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A Probabilistic Approach to Fatigue Design of Aerospace Components by Using the Risk Assessment Evaluation

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1. Introduction

Fatigue design of aerospace metallic components is carried out by using two methodologies: damage tolerance and safe-life. At present, regulations mainly recommend the use of the former, which entrusts safety to a suitable inspections plan. Indeed, a crack or a flaw is supposed to have been present in the component since the beginning of its operative life, and it must remain not critical, i.e. it must not cause a catastrophic failure in the life period between two following inspections, (Federal Aviation Administration, 1998; Joint Aviation Authorities, 1994; US Department of Defence, 1998). When a crack is detected, the component is repaired or substituted and the structural integrity is so restored.

If the damage tolerance criterion cannot be applied, the regulations state the safe-life criterion should be used, i.e. components must remain free of crack for their whole operative life and, at their ends, components must be in any case substituted.

Therefore, both methodologies have deterministic bases and a single value (usually the mean value) is associated to each parameter that can influence the fatigue phenomenon, which on the contrary has a deep stochastic behaviour.

To take these items into account and in order to protect against unexpected events, it is necessary to introduce safety factors in the fatigue life design (generally equal to 2 or 3 for damage tolerance and equal to 4 or even more for safe-life). They usually produce heavy or expensive structures and, in the past, they were not always able to protect against catastrophic failures, because the real risk level is in any case unknown. On the one hand, indeed, the inspected structures or the substituted components may be still undamaged, with high costs; on the other hand, highly insidious phenomena, such as Multiple Site Damage and Widespread Fatigue Damage (which are typical of ageing aircrafts) cannot be taken into account very well and in the past they were the causes of some catastrophic accidents.

For these reasons, researchers are hypothesizing the possibility of facing fatigue design in a new way, by using the risk evaluation from a probabilistic point of view. Indeed, the parameters that affect the phenomenon have a statistical behaviour, and this can be described by means of statistical distributions.

In such a way, by using a statistical method, such as the Monte Carlo Method (Besuner, 1987; Hammersley & Handscomb, 1983), all the parameter distributions can be managed and each simulated 'event' can be considered as a possible 'event'. So, the computer simulation of the fatigue life of a big amount of components and the evaluation of the real risk level are possible, making this approach extremely useful.

The Authorities are interested in this approach but, before allowing the use of it as a design criterion, they require impartial evidence, first of all about the reliability of the analytical models used for fatigue simulation and for parameter distribution evaluation.

This paper intends to show a computer code – PISA, Probabilistic Investigation for Safe Aircrafts – and how it can be applied to the fatigue design of typical aerospace components, such as riveted joints, making it possible to integrate damage tolerance and the evaluation of the real risk level connected to the chosen inspection plan, (Cavallini et al., 1997; Cavallini & R. Lazzeri, 2007).

2. The parameters that mainly affect the fatigue phenomenon

A metallic component subjected to repeated loads can fail due to the fatigue phenomenon, (Schijve, 2001). Many research activities on this subject are known from both the theoretical and the experimental points of view and it is well known that fatigue has a random behaviour, with a high number of parameters (mechanical behaviour of the material, loads, geometry, manufacturing technologies, etc.) that can affect it.

Almost all these parameters have a statistical behaviour, but some among them play a more important role compared to the others and must be taken into account with their distributions, while the others can be assumed to be constant.

In detail, we can assume four main parameters as statistically distributed:

- the Initial Fatigue Quality (IFQ), described by using the (Equivalent) Initial Flaw Size, (E)IFS, or the Time To Crack Initiation, TTCI, distribution, (Manning et al., 1987);
- the crack grow rate, CGR (constant C in the Paris law);
- the fracture toughness K_{Ic}, and
- the inspection reliability, i.e. the Probability of crack Detection, PoD.

They are described in the following.

2.1 The Initial Fatigue Quality (IFQ)

Structural components can have, until the end of the manufacturing process, defects due to metallurgical effects, scratches, roughness, inclusions, welding defects, etc.

So, the IFQ can be considered as a property linked to the material and the manufacturing process. Defects can be the starting point for fatigue cracks. For this reason it is extremely important to know their position and size, but, as they are very small, they are very difficult to be measured even if by using very sophisticated inspection methods.

As a consequence, this information can be reached only through an indirect evaluation by means of a 'draw-back' procedure starting from experimental data about detectable cracks.

Therefore, a 'tool' able to characterize the component initial condition is necessary, in order to predict the fatigue life. At present, two approaches are available, Fig. 1:

- the (Equivalent) Initial Flaw Size distribution,
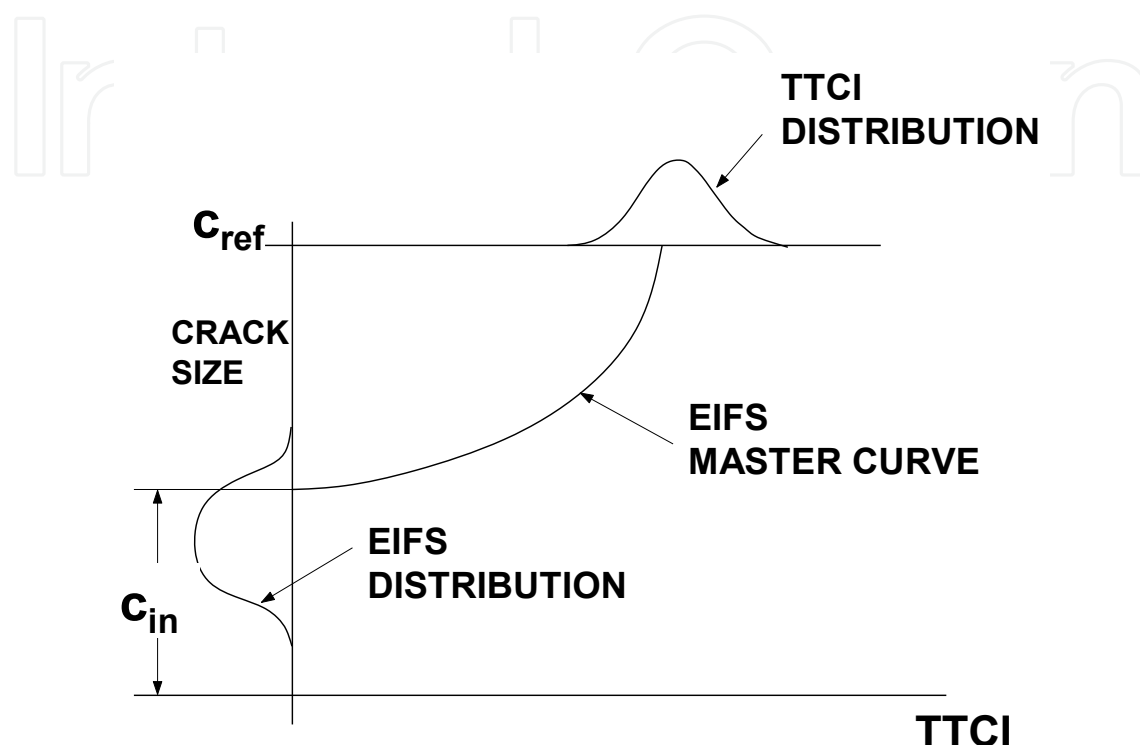- the Time To Crack Initiation distribution.

Fig. 1. TTCI and EIFS distributions.

