# FATIGUE CRACK INITIATION FOR AERONAUTICAL COMPONENTS

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## ABSTRACT

In the aeronautic field, the most frequent locations of MSD (Multi Site Damage) are fuselage lap and butt joints. For such components a great part of the fatigue life is related to crack initiation times whilst in comparison propagation times are generally less relevant, so that great interest arises in forecasting the initiation times of fatigue cracks. Most of such initiation numerical models are based on a statistic approach. In this work, which rely on the results of the European research project SMAAC (Structural Maintenance of Ageing Aircraft), some fatigue initiation models, to be applied to thin or thick section complex structural components, will be reviewed. Analytical expression and numerical results are derived from two different approaches: Order Statistics and Monte Carlo Procedure. Such models are checked by comparing numerical predictions against data coming from experimental tests on a range of specimens, starting with those relatively simple but gradually increasing their complexity. Most of the specimen tested were simulating fuselage structures and were designed in such a way to reproduce the most important phenomena affecting the real items.

## SOMMARIO

In campo aeronautico, tra i componenti ove più di frequente si registra una condizione MSD (Multi Site Damage) vi sono i giunti a semplice sovrapposizione della fusoliera (*lap* e *butt joint*). Per tali componenti una parte considerevole della vita a fatica è legata ai tempi di innesco del danno mentre, a confronto la propagazione procede in maniera relativamente rapida, per cui esiste un forte interesse nella messa a punto di modelli previsionali dei tempi di innesco delle cricche da fatica. Tali modelli sono per lo più basati su un approccio statistico. In questo lavoro, che raccoglie i risultati prodotti dai vari partner nel progetto di ricerca europeo SMAAC (Structural Maintenance of Ageing Aircraft), sono descritti alcuni modelli di innesco, applicabili a tali componenti strutturali a sezione sottile e spessa. Espressioni analitiche e risultati numerici vengono derivati da due approcci differenti: *Statistica ordinata e metodo Monte Carlo*. Tali modelli vengono valutati attraverso l'analisi comparata dei risultati della simulazione e di quelli sperimentali, questi ultimi basati su una varietà di provini a differente complessità. La maggior parte dei provini testati simulano strutture della fusoliera e sono studiati in modo tale da riprodurre i fenomeni più rilevanti che si manifestano sul componente reale.

## INTRODUCTION

The prevention of widespread fatigue damage (WFD) is central to the continued safe operation of ageing aircraft and the latest amendment to the airworthiness regulations of the United States contains the following statement: "*Special consideration for widespread fatigue damage must be included where the design is such that this type of damage could occur. It must be demonstrated with sufficient full-scale fatigue test evidence that widespread fatigue damage will not occur within the design service goal of the airplane*".

The main Original Equipment Manufacturer (OEM) are currently committed to undertake a full structure evaluation for WFD as a part of a general life extension program. The current approach to structural assessment within the airworthiness regulations emphasises the damage tolerance of the structure, with an inspection strategy that will detect defects before the strength of the structure is significantly affected. A damage tolerance assessment of an airframe component will include a determination of the stress state, the overall fatigue life, the crack growth period (possibly including retardation effects) and the critical crack size for principal structural elements.

An inspection strategy for a damage tolerant structure is defined by the threshold and repeat inspection intervals, as follows:

- the threshold inspection interval, not greater than half the design service goal (DSG), during which detailed inspections are not required, which is normally determined by fatigue endurance *(S-N)* calculations;
- the repeat inspection interval, which is normally determined by crack propagation and residual strength analysis.

Both analytical and experimental evidence is required to justify the threshold and repeat inspection intervals.

The principal objective of the BRITE European project SMAAC (Structural Maintenance of Ageing Aircraft) has been the development of overall methodologies for use in the support of maintenance activities to prevent WFD in ageing aircraft, and in the improved design of aircraft structures known to be susceptible to WFD.

Following comparison with experimental results, the theoretical models developed within the SMAAC project have been shown to give acceptable predictions of the fatigue life and residual strength under MSD (Multiple Site Damage) conditions. However, a detailed analysis may not be necessary in every case; if a prediction based on the assumption of pessimistic multiple crack scenarios gives a fatigue life or residual strength for a structure that is satisfactory for design purposes, then no further analysis is necessary.

This work is aimed to synthetically describe the main methodologies and results coming from that part of SMAAC project that concern crack initiation [1-3], with particular regard to MSD conditions.

## PROBABILISTIC ASSESSMENT OF STRUCTURES SUSCEPTIBLE TO MSD

A fatigue endurance test of a structure containing a row of nominally identical fastener holes is analogous to testing a series of simple coupons with a single fastener hole. Each single hole coupon initiates detectable cracking at different times, despite being manufactured to a common procedure; similarly, multiple hole structures will not initiate detectable cracks at the same time at each hole. It is assumed that the crack initiation time at each site susceptible to fatigue cracking is connected to the probability distribution for fatigue endurance given by testing a large number of single hole coupons. A good estimate of the scatter *(i.e.* the standard deviation) in the fatigue endurance of details representative of the aircraft structural feature is therefore fundamental to the MSD assessment.

