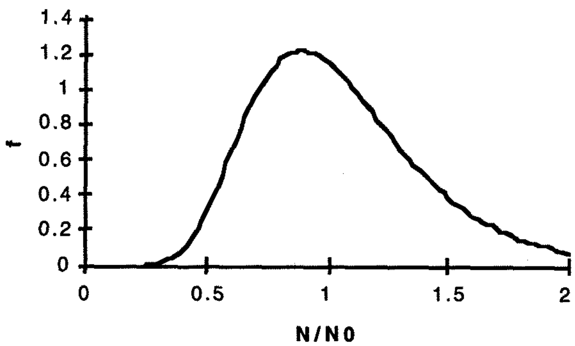

Figure 6 : Density function, log-normal law, $\sigma = 0.15$.

4.1.2 Multiple site damage.

For a given value of N/N0, the existence of single site damage has a probability of occurrence p. If we consider a structure including n similar details, with equal loading, the probability occurrence of k simultaneous cracks can be given by the binomial law :

$$p(k,n) = \binom{n}{k} p^k (1-p)^{n-k} \quad \text{(eq 1)}$$

Much information about the probability of different damage patterns may be extracted from this simple formula.

In Fig 7, results are presented for n=20 and k=0;1;3 or 10 cracks.

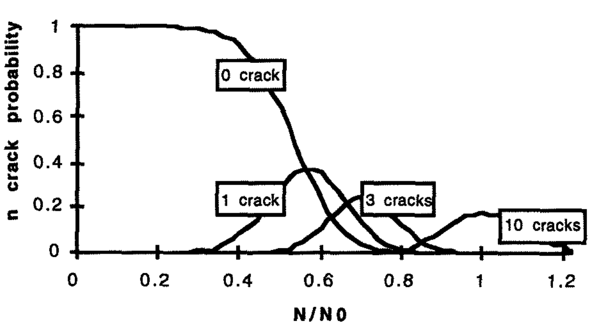

Figure 7 : Initiation probability of MSD, σ=0.15.

4.1.3 Discussion.

From this example, it is possible to formulate some significant remarks :

- Predictions of MSD/MED initiation based on a single site damage mean life analysis are unconservative.
For instance, Figure 7 shows that the probability of having a crack at 65% of the single site damage mean life is greater than 95%.
However, the factor 0.65 applied to single site damage mean life allows to have a simple and realistic estimation of the occurrence of MSD/MED.

- In normal condition, simultaneous initiation of many identical cracks is unlikely. From (eq 1) and various derived equations, the probability to have a great number of cracks is always low. At 65% of the single site damage mean life, the probability to have at least one crack is greater than 95%, but the cumulative probability to have more than three cracks is less than 20%, and the probability to have more than three adjacent cracks is less than 1%.
If we add that at least slight loading differences always exist in a real structure, it is most probable that MSD/MED develops first in a localized area with few cracks. These cracks will coalesce before significant damage exist in other areas, leading to the concept of the existence of a lead crack, associated with small neighbouring cracks.

- The presented results are dependent on the standard deviation σ.
It is known that, for high stresses, this value can be lower than 0.15. It can be noted that in this case, results may vary significantly.

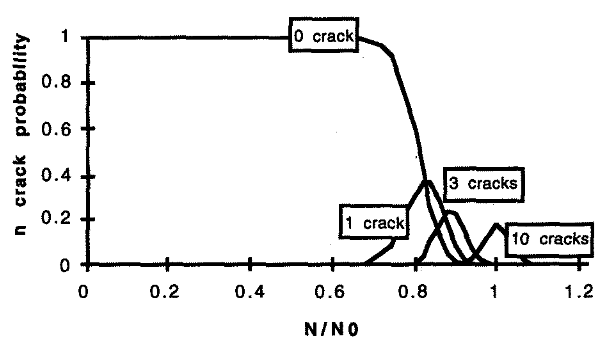

Figure 8 : Initiation probability of MSD σ=0.05.