2.1.1 The Time To Crack Initiation distribution (TTCI)

The TTCI model can be used to describe fatigue crack nucleation in metallic components. It can be defined as the time (in cycles, flights or flight hours) necessary for an initial defect to grow to a detectable reference crack, c_{ref}. In such a way, this method does not reveal the crack dimension during the early steps of the component life. The TTCI can be described by using a Weibull, (Manning et al., 1987), or a lognormal distribution (Liao & Komorowski, 2004). It must be noted that the TTCI distribution is not only a material property, as it is connected to the crack growth, and so to the loading fatigue spectrum.

2.1.2 The (Equivalent) Initial Flaw Size distribution (EIFS)

The EIFS is the (fictitious) dimension of a crack at time t=0. The use of the adjective 'equivalent' indicates that the initial flaw is not the actual one and its size is only 'equivalent' to it because it is very difficult to account for the influence of all the relevant parameters. The distribution can be numerically obtained starting from experimental crack size data by using a 'fictitious' backward integration of the crack growth. It is affected by the material properties and the stress distribution: cold-working, rivet interference, … have to be taken into account, too.

The EIFS can be described by using a lognormal or a Weibull (Manning et al., 1987) distribution. In the present paper, a lognormal distribution is assumed.

2.2 The Crack Growth Rate, CGR (C constant in the Paris law)

Different models are available to describe the crack growth law according to Linear Elastic Fracture Mechanics and the distribution of the involved parameters. We assumed to use the simple and effective Paris law $dc/dN = C(\Delta K)^m$. The parameter m is assumed to be constant and all the scatter is consolidated in C, which is assumed to belong to a normal distribution.

2.3 The Fracture Toughness K_{Ic}

Fracture toughness is a very important material property because it identifies a failure criterion (crack instability). Unfortunately, few experimental data are available to characterize its distribution. Anyway, a normal distribution (Hovey et al., 1991), or a lognormal distribution (Johnson, 1983; Schutz, 1980) can be supposed. We assumed the fracture toughness can be described through a lognormal distribution.

2.4 The Probability of crack Detection (PoD)

Non destructive inspections are among the principal items of the damage tolerance methodology. Indeed, during inspection, it is supposed that cracks are detected and the component can be re-qualified for further use. This action depends on many parameters, included the human factor and so it can be described only by using a probabilistic approach. Usually, (Lincoln, 1998), we define the inspection capability as the 90% probability of crack detection with the 95% of confidence.

Many distributions have been proposed for the Probability of Detection, (Tong, 2001; Ratwani, 1996).

In the present work we assumed a three parameters Weibull distribution, [Lewis et al., 1978]:

$$PoD = 1 - e^{-\left[\frac{c - c_{\min}}{\lambda - c_{\min}}\right]^{\beta}} \tag{1}$$

where, $c_{\min}$ is the minimum detectable crack size, c is the actual crack size and λ and β are parameters connected to the chosen inspection method.

3. The Monte Carlo method

A tool is necessary to manage all the parameter distributions together and at the same time. Some reliable approaches are available - FORM (First Order Reliability Method), SORM (Second Order Reliability Method) and many others (Madsen et al., 1986) – but we decided to use the Monte Carlo method because of its simplicity and effectiveness, as it can handle high numbers of different distributions for the stochastic variables to simulate many different deterministic situations. In addition, the Monte Carlo method easily allows the introduction of the repairs, that is a non-continuous change in the crack size.

The Monte Carlo method is based on a very easy assumption: the probability of an event p_f – in the present paper the component failure – is evaluated by using the analytical expression

$$p_f = n / N \qquad (2)$$

where N is the total simulation number and n is the number of positive results.

Each simulation reproduces only one deterministic event, in which, for each deterministic or random variable a value is assumed; for the stochastic parameters, the value is randomly obtained from its distribution.

After a high number of trials, the method converges to the solution.

The only disadvantage of this method is that it requires a high number of simulations to have a low probability of the event. As an example, if the required probability is 10^{-6}, with a confidence level of 95%, at least (Grooteman, 2002)

$$N_{trials} > \frac{3}{10^{-6}} = 3x10^6 \qquad (3)$$

are necessary.

4. The PISA code and the simulation of the fatigue phenomenon

The PISA code (Cavallini et al., 1997; Cavallini & R. Lazzeri, 2007), developed at the Department of Aerospace Engineering of the University of Pisa, allows the simulation of the whole fatigue life of typical aerospace components, such as simple plane panels, riveted lap-joint panels, Fig. 2, or stiffened panels, subjected to constant amplitude fatigue loading.
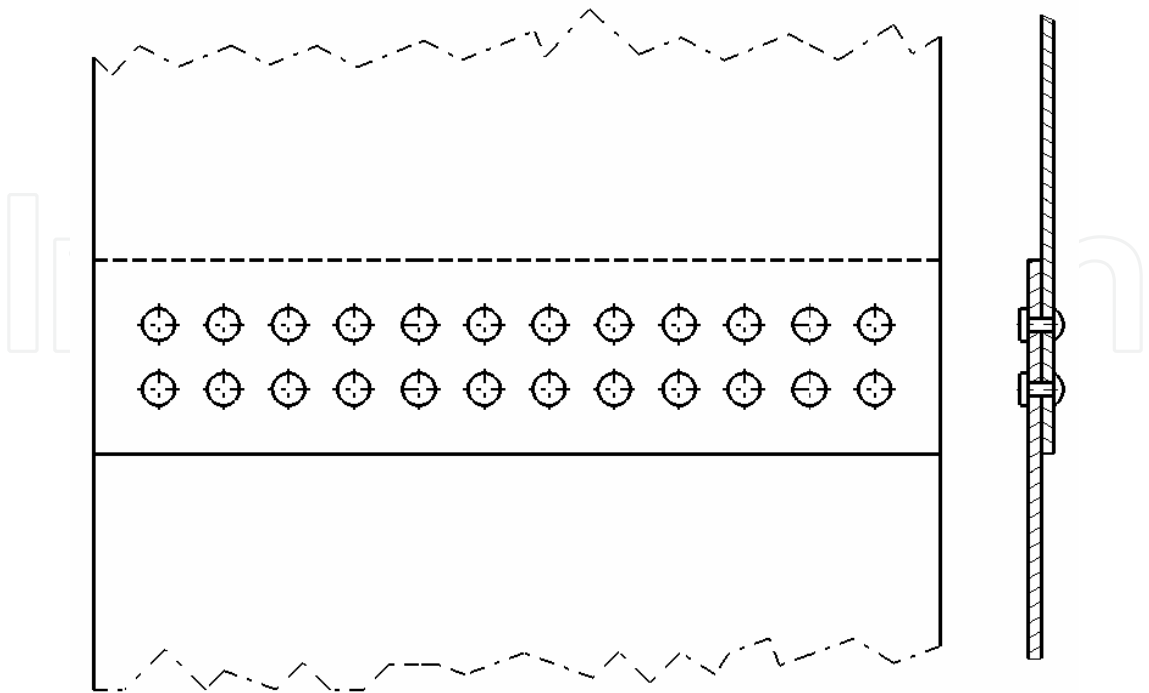

Fig. 2. Riveted lap-joint panel.