If more than one single crack appears at adjacent rivet holes two major feature are responsible for the fact that MSD is a very serious phenomenon [4]:

- in MSD-like scenario crack sizes tend to be of relatively similar size in a certain region of nearly equal remote stress;
- after reaching a considerable crack size the cracks start to influence their crack growth mutually.

The degree of variability in the manufacturing process originally used in the production of the component determines whether MSD will occur, since poor quality control in manufacture results in isolated rogue flaws and the ’lead crack’ scenario of traditional damage tolerance criteria. It may be extremely difficult to establish the appropriate level of scatter for a structural evaluation in an ageing aircraft. Unfortunately, a supplemental fatigue endurance test programme may not furnish the required information, since 'new build' test coupons are unlikely to be representative of the original production standard, due to process and material changes over the service life of the aircraft. Consequently, the conservative assumption of low scatter in fatigue endurance may have to be adopted in order to induce MSD scenarios within the analysis. The assumption of high scatter suppresses multiple cracking scenarios and encourages isolated 'lead crack' scenarios, and may result in a shorter overall fatigue endurance for a multiple hole structure. The magnitude of the scatter directly affects the mean of the important outputs from a typical MSD fatigue assessment, *viz.* the period to first detectable crack, the period from detectable cracking to a critical crack scenario, and the overall fatigue endurance of the multiple hole structure. Where there is any uncertainty in the scatter, a fixed standard deviation based upon the largest known values will always give a conservative analysis of fatigue endurance, although the simulation may not include many MSD scenarios.

*Environmental effects.* With the relatively high scatter in natural fatigue crack initiation observed in typical mechanically fastened joints, the development of isolated fatigue damage, and consequently the 'lead crack' scenario of classical damage tolerance assessments, is much more probable than the multiple crack initiation necessary for the MSD condition. Thus, additional factors, such as corrosion damage or poor repairs, are required for the development of multiple fatigue cracks, and properly maintained aircraft are unlikely to encounter an MSD problem, especially in the period up to the original DSG. Since all commercial transport aircraft are manufactured with extensive corrosion inhibition systems such as shot peening, anodising and painting, with subsequent maintenance including mandated Corrosion Prevention and Control Programmes (CPCP), it is not reasonable to include such environmental effects at the design stage. However, the effect of corrosion in structure susceptible to MSD should be examined during an ageing aircraft assessment, particularly if in-service experience shows evidence of a corrosion problem. The experimental programme conducted during the SMAAC project suggests that the principal influence of corrosion is manifested in a reduction in the scatter of fatigue crack initiation. With a low scatter, the early initiation of multiple fatigue cracks, and consequently an MSD scenario, is much more likely than in an uncorroded component. It is normal practice to remove any corrosion once detected, usually by 'blending out' the affected area, and standard repair procedures include permissible rework limits, with a minimum allowable skin thickness, This may have a further detrimental influence on the scatter in fatigue crack initiation, due to the loss of cross section and the subsequent increase in local stress, although such effects are readily quantifiable within existing assessment methodologies. A more uncertain dilemma is presented by the possibility of undetectable corrosion within a structure susceptible to MSD.

## INITIATION MODELS USED BY PARTNERS IN ROUND ROBIN TESTS

With reference to thin (and thick) structures, the MSD initiation in a realistic structural item was to be studied. The results obtained from analytical expression derived from statistical theory and/or the Monte Carlo procedure were compared with experimental data. Each of the partners started with the view that a statistical approach would be required in order to evaluate all the potential possibilities for crack initiation in a multiple hole joint. It is self evident that in the presence of a relatively uniform stress field, there is no deterministic way to identify which specific hole, of many in a joint will crack first. Each of the partners made the assumption that simple test coupon data can be used to estimate the fatigue crack initiation period at a single fastener hole. When this association is made it is possible to use the scatter in fatigue endurance of simple coupon to model the possible range of crack initiation periods within a multiple hole joint. However it is critical that fabrication procedure for assembling small test coupon bears some relation to the procedure used during full scale manufacture. This is to assure that the complex micro-mechanism causing crack initiation in a

structural joint are also associated with crack initiation within a test coupon. It is also important to ensure that the test coupon adequately models the stress state within the large structural component.
Two basic analysis procedure were used by the partners to predict the probability of arbitrary crack patterns using simple coupon data. The first approach was to use analytical expressions derived from statistical theory. Whilst the second approach used numerical procedures based upon random number generators.