As shown on Figure 8 for $\sigma=0.05$, the 95% probability of having at least a crack is reached for 85% of the single site damage mean life, instead of 65% for $\sigma=0.15$.
At this time, it is more likely to have a greater number of cracks. The probability to have more than three cracks is greater than 40%.
In summary, with a smaller standard deviation, the reduction factor to be applied to single site damage mean life to predict MSD/MED initiation is greater, but the number of simultaneous cracks may also be higher. So, MSD/MED is more likely to become widespread with high loading. As shown in the first paragraph, this behaviour is not expected for usual MSD/MED susceptible structures, because their lives are relatively high and with greater scatter. Only additional causes, such as debonding or manufacturing defects may lead to a reduced standard deviation and so to a significant probability to have an important number of simultaneous cracks.

A great number of other results may be obtained from the use of binomial law, and are not presented here.
Extensions of the formulation make it possible to compute the probability of occurrence for any possible cracking scenario, and may be used as the first tool for multiple site damage simulation. All these results do not modify the basic conclusions of this paragraph.

<u>- Single site damage evaluation may be used to predict multiple site damage initiation through a single reduction factor applied to the single site damage mean life results.</u>

<u>- In most cases, an initial MSD/MED scenario including only a few cracks is adequate.</u>

<u>- The concept of lead crack is applicable.</u>

<u>- Unexpected events, such as debonding or manufacturing defects, by reducing fatigue scatter, may lead to the simultaneous initiation of a great number of cracks, more likely to become widespread.</u>

4.2 <u>Crack propagation time.</u>

Crack propagation may be derived from linear fracture mechanics :

The stress intensity factor ΔK is described as :

$$\Delta K = \beta(a)\ \Delta\sigma \sqrt{\pi a} \qquad \text{(eq 2)}$$

where a is the crack length,
$\Delta\sigma$ is the gross stress,
$\beta(a)$ is a function of crack length.

For an infinite sheet, $\beta(a)$ is constant and equal to 1.

In the case of multiple cracks, an interaction exist. This interaction should be modelled through stress intensity factor solutions. In (2) for instance, some expressions of the stress intensity factor for two equal length cracks in an infinite sheet are given. The factor $\beta(a)$ includes the interaction effect, compared to a single crack in an infinite sheet. An example of $\beta(a)$ is given in Fig 9 :

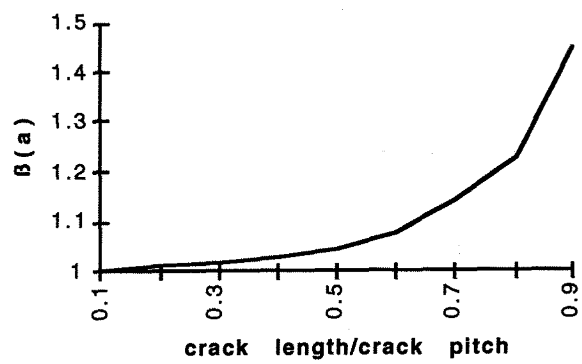

Figure 9 : Stress intensity corrective factor for 2 cracks in an infinite sheet.

The interaction effect reaches 10% when the residual section between the two cracks is reduced by 65%.
In terms of crack propagation time before coalescence, the interaction is expected to have little influence, as its effect is only significant in the last and shortest part of the crack propagation.
As an example, a simple calculation has been made, comparing an infinite sheet with one crack and an infinite sheet with two cracks. Both cracks are through the thickness. Some calculation parameters are presented in table 1 :

Initial length	1.25 mm
Final length	9.5 mm
Crack pitch	22 mm
Gross stress	150 Mpa
Material	2024

Table 1 : Calculation parameters.

For the two crack example, the crack propagation is decreased by 10%. As expected, the difference is low.

Now, it is possible to take into account the effect of the reduction in section due to the presence of cracks in the vicinity of the two cracks considered in this example. In this situation, if the constant effect of a 10% decrease in net section is assumed, the crack propagation time until coalescence is reduced by 40%.