As far as the panel is concerned, the following hypotheses can be made:

Geometrical	Plane panel
	Uniform thickness
	Constant rivet pitch
	Rivets with or without countersunk head
	Through cracks
	Cracks on one or both hole sides and orthogonal to the load direction
Physical	Uniform stress
	Plane stress
	Uniform pin load in the same row
	Rivets with extremely high stiffness
	Fretting and corrosion effects are negligible

Table 1. Assumed geometrical and physical hypotheses.

The code can simulate crack nucleation, growth, inspection actions and failures in components subjected to uniform loading. The basic idea is that the damage process can be simulated as the continuous growth of an initial defect due to metallurgical effects and/or the manufacturing process, and/or other parameters.
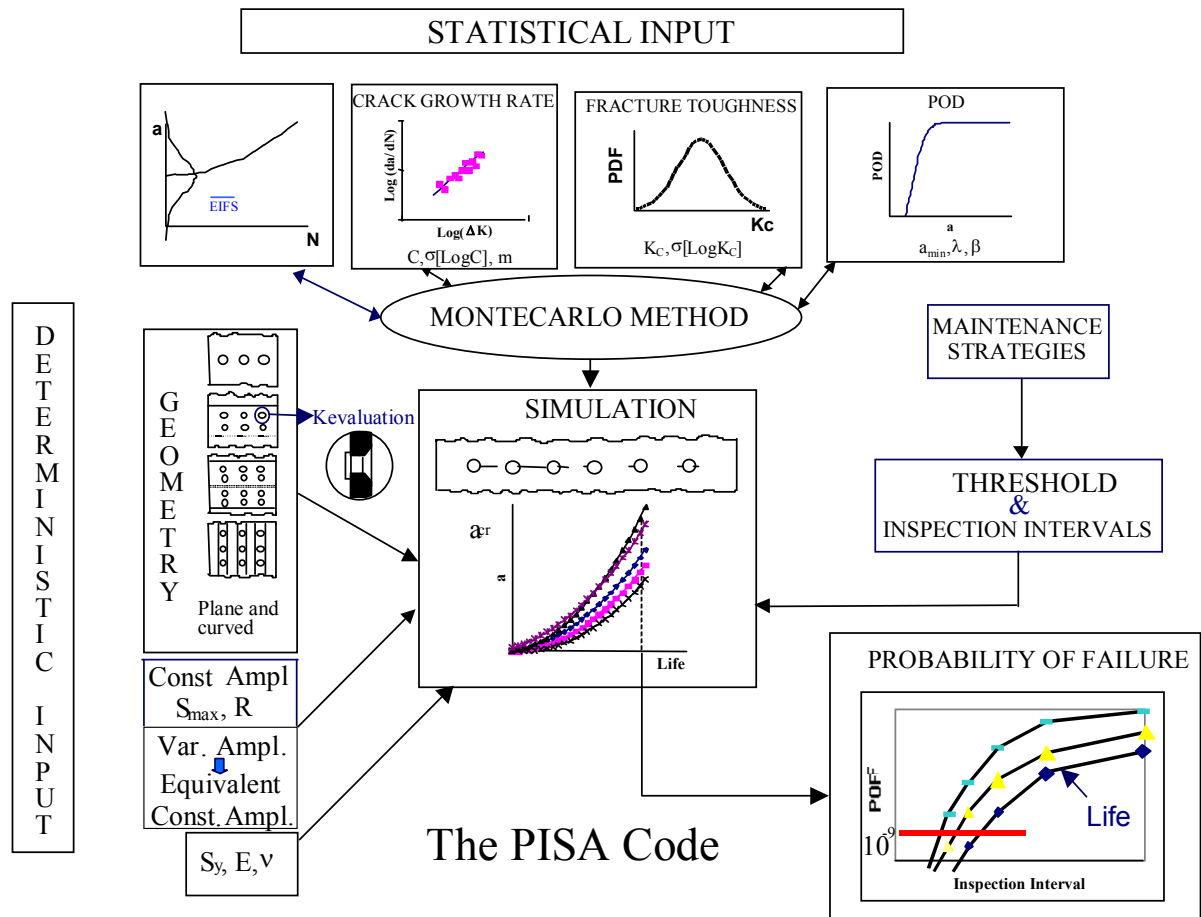
Fig. 3. Structure of the code.

Many deterministic simulations can be run and the risk assessment can be evaluated by using the Monte Carlo method, Fig. 3. In each simulation, the deterministic parameters are assigned by taking off a value from their own distributions.

The first phase – crack nucleation at holes – is simulated by using the EIFS distribution, which can be considered as an indication of the initial fatigue quality. In this context, this approach has to be preferred to the TTCI, as it allows to consider the whole life as the only propagation phase.

The second phase – crack growth – is simulated by using the simple, well-known Paris law $dc/dN=C(\Delta K)^m$

The core for the evaluation of the crack growth is the expression of the stress intensity factor K from the beginning of the life to the final failure.

In the stress intensity factor evaluation, suitable corrective factors (Sampath & Broek, 1991; Kuo et al., 1986) have been used to take into account the different boundary conditions, and the load transfer inside the joints has been simulated by using the Broek & Sampath model, (Sampath & Broek, 1991).

In detail, the effect of different boundary conditions can be taken into account by using the composition approach (Kuo et al., 1986).

K is analytically evaluated by means of a corrective coefficient which has been found by splitting the complex geometry into simple problems (open hole, finite width, …), whose solutions are known.

With regard to the open hole

$$K = K^R \cdot CR_1 \cdot CR_2 \cdot CR_n \tag{4}$$

$$K^R = S\sqrt{\pi(c-r)} \tag{5}$$

where S is the uniform membrane stress and (c-r) the crack length, Fig. 4.
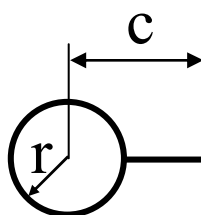

Fig. 4. Crack at an open hole.

As to the rivet effect, the load P on the hole has been approximated with a uniform pressure p on the hole, (Kuo et al., 1986), Fig. 5.

$$P = t \cdot \int_0^\pi p \cdot sen\theta \cdot r \cdot d\theta = t \cdot p \cdot r \cdot \int_0^\pi sen\theta \cdot d\theta = 2 \cdot p \cdot r \cdot t \tag{6}$$

$$p = \frac{P}{2 \cdot r \cdot t} \tag{7}$$
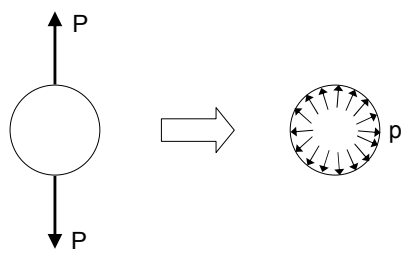

Fig. 5. Approximation of the P load with a uniform pressure p.

$$K = K^P \cdot CP_1 \cdot CP_2 \cdots CP_n \tag{8}$$

$$K^P = p\sqrt{\pi\ c} \tag{9}$$

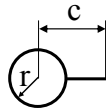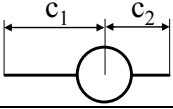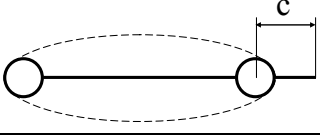The main corrective factors for open holes and for filled holes taken into account are summarized in Table 2.
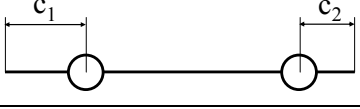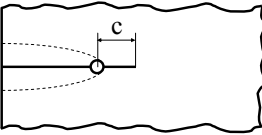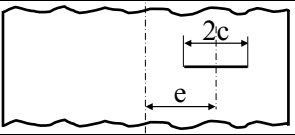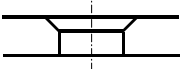
Crack at a hole (Kuo et al., 1986),	
Two cracks at a hole (Kuo et al., 1986),	
Link-up, with one crack (Kuo et al., 1986),	
Link-up, with two cracks (Kuo et al., 1986),	
Edge crack (Kuo et al., 1986),	
Panel finite width (Kuo et al., 1986),	
Countersink (Kuo et al., 1986),	
Secondary bending, (Sampath & Broek, 1991)	

Table 2. The main corrective factors for open holes and for filled holes taken into account in the PISA code.