*Order statistics.* The first procedure is based upon binomial order statistics where the derived expressions can estimate the period at which any required crack pattern would occur, to a predefined confidence level. However this approach is only easily applicable to multiple hole structure, with a uniform applied stress distribution. Nonetheless, computationally efficient analytic expressions have been developed which may be applied if it is possible to use conservatively a uniform stress field across a joint width.
With such methodology [5], if the fatigue endurance of a single detail is known, the average period for the development of a given MSD scenario, such as *r* cracks out of *n* located anywhere within the component, may be predicted as follows:

$$G(x) = \sum_{i=r}^{n} [C_i^n F(x)^i (1 - F(x))^{n-i}] \qquad (1)$$

where $$C_i^n = \frac{n!}{i!(n-i)!}.$$

This expression allows the evaluation of the cumulative probability G(x) of at least *r* cracks occurring at *n* equally probable sites after a period *x* has elapsed. The *r* sites will be randomly distributed across the *n* potential sites. It is necessary to know the probability F(x) for the occurrence of a crack at a single site after the same period.
The initiation procedure cannot be fully separated from the crack growth aspects. As a matter of fact Eq. 1 is only relevant to the prediction of the initiation of a small number of cracks relative to the number of fasteners in the joint, since subsequent crack growth and link-up will invalidate an assessment based on a uniform stress distribution along the width of the joint. However the expression does give an indication of when MSD conditions are possible, and a conservative estimate of the fatigue life of the joint under MSD conditions. The results may be used to provide an estimate of a threshold period for a MSD inspection programme.

*Monte Carlo procedure.* The second approach uses Monte Carlo procedure, which combined the quantified scatter of the fatigue endurance data with a random number generator [6]. A simple computer routine can be used to provide a distribution of fatigue initiation times randomly to the critical sites in a multiple hole joint. If this procedure is repeated many times a statistical view of the occurrence of a predefined crack patterns can be established. This approach can easily include stress variation along the row of holes being considered. Because of the flexibility of the Monte Carlo procedure all the partners subsequently adopted it as the main tool for assessing crack initiation patterns.
The calculation procedure is described in the following:

- Each potential damage site in the structure (generally two per fastener hole) is allocated a different fatigue endurance, drawn randomly from the overall distribution (Log-normal or Weibull) of fatigue lives for the simple coupons.
- The crack growth period is divided into intervals within a timestepping routine, with the following calculation at each discrete timestep:
  - each damage site is checked for the initiation (or otherwise) of a fatigue crack;

- the growth of each initiated fatigue crack is estimated through the techniques of linear elastic fracture mechanics;

- the link-up of adjacent cracks is included within the crack growth calculation;

The calculation stops at some pre-defined condition, *viz.* growth to a given lead crack size or structural failure according to a residual strength criterion;

- These stages form a single 'Monte Carlo' iteration; the calculation is now repeated many times, but with a different fatigue endurance (randomly allocated) at each potential damage site, such that each individual calculation represents a different damage scenario.

A method for modifying initiation time during crack growth is illustrated in the following:

- A calculation of the reduction in fatigue life due to an incremental increase in stress can be made by using the quantitative $S$ - $N$ relationship, $N \propto \sigma^{\beta}$, where $N$ is the number of cycles to failure under an alternating or maximum stress $\sigma$;
- A series of fixed length timesteps, $\delta t$, are used within the calculation. During each timestep the initiation status of each cracking site is assessed. The fatigue life at a specific uncracked site is $N_i$ under a remote stress $\sigma_i$. For the subsequent timestep the remote stress may have effectively increased to $\sigma_{i+1}$ due to crack growth elsewhere in the hole row. Consequently the new fatigue life, $N_{i+1}$ due to the stress increase, can be simply calculated as:

$$N_{i+1} = N_i \left(\frac{\sigma_{i+1}}{\sigma_i}\right)^{\beta}$$

- Using a Miners Law damage summation the crack life of the hole is reached (i.e. crack initiation is achieved) when

$$\sum_{i=1,n} \frac{\delta t}{N_i} = 1$$

- However, this approach is modified if the hole contains one cracked site and one uncracked site. The initiation calculation at the uncracked site must include the local enhancement in stress due to the cracked site. This change manifests itself as a change in $K_t$ the stress concentration factor at the hole edge.

## ASSESSMENT OF APPLICABILITY OF DIFFERENT MODELS

*General description.* Task 5 of SMAAC programme was concerned with experiments on WFD with two main objectives:

- the first objective was to generate data on crack initiation, crack growth and residual strength in such components which can be used to assess and improve the predictive models being developed;
- the second objective was to perform "numerical round-robin tests" calculations and subsequent comparisons.

In order to achieve both objectives it was important to ensure that experiments were carried out on test specimens which accurately simulate aircraft structural locations where WFD is likely to form. It was important to ensure that all the structural areas of interest were simulated by the selected test specimens, and that all the local design features were also investigated. Having defined suitable complementary test specimens, it was important to ensure that suitable test measurements were carried out in order to achieve the first objective. There were three main areas to be studied namely crack initiation, crack growth and residual strength. All three areas were studied experimentally and, where possible, tests were defined such that more than one parameter was studied in an individual test. Anyway, in this work the focus is on crack initiation.

In order to achieve the second objective it was important that test configurations were closely aligned to the capability of the analytical models being developed. The approach selected for validating these models was to compare predictions against data generated experimentally on a

range of test specimens, starting with relatively simple examples, but gradually increasing their complexity. The definition and testing of relatively simple test specimens was followed by testing on more complex specimens, which included stiffened structures and curved test panels.
The most frequent locations of MSD were fuselage lap and butt joints, consequently most interest was focused on this type of joint. It was decided, therefore, to concentrate the model validation exercise on this type of feature (but also joints of the wing structure were considered).
The Round Robin Problems were defined based on test results achieved in Tasks and were arranged in different 'Types' according to the main phenomena treated in the models.