This example shows that the most important accelerating factor when considering crack propagation is decreased net section, not interaction between crack tips.

4.3 Residual strength.

As the net section has a significant effect on crack propagation, it can be expected that this parameter is also important for residual strength.

Based on this, simple methods may be derived to predict residual strength, using the net yielding section criterion (3), (4).
For instance, in some methods, failure occurs when plastic zones ahead of crack tips become adjacent.
When equal length cracks are considered, this criterion is expressed by :

$$P-2a = 2R \qquad \text{(eq 3)}$$

where, see Fig. 10:

P is the crack pitch,
R is the plastic zone size, expressed by :

$$R = \left(\frac{K}{\sigma_y}\right)^2 \frac{1}{2\pi} \qquad \text{(eq 4)}$$

σ_y is the yielding stress.

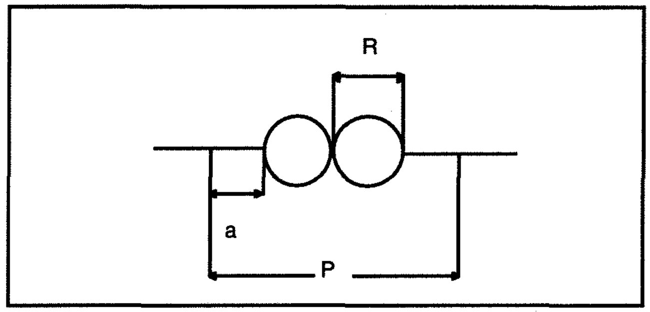

Figure 10 : Net yielding section criterion.

The application to the crack propagation example with two interacting cracks in an infinite sheet gives a failure length of 9.5 mm, which is very small compared to single crack critical length.

4.4 Detectability.

In the aeronautical field, the non destructive inspection of a structure is made according to a procedure described in a manufacturer-approved document. The aim of this procedure is to ensure optimum detectability and reproducibility. The performance of the inspection can then be described by a single probability of detection (POD) curve.
Usually, within the industry, the results of n inspections of similar details are considered to be independent events. This is also the case for one inspection of n locations in the same component. The cracking scenario of an MSD susceptible structure, where n cracks of length ai are present, can be considered as an example. Total detection probability of at least one crack should be defined as :

$$PDET = 1- \prod_{i}^{n}(1-pdet(a \leq ai)) \qquad \text{(eq 5)}$$

where n is the number of cracks, and ai the crack length at location i.

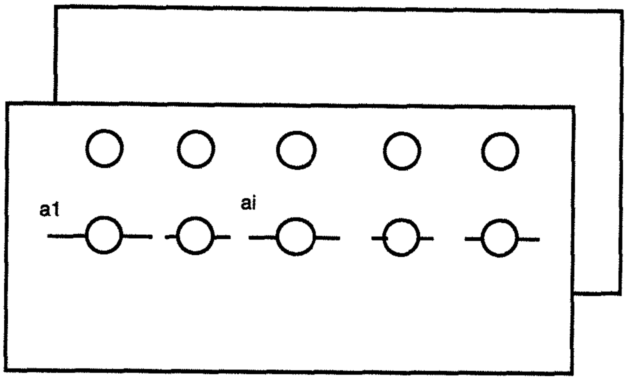

Figure 11 : Example of MSD crack pattern.

The example may be simplified by assuming n equal length cracks. In this case, the above expression becomes :

$$PDET\ (n) = 1-(1-pdet(a \leq ai))^{n} \quad \text{(eq 6)}$$

Fig 12 shows the evolution of total detection probability for different values of n.

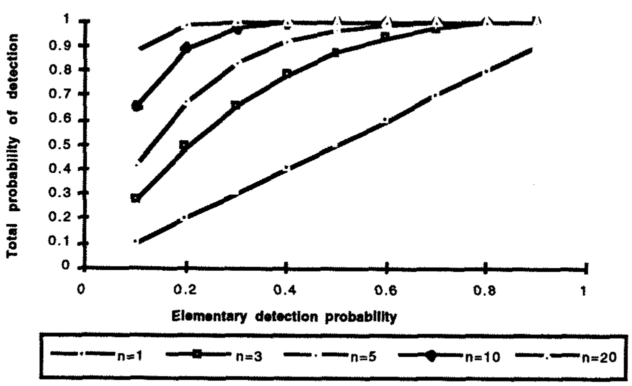

Figure 12 : Multiple inspection effect.