The Broek & Sampath model joins the solutions related to the open hole and the loaded hole by using the superposition approach, Fig. 6.
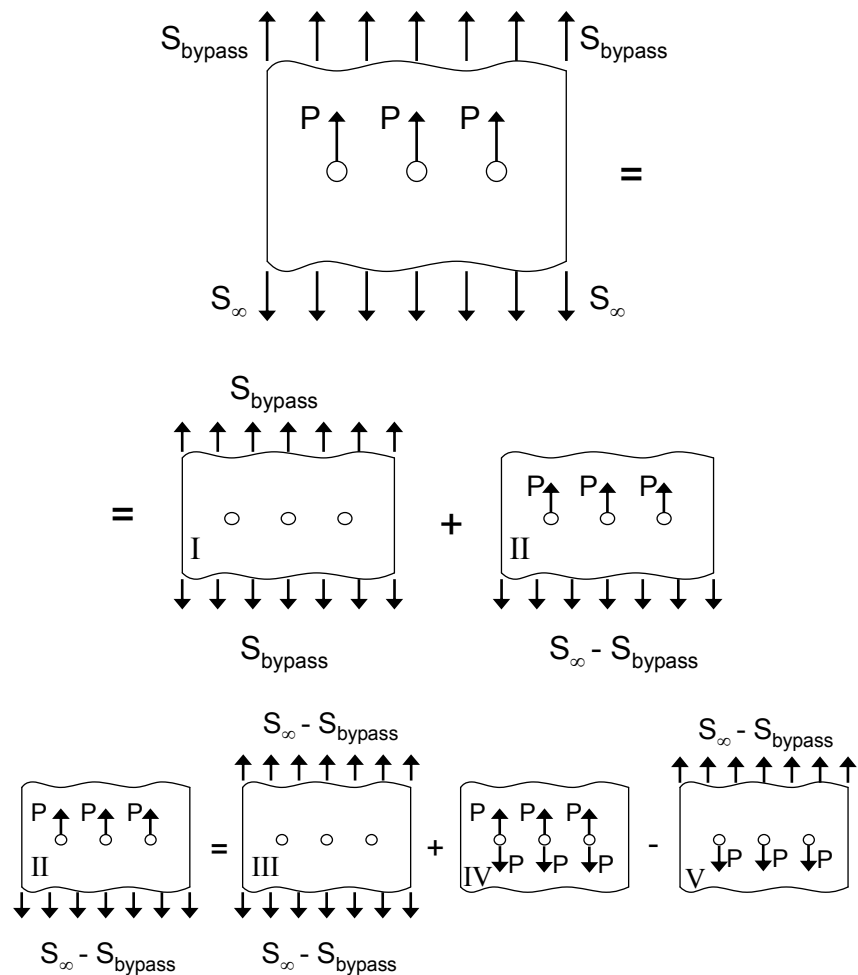
$$K = K_I + K_{II} = K_I + \tfrac{1}{2}(K_{III} + K_{IV})$$

Fig. 6. The Broek & Sampath model.

$$K = \frac{1}{2} \cdot CR \cdot \left(S_\infty + S_{bypass}\right) \cdot \sqrt{\pi \cdot c} + \frac{1}{2} \cdot CP \cdot p \cdot \sqrt{\pi \cdot c} \qquad (10)$$

S_∞ is the membrane uniform stress and S_{bypass} is the bypass stress, i.e. for each row, the stress not transferred by the rivets.

Also rivet interference introduces an additional stress distribution. Its main effect is that only a part of the applied load amplitude $S_{max}-S_{min}$ is effective for crack propagation. This effect can be taken into account by using the Wang model (Wang, 1988) for the evaluation of the lift-off stress S_o, corresponding to the separation of the rivet from the hole, and then by introducing in the simulations carried out with the PISA code only the effective amplitude $S_{max}-S_o$ for crack propagation.

Once the stress intensity factor is calculated, crack growth simulation can start.

Two collinear cracks are considered as linked according to the Swift criterion, i.e. when their plastic radii r_p - evaluated by using the Irving expression - are tangential.

Inspections at planned intervals are simulated through the PoD distribution, applied at each crack at both hole sides. Though the repair of the hole has the same quality as the pristine panel, the repair itself of the detected crack is not immune from the possibility of having some tiny cracks.

The final failure can happen either for crack instability (K_max higher than the fracture toughness, $K_\mathrm{max} \geq K_\mathrm{Ic}$) or for static failure (S_max higher than the yield stress in the net section evaluated without the plastic zones, $S_\mathrm{max} \geq S_{02}$)

5. Experimental activity as a support for the evaluation of the statistical distributions

To support this activity, all the parameter statistical distributions and the coefficients for the used analytical law (for example, the EIFS distribution, C and m coefficients for the Paris law, etc.) have to be experimentally evaluated. Of course, they cannot be obtained from tests on real components, but we have tested realistic simple specimens and we have demonstrated the applicability of the obtained results to the life evaluation of the actual components.

In this paper the activity carried out to find the distributions of the EIFS and the C constant in Paris law are shown. A similar approach can be used for the definition of the distributions for K_Ic and PoD.

5.1 Equivalent Initial Flaw Size distribution evaluation

For the evaluation of the EIFS distribution it was necessary to use a 'fictitious' negative integration (draw-back) which, starting from the experimental crack data at assigned number of cycles, would be able to find the 'equivalent' initial size, i.e. the crack size at $N=0$.

To support this approach, a wide experimental activity was performed on 29 simple strip lap-joints, Fig. 7, in aluminum alloy 2024-T3 (Cavallini & R. Lazzeri, 2007). They were fatigue tested under a constant amplitude load spectrum with S_max=120 MPa and R=0.1. The tests were stopped at a set number of cycles, the specimens were statically broken and the crack dimensions were carefully measured. The tests confirmed an already well known result: all the cracks were found in the most critical location, i.e. in the first row, at the countersunk side.