*Basic specimen initiation data.* The statistics of the initiation process can be quantified by testing a large number of simple coupons [7], manufactured to the same standard as used in multiple hole coupon or airframe joint. In particular the simple test specimen data were obtained from coupons based upon the large butt joint design but with only two columns of fasteners (Fig. 1).
The resulting lifetimes can be modelled by an appropriate distribution function (Weibull, log-normal, etc.). It is found, in practice, that the variability in fatigue life is often a function of stress level so testing may need to be performed at a number of stress levels.
In this case a log-normal distribution for the scatter in fatigue life was assumed. The required parameters for generating a probability-time distribution are a mean life and standard deviation appropriate to the stress and material under investigation. The initiation model adopted assume a condition of heteroscedasticity, that is, the standard deviation for crack initiation across all holes was assumed to vary with stress, in order to allow for the decrease in standard deviation resulting from an increase in ligament stress. As a matter of fact the overall stress on uncracked holes will increase as crack growth proceeds from holes where initiation has already occurred; this should lead to a decrease in the scatter associated with the population of remaining initiation lives.
The crack initiation model is based on the P-S-N curves concept. The fatigue life of a joint is determined by scaling the actual stress state to that of a reference joint for which *S-N* curves are available and from which the fatigue life can be obtained. The main assumption behind this method is that a joint of certain geometry has the same fatigue life as the reference joint if the peak stress at the initiation site is the same for both joints. The variability found in the experimental determination of the S-N curves is included by means of a probability distribution called P-S-N curves.
The *S-N* data contains some approximations with regards to the requirements of the multiple hole model. Firstly, the stress concentration within the coupon used to generate the *S-N* data, could be slightly different than in the multiple hole coupon. The initiation time depends upon the local edge stress (i.e. remote stress x stress concentration factor) so that a correction would be necessary before to use the simple specimen data for the multiple hole coupon.
The second approximation arise from the fact that in the basic coupon there are two possible crack initiation sites available per hole. Only one site, in one of the $n$ holes ($2n$ sites) where the initiation was found to occur, has to develop a crack for the specimen to fail (although crack growth at the first site may rapidly induce initiation at the second site on the same hole). Therefore the *S-N* data does not provide the probability for cracking at a single site but instead the probability that at least one crack site out of $2n$ has initiated a crack ($p_{1:2n}$).
For the MSD analysis adopted by the partners of the SMAAC project it is necessary to have the probability of crack initiation at an individual site ($p_s$), consequently the specified fatigue data (Table 1) per basic specimen (Fig. 1), are transferred to fatigue data per site as follows:

$$p_s=1-(1-p_{1:8})^{1/8} \qquad (2)$$

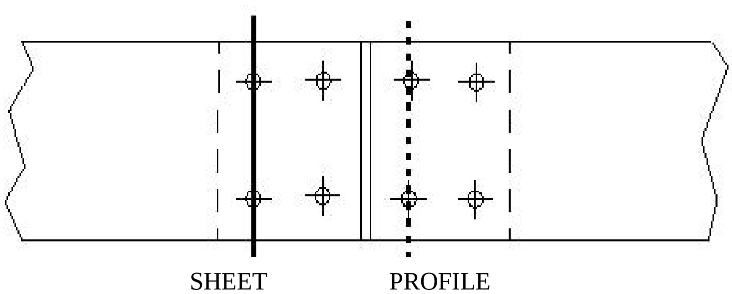
$$\mu_{s,LogT}=\mu_{1:8,LogT}+2.65*s_{1:8,LogT} \qquad (3)$$

In Eqs. 2-3 it has been considered that the failure modes recorded for the two sheets of the basic specimen involve four holes (the highest loaded), or eight sites. The same equation is applied to different percentile values (in Eq. 3 a percentile value of 50% was adopted). A new distribution function is fit to the modified data and a standard deviation is defined for the new function (Table 1). The "data per site" in Table 1 are adopted by all partners for the simulation on the complex joint.

*Experimental programme for a large butt-joint.* The intention of this problem is to demonstrate whether it was possible to predict the initiation of fatigue cracks in a multiple fastener joint using fatigue data obtained from smaller laboratory test coupons. The Round Robin fatigue tests were performed by SAAB on five large asymmetric unstiffened butt joints (Fig. 2), with four rows of rivets (two per sheet) with 2 rivets per column and 24 rivets per row. Two rows of rivets, on each side of the joint, were used to join a 1.27mm thick sheet to a 3.2mm thick splice plate. There are 20 identical fastener holes in each row. In addition, a modified fastener pattern was used at the outer edges of the specimen devised in order to suppress the possibility of early cracking adjacent to the specimen edge. The specimens were tested at 100 MPa gross area stress and the stress ratio R was fixed to R=0.1 (constant amplitude test only). The objectives of the numerical analysis was to predict crack initiation, based on given simple coupon P-S-N data (2 rivets per row). P-S-N data were given for 3 different stress levels (85, 100, 115 MPa) and consisted of the mean and standard deviation, describing the probability content at the stress level. In order to obtain the probability content on another stress level than the 3 specified ones, the mean and standard deviation are interpolated using a power law.
In particular, the requirement of this problem is the determination of the probability of *at least K cracks* and the probability of *at least K adjacent cracks,* within a period T. It was agreed to supply the predictions starting at T=50000 cycles and then at subsequent 5000 cycle intervals. Some experimental results are illustrated in Table 2.