From this, a simple, evident, but important remark may be made : <u>the detection probability when several cracks exist is higher than the detection probability for a single site crack.</u> A "total probability of detection versus detectable crack length curve" may be derived. Crack sizes, at small detection probability for a single site location, may be found with a greater detection probability, when several cracks exist. This benefit can be shown by drawing the cumulative total detection probability curves for different values of n.

In Fig 13, the results are presented for a high frequency eddy current inspection.

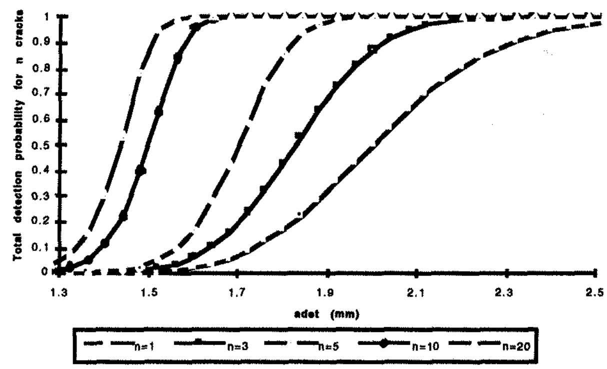

Figure 13 : Multiple inspection POD.

However, with eq 5, the multiple inspection effect is not limited and the 95% MSD/MED detectable length might be very small. A careful interpretation, used here is to limit this effect by using a threshold value. In this paper, the lower value is limited to 40% of the single crack detectability. The 95% total detection probability results for a high frequency eddy current inspection are shown in table 2.

n	adet 95% (mm)
1	2.4
3	2.08
5	1.95
10	1.95
20	1.95

Table 2 : Detectable crack length for MSD.

<u>From this, it appears that detectability is better, or very similar for MSD than for single site cracking.</u>

For information, a generalized formulation of eq 5 and Fig 12 has been included in the Aerospatiale probabilistic code PERFORM since 1988. More details may be found in (5).

4.5 Inspection program.

The previous paragraph has shown that detectability can be considered to be good for MSD. This leads to an important question : is MSD manageable by in-service inspections?
An initial answer may be given by applying the usual damage tolerance rules to MSD cracking.
An example is presented below.
Table 3 summarizes the characteristic parameters.

W	220 mm
Material	2024
Gross stress	150 Mpa
Crack pitch	22 mm
Limit load	173 Mpa

Table 3 : Example parameters.

A through crack model is run. The stress intensity factors are extracted from (2).

The results are presented for three different cases : one crack, three cracks of equal length and 10 cracks of equal length.

4.5.1 Visual inspection.

In the first step, visual inspections are used. 95% detectable crack lengths are based on the method used in the previous paragraph.

Number of cracks	95% detectable length (mm)	Critical length (mm)	Gross inspection interval
n=1	7.6	>19.5	12475
n=3	5.22	9.5	7000
n=10	3.8	9.5	13500

Table 4 : Visual inspection example results.

Taking normal fatigue scatters into account, an inspection program could be determined. However, compared to operators maintenance schedule, inspection intervals are rather short.

4.5.2 Non destructive Inspection (NDI).

The same example is now run with a high frequency eddy current inspection.

Number of cracks	95% detectable length (mm)	Critical length (mm)	Gross inspection interval
n =1	2.4	>19.5	37975
n =3	2.08	9.5	30062
n =10	1.95	9.5	32222

Table 5 : NDI inspection example results.