At present, several numerical codes are available to simulate the growth of a single crack in the long crack range, but few can manage also the short crack range and none is able to carry out a direct negative integration that starting from the experimental crack data can find the initial dimension. For this reason, we decided to use the PISA code itself and the simplified model of a specimen with a through crack at a lap-joint, taking into account the effects of countersink of the hole, membrane stress, by-pass loading and pin load, Fig. 8, (Cavallini & R. Lazzeri, 2007).
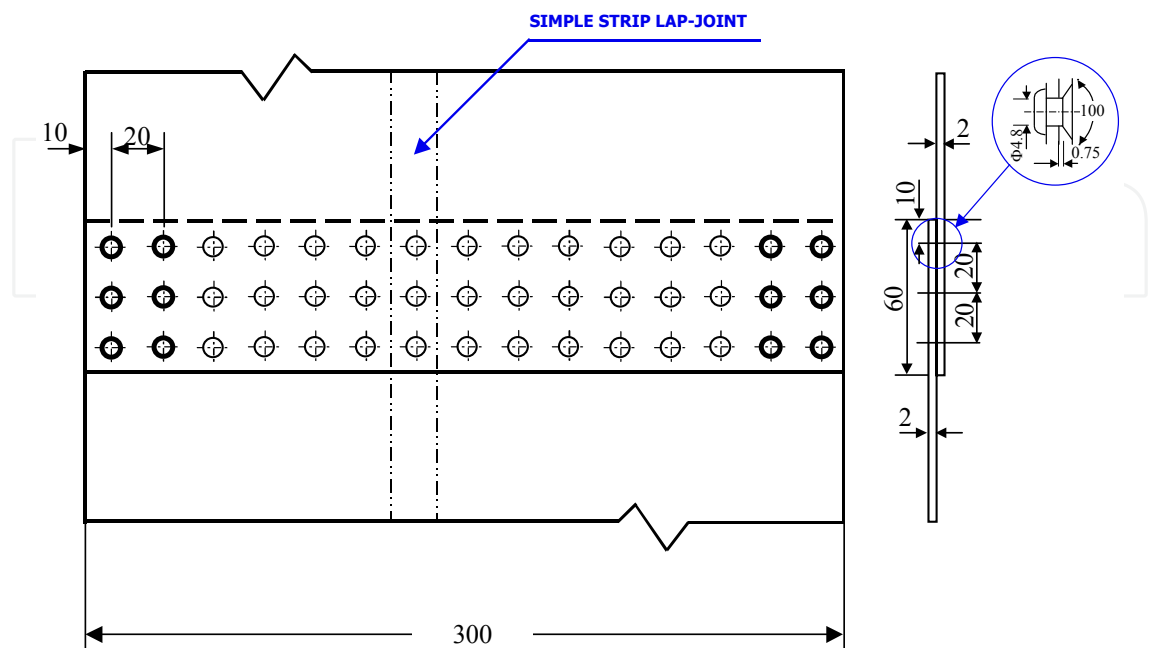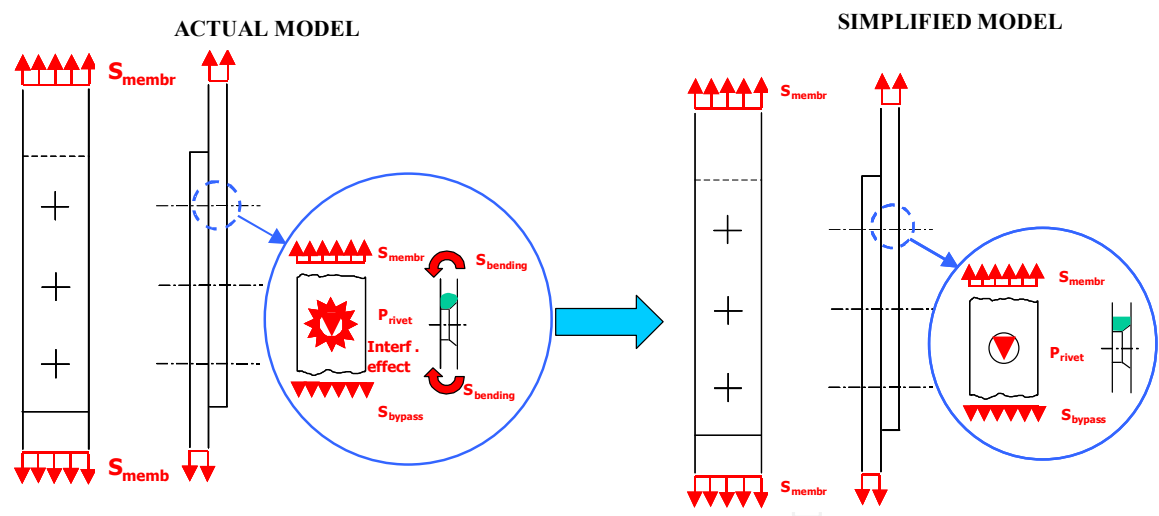
Fig. 7. Specimen geometry, all lengths in mm.

Fig. 8. Simplified model implemented inside the PISA code in order to evaluate the EIFS distribution.

In addition, an iterative positive integration was carried out starting from an initial tentative crack size value and stopping at the same number of cycles of the experimental result. The simulated final crack dimension was compared with the experimental one, and an iterative process was carried out to the required convergence.

In this way, a lognormal distribution for the EIFS was found, with $\mu[\text{Log}_{10}(c_0)]$=-2.88605, and $\sigma[\text{Log}_{10}(c_0)]$=0.28456, Fig. 9.
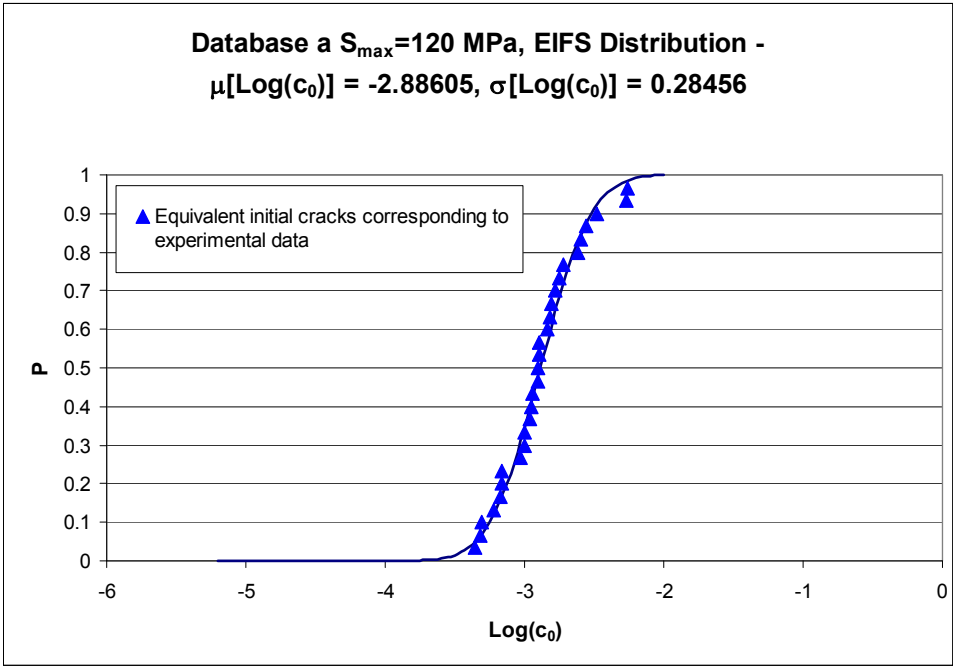
Fig. 9. EIFS distribution obtained by using the draw-back procedure.

5.2 The Crack Growth Rate (CGR) (C constant in the Paris law)

The crack growth law must be experimentally characterized, in order to evaluate the parameters involved in the selected crack growth law (Paris).