| Stress (MPa) | Mean Data $\mu_{LogT}$ (Log Cycles) | Est. Std. $s_{LogT}$ (Log Cycles) | Mean Data $T_{\mu LogT}$ (Cycles) | Stress (MPa) | Mean Data $\mu_{LogT}$ (Log Cycles) | Est. Std. $s_{LogT}$ (Log Cycles) | Mean Data $T_{\mu LogT}$ (Cycles) |
|---|---|---|---|---|---|---|---|
| 115 | 4.695 | 0.069 | 49600 | 115 | 4.878 | 0.135 | 75510 |
| 100 | 4.987 | 0.072 | 97030 | 100 | 5.177 | 0.138 | 150310 |
| 85 | 5.254 | 0.081 | 179490 | 85 | 5.470 | 0.157 | 295120 |

*Table 1: Fatigue data used by partners- Initiation (-0.22 Hz) - Per Basic Specimen (left) and per site (right)*




number of rows= 2
row pitch= 20 mm
rivet pitch= 24 mm
hole diameter= 4 mm
sheet thickness= 1.27 mm
profile thickness= 3.2 mm
number of rivets per row= 2

*Figure 1: Illustration of the failure modes occurred in basic specimen*

*Test conditions.* One of the main problems was to assess the difference between initiation and failure during the fatigue tests of the basic specimen. The test procedure applied to the simple specimens included a means for determining the presence of cracks before they become visible. This allowed several possibilities for the definition of crack initiation. A criteria based on the natural frequency variation of the coupon as a consequence of crack initiation and propagation was proposed. The frequency variation chosen ($\Delta f=-0.22$) corresponded to a “non visual damage” (Fig.3). The inspection results from destructive testing, strongly indicate that almost each of the highest loaded holes in the sheet, i.e. four per specimen, are damaged after fatigue cycling to applied stop criteria. Of course, the damage size on average is dependent of applied stop criteria.

*Strain measurement indication.* The strain measurements performed demonstrate a non-uniform distribution across the width of the specimen. Each of the tested five specimen have a unique strain distribution. Furthermore, it appears that the fatigue cycling affects the virgin distribution (shake-down effect). The location of strain gauges is illustrated in Fig. 4. Such measured strain data (Fig. 5) were proposed as the basis for analysis to the partners not working with FE-modelling of the specimen.

*Overall methodology and results by each partner.* The partners involved in this Round Robin problem adopted, for their calculations, the criteria illustrated in Table 3. In Figs. 6-7 are illustrated their numerical predictions against experimental evidence.

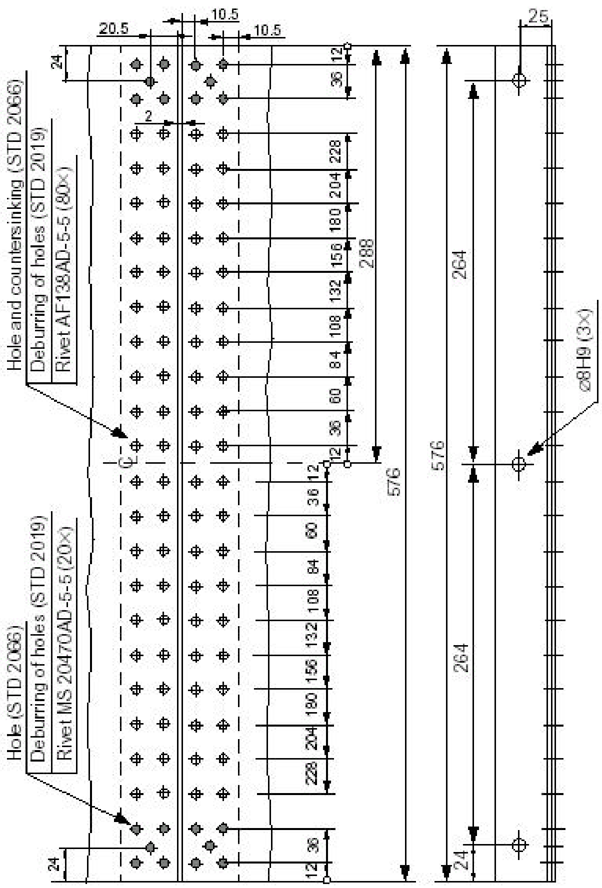



Figure 2: Large asymmetric butt joint

number of rows= 2
row pitch= 20 mm
rivet pitch= 24 mm
hole diameter= 4 mm
sheet thickness= 1.27 mm
profile thickness= 3.2 mm
number of rivets per row= 24