The results are plotted in Fig 14 :

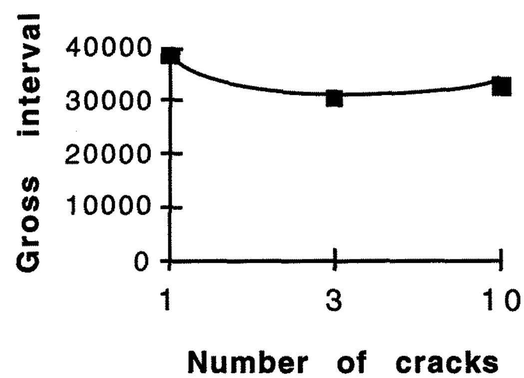

Figure 14 : NDI inspection intervals.

Two remarks can be made :

- NDI of MSD susceptible structure is possible and may lead to maintenance programs that are satisfactory from both safety and operational aspects.

- The shortest interval is not obtained with the greatest number of cracks.

5. Elements of experimental evaluation.

Some ideas regarding WFD have been presented in this paper and supported by typical, simple calculations. The purpose of this paragraph is to summarize available experimental background.

5.1 Initial cracking scenario.

A small database including Aerospatiale extensive test experience on MSD has been built. 7 full scale tests have been used, as well as barrels or large panel tests
For full scale tests, the test geometry and loading are representative of in-service aircraft. Tests are conducted for at least 2.5 Design Life Goal and followed by extensive Tear-down. The use of microfractographic analysis allows cracking scenario to be identified . The following conclusions apply :

- MSD cracking has always initiated in the last period of the test, after 2 aircraft lifetimes,
- no more than 3 adjacent initial cracks have been experienced,
- the simple use of a corrective factor applied on single site mean life is adequate to predict the initation of first crack in all cases.

In the framework of the Industry Committee on Widespread Fatigue Damage, a round-robin analysis was made on MSD susceptible structures. A comparison of major manufacturer's evaluation was made based on MSD test results (6).

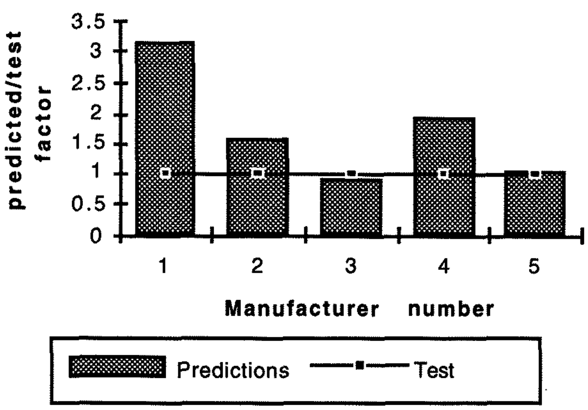

Fig 15 : Initiation predictions.

Aerospatiale predictions(n°3) were made according to the method described in this paper for initiation and have demonstrated accurate results, compared to the test results.

5.2 Crack propagation.

The net section effect may be illustrated by the following example. A large panel, representative of an aircraft lap joint was tested under constant amplitude loading. MSD was experienced, and the test conducted up to natural failure. Close monitoring of the crack propagation and microfractographic investigations allowed crack propagation curves to be determined. From this, an experimental stress intensity factor was derived.
Then, the comparison was made with theoretical stress intensity factor solution for single site crack extracted.

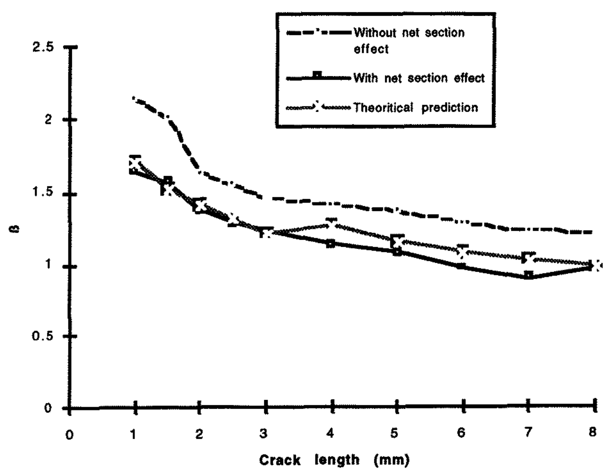

Figure 16 : Stress intensity correction factor.