For their evaluation, a test campaign on a 2.1 mm thick Center Crack Tension (CCT) specimen with an open hole (4 mm in diameter) in aluminium alloy 2024-T3 was carried out (Imparato & Santini, 1997), Fig. 10.
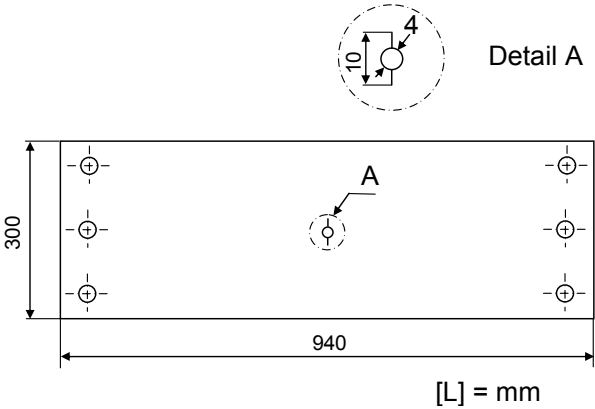

Fig. 10. CCT specimen in Al 2024-T3.

They were pre-cracked and the further crack propagation in the 5 to 40 mm range was investigated by using the Potential Drop Technique.

Tests were carried out under a constant amplitude (C.A.) spectrum, at the same S_{max}=68.7 MPa, with 4 different $R=S_{min}/S_{max}$ values (R=0.1, R=0.25, R=0.4, R=0.55). In Fig. 11 the experimental results for one test are shown.
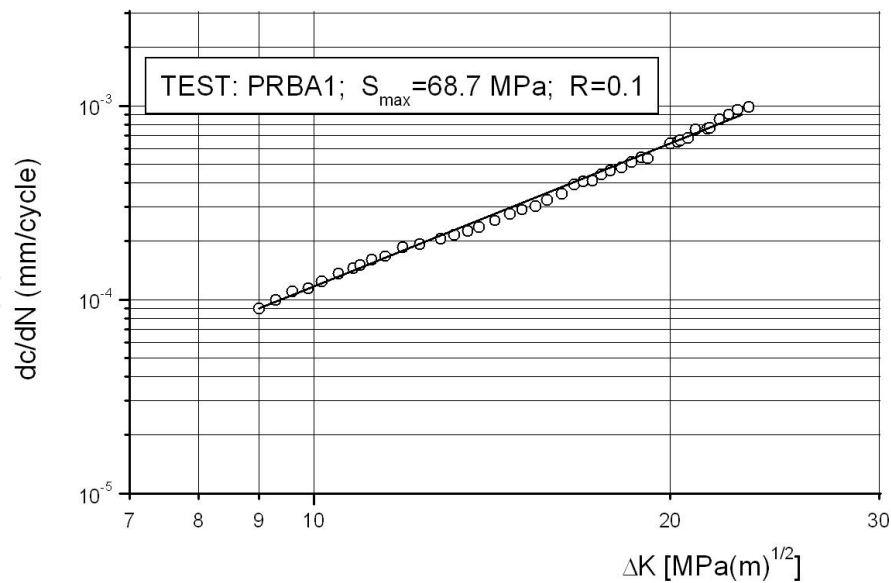
Fig. 11. Result for one CCT coupon test.

The test results were elaborated splitted for the different R values. For the characterization of the linear portion of the curve, we assumed *m* as a deterministic parameter (equal for each test, Fig. 12), and we considered only *C* as normal distributed.

In such a way, for *R*=0.1, we found that *m*=2.555 and *C* is normal distributed with $\mu[(C)]=2.8834 \times 10^{-7}$, and $\sigma[(C)]=0.036792$.
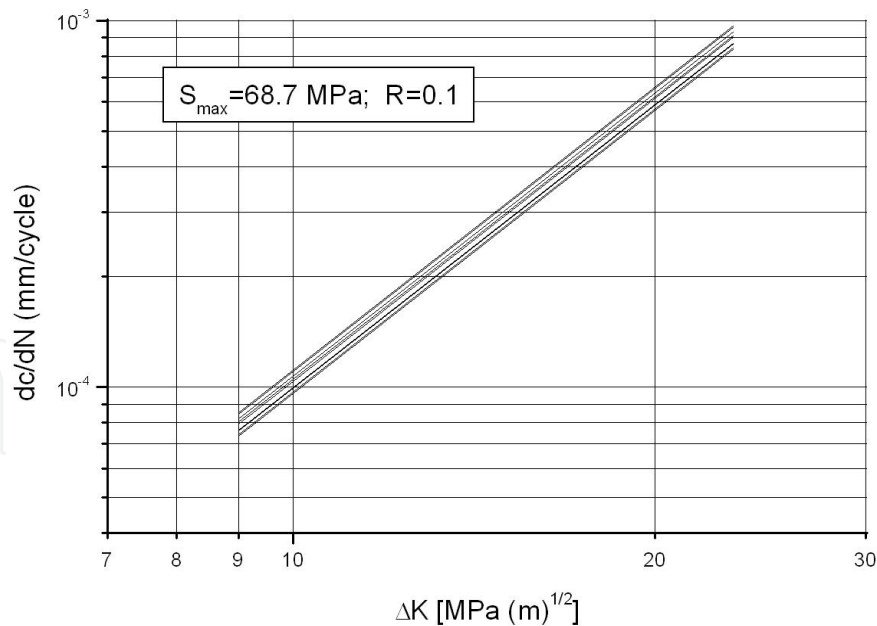

Fig. 12. Elaboration of the results for the tests at the same *R* value.

5.3 The validation of the analytical models implemented inside the PISA code

To validate the approach and to verify the capability of the PISA code to simulate the fatigue behavior of aerospace structural components, further experimental tests were carried out on

wide lap-joint panels, in the same aluminum alloy as the simple strips, Fig. 7, loaded under a constant amplitude spectrum (S_{max} = 120 MPa, R=0.1).

A group of panels was fatigue tested for an assigned number of cycles (1 at 70,000 cycles, 4 at 75,000 cycles, 4 at 80,000 cycles, 3 at 85,000 cycles) and then statically broken to measure the sizes of the nucleated cracks. Also, in these panels the cracks were found only in the most critical row, i.e. the first one, at the countersunk side.