*Material property.*
material type=Al2024 T3
modulus of elasticity=72700 Mpa

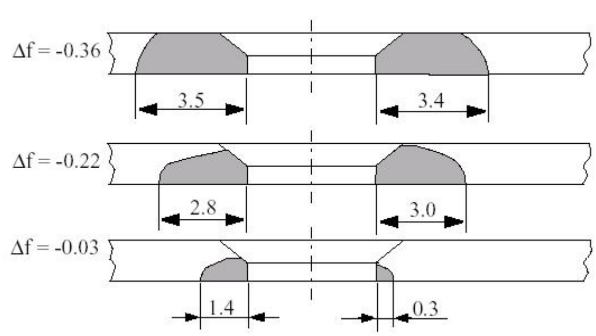



Figure 3: Damage conditions detected at a specified criterion on fatigue initiation.

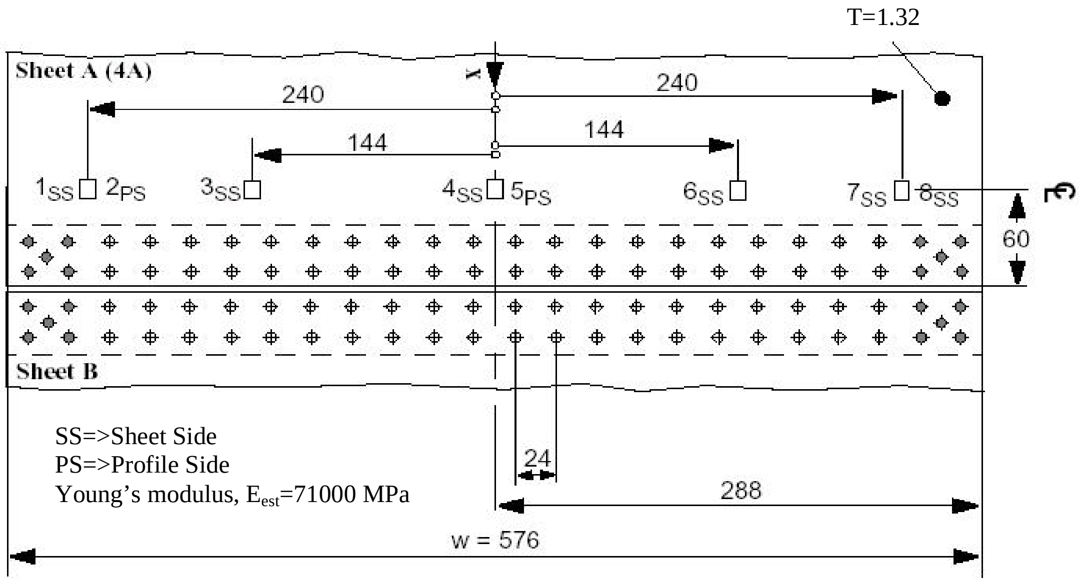



*Figure 4: Illustration of the strain gauge positioning.*

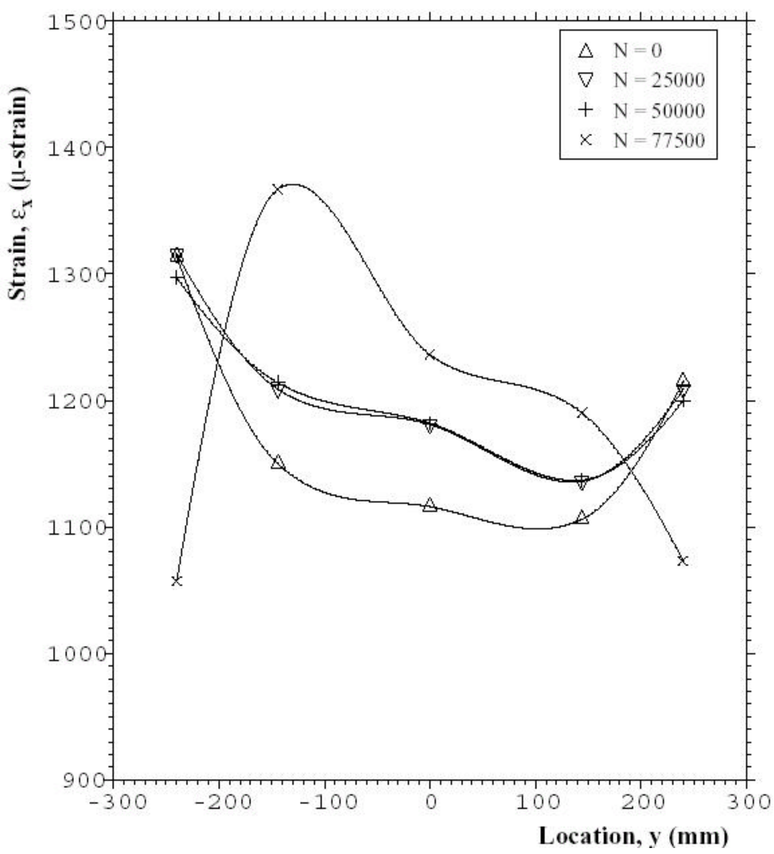



*Figure 5: Strain distribution at different number of cycles for test 5. Note the completely different curve near failure at N = 77500 (caused by extensive crack propagation). Strain values recorded on the sheet side are shown.*