When compared to a single crack theoretical model, the experimental stress intensity correction factor does not show any significant interaction. Both curves remain parallel, with higher experimental values. If the experimental stress intensity correction factor is determined with net section stress, instead of remote stress, the correlation with the single crack model is good, showing that net section effect is an important parameter.

5.3 Residual strength.

In all fatigue tests coming from the database, few cracks appears first in localized areas. In all cases, these few cracks coalesced without total failure of the component and before large damage extensions in neighbouring similar locations. No widespread fatigue damage was experienced. In all cases, the final crack length predictions using a net yielding section criterion are very conservative.

5.4 Detectability.

A significant number of detection probability curves have been established with structures in which several cracks exist, such as large panels, or coupons, or full scale fatigue tests.
It is easy to demonstrate experimentally that the probability of detecting at least one crack among several is significantly higher than the probability of detecting a single site crack.

A simple example illustrates this. 20 similar holes, from an aircraft structure, were inspected by 11 NDI operators with the required qualification level. 6 holes were cracked by fatigue. Various crack sizes existed. Only 3 operators succeeded in finding all cracked holes, but each inspector was able to identify at least one crack. Note that the largest defect was detected by 5 operators only. A comparison between the percentage of detection of at least one crack and the percentage of detected cracks is shown in Fig 17.

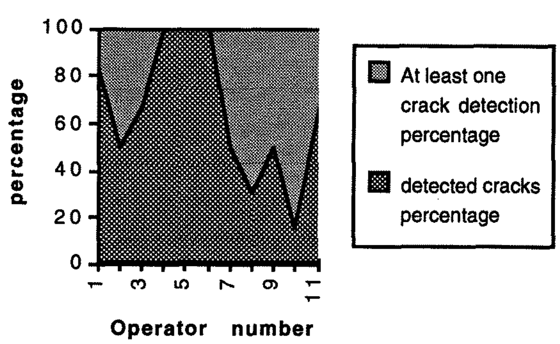

Figure 17 : Probability of detection of at least one crack.

The detection of one crack only is enough to take additional precautions, such as more detailed inspections or repair.

6. Conclusion.

The aim of this paper was to formulate some MSD/MED concerns and some ideas which could form the basis of a simple methodology for assessing MSD/MED.

- For MSD susceptible structures, the condition of initial identical loading rarely exists. Slight differences in loading are likely, leading to crack initiation in localized areas.
Even if an equal loading condition is assumed, the consideration of natural fatigue scatter shows that MSD/MED scenario begins with the simultaneous initiation of a few cracks. This initiation time may be derived from single detail coupon tests.
- Fatigue crack propagation of MSD is mainly influenced by a net section criterion. As long as this effect is small, the existence of a lead crack, with small neighbouring cracks is the most probable configuration.
The net section effect is important for tests on limited size coupons. These coupon tests are not representative for MSD.
- With MSD/MED, the residual strength of the structure is decreased. A simple criteria may be applied, based on net yielding section.
- The existence of multiple cracks of different lengths has an influence on the total detectability of the damage.
All these ideas concur in that :

- most of the MSD propagation life is spent with a localized damage (lead crack concept),
- management of MSD by NDI is possible in most situations.

Partial experimental verification of these ideas has been made.

Some concerns remain :

- external causes such as debonding or accidental damage may reduce initiation scatter by a load level increase. In this case, MSD is likely to become widespread.

- discrete source damage, on a structure susceptible to MSD may lead to an immediate residual strength issue.

To sum up, for most situations where scatter on initiation exist, MSD on susceptible structures may be predicted accurately and controlled through an adequate inspection program.
MSD itself can be managed. However, in conjunction with additional external events, MSD is potentially far more critical. In such situations, particular attention should be paid to MSD.

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