After having statically broken the tested panels, it was not possible, at all the hole sides, to detect a crack and they were considered as run-outs. The run-out effect has been introduced inside the crack size distribution by using the maximum likelihood method (Spindel & Haibach, 1979). Their crack dimensions have been supposed less than 0.1 mm. We supposed that the crack sizes (both with and without the run-outs) belong to two lognormal distributions.
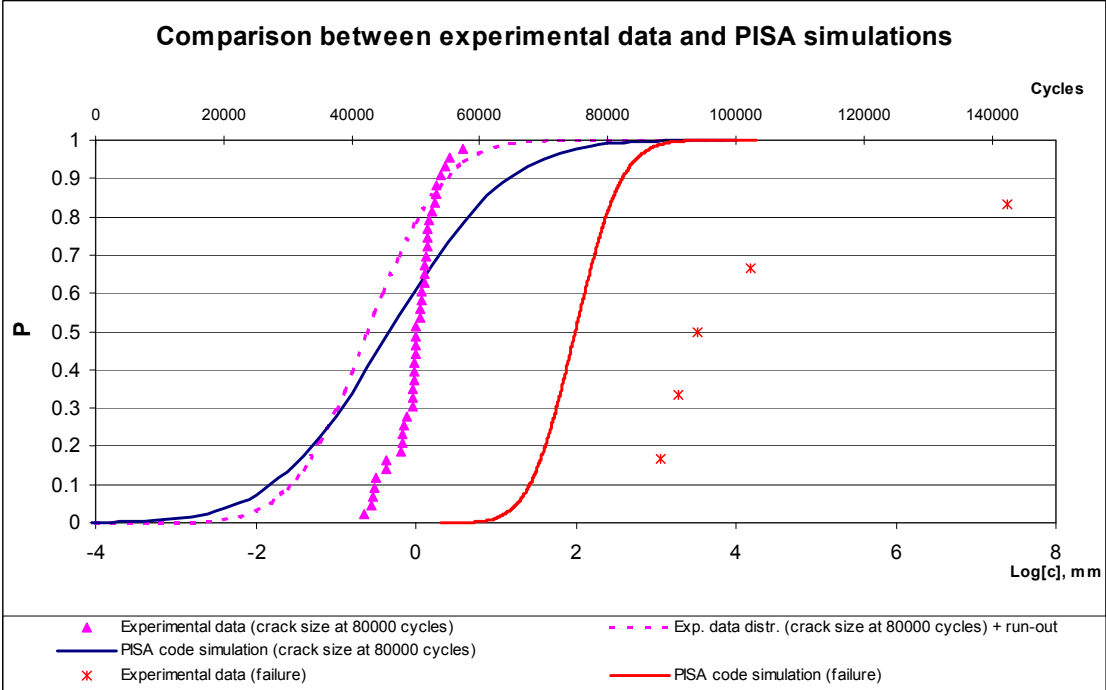

Fig. 13. Comparison between experimental data and PISA simulations (crack dimensions at 80,000 cycles and cycles to failure for the lap-joint panels).

Starting from the EIFS distribution obtained by the simple strip joints and by using the PISA code, the capability of the procedure has been verified by simulating the behavior of the cracks in the most critical row of the lap-joint panels.

The comparison has been made by generating 1000 runs, i.e. by simulating the crack sizes at different number of cycles in the most critical row of 1000 lap-joint panels similar to the tested lap-joint panels (i.e. 15 holes x 2 sides = 30 positions for each panel). In Figure 13 (Cavallini & R. Lazzeri, 2007) the comparison is shown between the predicted crack dimensions and the corresponding experimental results at 80,000 cycles.

The agreement between predictions and experimental results can be seen; in detail, the predicted distribution obtained by using PISA is included between the experimental data distribution with and without the run-outs, Fig. 13.

In addition, 5 further lap-joint panels were fatigue tested till failure. In Fig. 13 the comparison between PISA simulations and the experimental results is also shown. The agreement is good, though the simulation results are a little conservative.

6. Applications of the PISA code

The Pisa code is organized in such a way that all the information about geometry, material characterization, loads, inspection methods, failure criteria are collected in an input file.

The code can be used for the evaluation of the fatigue behaviour of only one component, starting from an initial known crack path, or for the generation of high numbers of deterministic simulations for the probabilistic approach.

6.1 The simulation of a single panel

In Fig. 14, the fatigue behaviour of a very simple panel, with only four open holes (diameter=4 mm), in Al 2024-T3, loaded under a constant amplitude load with S_{max}=100 MPa and R=0.1, is simulated. The initial crack path is extracted from the EIFS distribution, but it would be assigned also as an external input. The assigned life was 100,000 cycles. Inspections were planned every 25,000 cycles. For the probability of detection parameters, we assumed c_{min}=0.65 mm, λ=1.62 mm, β=1.35, (extrapolated from Ratwani, 1996).
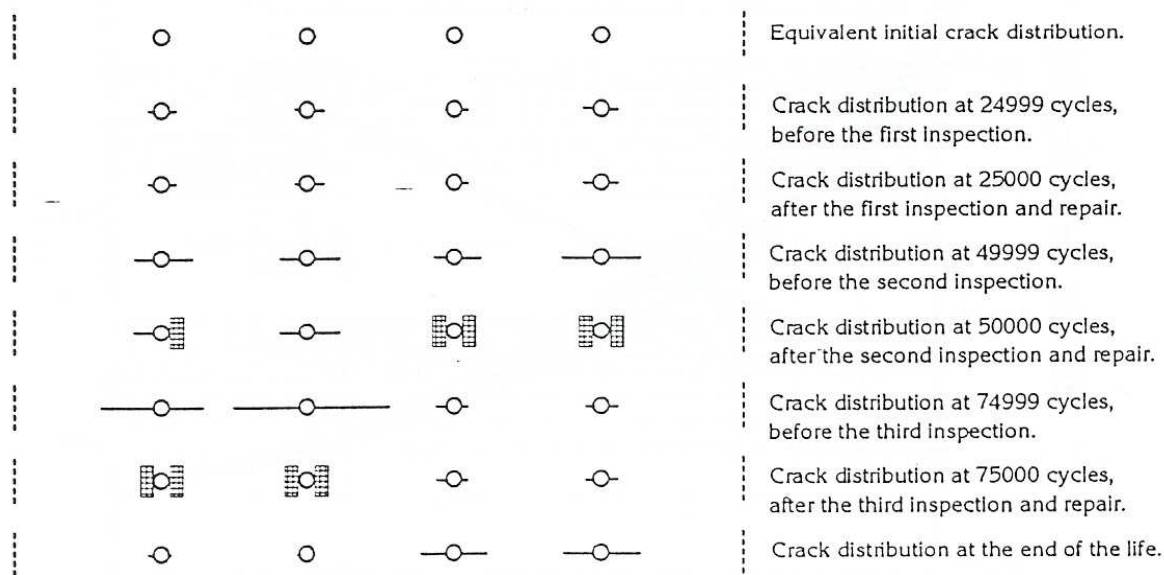

Fig. 14. Simulation of the fatigue life of an open hole panel (damage tolerance criterion).

As it can be seen in the Figure, during the first inspection (at 25,000 cycles) cracks were too small and were not detected. They grew till the second inspection (at 50,000 cycles), when

five cracks were detected and the panel repaired. The simulation went on till the following inspection, when four more cracks were detected and repaired. With this inspection plan the panel could reach the target life.

6.2 Applications of the PISA code for the probabilistic risk evaluation

Before applying the Pisa code for the evaluation of the probability of failure of an aerospace component, an acceptable risk level must be identified. Indeed, one among the most debated items connected with the application of this methodology is the definition of the 'acceptable' risk level. Usually, 'risk' defines the probability of failure of some components within an assigned period.

Lincoln (Lincoln, 1998), says that for the USAF an acceptable global risk failure is 10^{-7} for flight, even if other authors suggest a safer $r(t) \le 10^{-9}$ per hour (Lundberg, 1959).

We fixed $r(t) \le 10^{-7}$. To reach a 10^{-7} probability of failure, at least $3 \times 10^{+7}$ simulations must be run.

Starting from a lap-joint in Al 2024-T3, Fig. 7, loaded at C.A. with S_{max}=120 MPa, R=0.1, our aims were the definition of a 'safe' maintenance plan, the comparison of the effects of the deterministic (safe-life and damage tolerance) and the probabilistic approaches, and the evaluation of their respective advantages and disadvantages, (Cavallini & R. Lazzeri, 2007).