| ID | Sheet | Number of cracks K indicated at the period T (thousands of cycles) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 50’ | 55’ | 60’ | 65’ | 70’ | 72.5’ | 75’ | 77.5’ | 80’ | 82.5’ | 91.4 |
| 1 | 1B | No inspections performed | | | | | | | | | | 5 |
| | 4A | | | | | | | | | | | 20 |
| *2* | 5A | 1 | - | - | - | 26 | >=26 | 28 | 30 | Failure at 78245 cycles | | |
| | 6B | 2 | - | - | - | 23 | >=23 | 28 | 33 | | | |
| *3* | 4B | 5 | >=5 | 19 | 25 | 28 | 33 | Fatigue testing interrupted at 74000 cycles | | | | |
| | 1A | 0 | 0 | 0 | 0 | 0 | 0 | | | | | |
| *4* | 3A | - | 6 | 10 | 11 | 12 | 16 | 18 | Fatigue testing interrupted at 75000 cycles | | | |
| | 3B | - | 2 | 3 | 4 | 6 | 7 | 7 | | | | |
| *5* | 6A | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 3 | 4 | 9 | |
| | 2A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 5 | 9 | |

*Table 2: Fatigue damage pattern “K” versus testing period T for tested specimen*

| Partner | Gross stress (MPa) | Stress Distribution | | Remarks |
|---|---|---|---|---|
| | | T=0 (cycles) | T>0 (cycles) | |
| AS | 100 | FE-analysis | Changed due to crack growth | FE-model to allow for local stress distribution. Without cracks, less than 5% difference compared to test results. |
| Bae | 100 | Obtained from strain measurements | Not changed after crack growth | Constant stress between +/- 150 mm from CL, stress increase linearly with gradient defined by strain measurements. |
| NLR | 100 | Uniform | Changed due to crack growth | Model allow for stress distribution over butt-joint. Secondary bending stress included. |
| AEM | 100 | Uniform | Fixed, however crack growth accounted for | Increased peak stress at the intact site of a hole, to allow for one sided cracked hole. |

*Table 3: Stress level/distribution assumed or calculated by partners involved in the fatigue analysis of the Type I Round Robin Test.*

## CONCLUSIONS

The theoretical basis appears quite sound and alternative approaches are not at all evident. The only doubt concerns the need for the manufacturing route of the specimens to match that of the full structure features on aircraft. However, it is anticipated that the scatter factors applied to test data during normal design procedures will satisfactory meet this concern. Relatively wide panels are needed to produce real MSD scenarios. All the partners predicted curves for crack occurrence to the right of the experimental curve, providing un-conservative initiating lives.
The fact that even the first crack initiation (no crack growth present, no MSD) is predicted wrong by all partners is awkward and can have two causes:

- The given P-S-N data are not sufficiently accurate. The whole crack initiation analysis for the first crack is based on the P-S-N data only and should therefore give similar results as found in the experiment. The P-S-N data are obtained in this case by experiments on small specimens for which the riveting conditions could be different than in large joint.

- Furthermore, for the stress levels 85 and 115 MPa only 3 data points were available to determine the probability distribution, which is an insufficient number for obtaining a reliable probability distribution.
- The difference in analysis results, between the partners models, partly can be addressed by the input data used for the stress distribution across the width of the round robin specimen.
- The importance of using a model taking the crack growth into account is negligible for low values on K, however, when the number of sites K increases the crack growth issue must be considered. This is mainly due to a significant loss in structural area and consequently increased stresses.
- The transferring of fatigue test data, generated on a small coupon with a few equally loaded sites, to fatigue strength per site is theoretical correct. However, it is a critical step and may end up as an un-conservative approach.
- The use of a non-uniform stress distribution across the width, defined by the virgin behaviour of a specimen, may very well be an un-conservative approach, due to the possible *shake down effects* during fatigue cycling. Fatigue testing indicates that the virgin stress distribution may enter a stress distribution "close" to uniform during cycling. Therefore, great care should be taken in establishing the stress distribution. The use of FE-modelling, usually, does not take this *shake down effect* into account. In the design process, a uniform stress distribution always can be justified as a conservative approach.

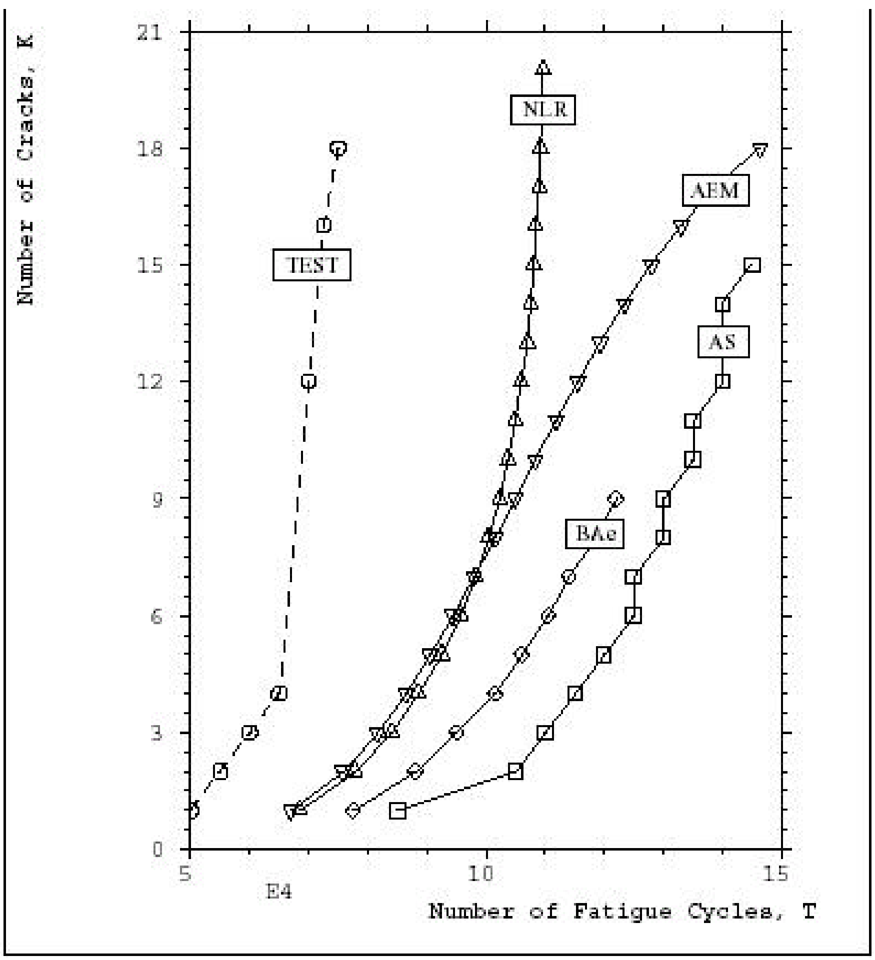



*Figure 6: Comparison of assessed fatigue test results and predictions of the event "At least K cracks to be present within the period T".*

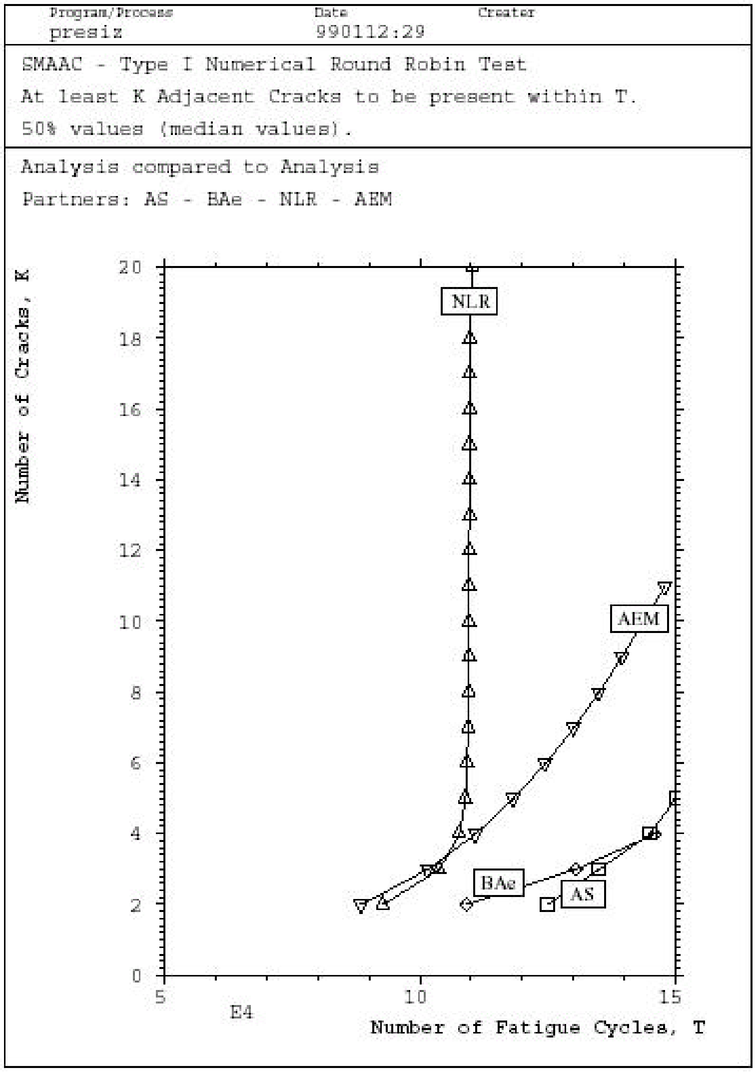



*Figure 7: Predictions made by the partners, of the event "At least K adjacent cracks to be present within the period T", on the condition of used input data.*

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