We assumed the following distributions for the stochastic parameters:

- The EIFS fits a lognormal distribution, with $\mu[Log_{10}(c_0)]$=-2.88605, and $\sigma[Log_{10}(c_0)]$=0.28456, $[c_0]$ in mm.
- The C parameter in the Paris law is normal distributed, with $\mu[(C)]$=2.8834x10^{-7}, and $\sigma[(C)]$=0.036792. The corresponding m value is m=2.555.
- The fracture toughness K_{Ic} fits a lognormal distribution, with $\mu[Log_{10}(K_{Ic})]$=1.65 (Koolloons, 2002), and COV= $\sigma[Log_{10}(K_{Ic})]/ \mu[Log_{10}(K_{Ic})]$=0.14, $[K_{Ic}]$=MPa$(m)^{0.5}$ (Schutz, 1980),
- The probability of detection is expressed as (1), with c_{min}=0.65 mm, λ=1.62 mm, β=1.35, (extrapolated from Ratwani, 1996).

At first, we simulated the fatigue behaviour of $3 \times 10^{+7}$ lap-joint panels without any inspection actions. The number of cycles with probability of failure equal to 10^{-7} is 51,000 cycles, Fig. 15. So, this number of cycles can be fixed for the first inspection (threshold).

The second run was made after having fixed, for each panel, the first inspection at 51,000 cycles. In such a way, we obtained the new probability of failure curve and it was possible to fix the second inspection at 63,000 cycles, that is (63,000 - 51,000) = 12,000 cycles after the first one.

In Fig. 15 the probability of failures corresponding to the different deterministic approaches are also shown.

The safe life criterion requires the component replacement after a portion (as for example ¼) of its mean life. The mean life (probability of failure equal to 50%) corresponds to 74,550 cycles that, divided by four, gives 18,638 cycles. So, for the safe life criterion, after 18,638

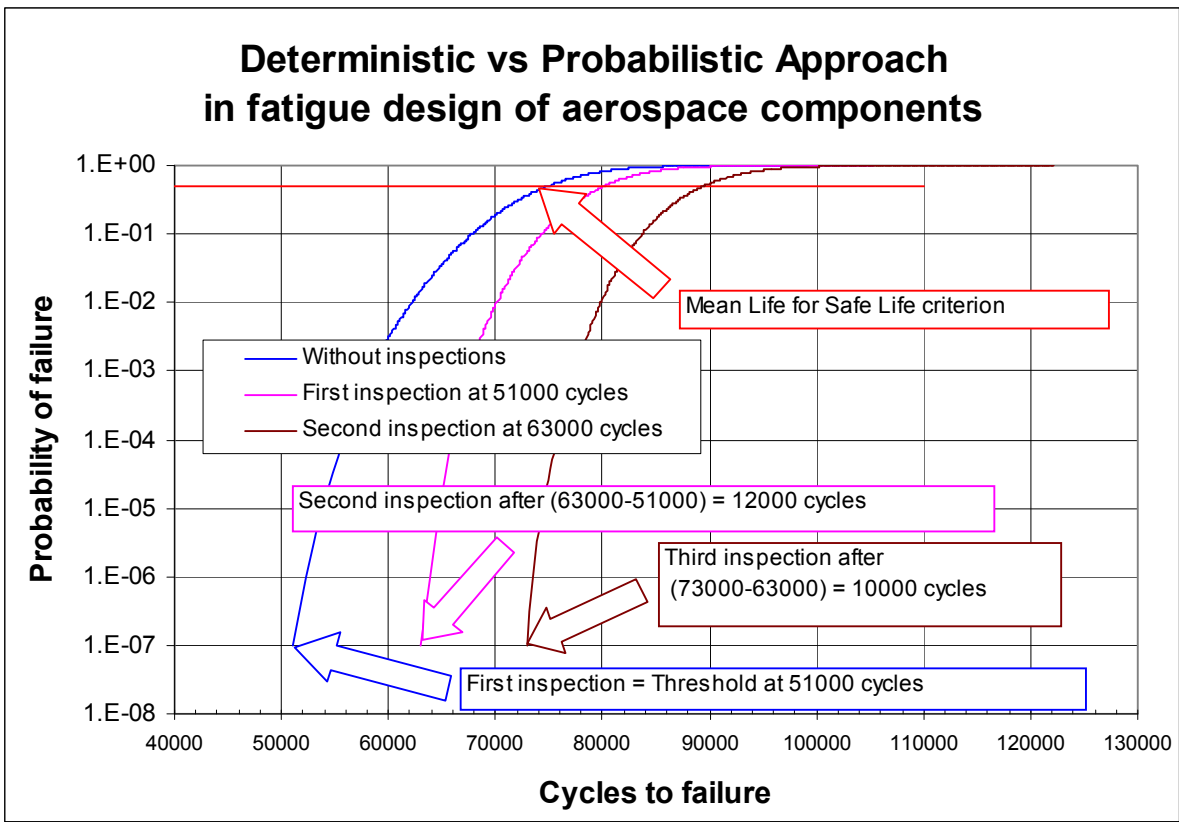cycles the component should be substituted, without any consideration about its real damage condition.

Fig. 15. Example of PISA simulation and maintenance strategy for a lap-joint panel.

The probability of failure at 18,638 cycles is extremely low, so the component could still be used without any loss in safety. In this situation, the component replacement only introduces costs.

As far as the damage tolerance criterion is concerned, the first inspection (threshold) is fixed by evaluating the number of cycles necessary for a crack of assigned dimension (regulations state a 1.27 mm size) to grow till the final failure. The inspections cited below are planned considering the propagation period of a sure visible crack (depending on the selected inspection method, in this case 6.35 mm) till the final failure. A safety factor equal to 2 at the threshold and 3 at the following period are additionally applied.

For this component, by analytical calculation or by using the PISA code itself, it can be found that the period necessary for a crack to grow from 1.27 mm to the final failure is equal to 57,700 cycles, and from 6.35 mm to the final failure is equal to 31,100 cycles.

Therefore, the first inspection will be carried out at 57,700/2=28,850 cycles and the next one after 31,100/3 = 10,367 cycles.

As it can be seen in Fig 15, the corresponding probability of failures is very low, and so the inspection plan, based on the deterministic damage tolerance approach, might be very expensive.

7. Conclusion

In this Chapter, a new possible and useful approach to fatigue design of aerospace metallic components is explained, founded on probabilistic bases, together with a tool – the PISA code - and the experimental test results used for the validation of the tool, and of the approach.

The validation analysis provided good results and therefore the PISA code can be used for the risk assessment analysis and to compare the effect of the deterministic approaches (damage tolerance and safe-life) with those of the probabilistic approach in the fatigue design of a wide lap-joint panel.

The advantages appeared to be very significant:

- the probability of failure can be defined as a design constraint (or goal), for instance 10^{-7}; so the risk level is well defined. In deterministic approaches, this important element is not known and the assumption of conservative values of the inputs can produce uneconomical designs without benefits;
- in each design condition, it is possible to know the "distance" from the critical condition in terms of probability of failure;
- the Multiple Site Damage event can be handled in a logical way because it is one of the possible statistical events. The same problem, faced on deterministic bases, could bring to heavy and/or very expensive solutions;
- components are inspected or withdrawn and substituted only if really necessary, thus avoiding too early inspections or the substitution of intact components.

The comparison between the different approaches, applied to a lap joint panel, shows that a more economic inspection plan can be applied if the probabilistic approach is used, without loss of safety.

Of course, this new methodology can be safely applied only if reliable models for the crack growth are available, and the parameter distributions have been carefully obtained.

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