SOME PRACTICAL APPLICATIONS OF THE EIFS (EQUIVALENT INITIAL FLAW SIZE) CONCEPT

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Abstract. *This work presents a methodology for crack propagation analysis which is based on the distribution of the initial flaw size a_0. Departing from fatigue test results for specific structural components, an estimation of the initial flaw distribution is obtained, and from this distribution it becomes possible to establish the appropriate initial flaw size for crack propagation analysis for the chosen statistical distribution, such as Weibull or Log-normal. The methodology allows to apply different values of a_0 for different components or structural details, reflecting the quality of the manufacturing process for the item evaluated. Two examples of practical applications of the EIFS concept are presented, corresponding to lugs and shear joints usually used for aerospace applications.*

Keywords*: EIFS, fatigue, damage tolerance, Weibull distribution, Log-normal distribution*

1. INTRODUCTION

The crack propagation analysis is an essential part of metallic aircraft design, in the scope of fatigue and damage tolerance. Based on supplied material properties, geometry characteristics and loading spectra, a large number of analyses are performed in order to assure that for every aircraft detail the crack growth intervals will be appropriately inserted into inspection intervals, as part of the aircraft maintenance plan.

One key parameter for a crack propagation analysis is the initial flaw size a_0. The reason for its importance seems quite apparent, once the majority of the crack propagation time will occur while the crack is smaller than a few millimeters. This parameter depends on the structural category of the crack scenario that is being evaluated, and for a certain structural category it will depend on the manufacturing quality.

Initially, the United States Air Force (USAF) proposed, by means of the MIL-E-83444 Rule (1974), deterministic values for the initial flaw size, which are basically 1.27 mm (the so-called "rogue flaw") for single load path structures and primary cracks in multiple load path structures, and 0.127 mm (the so-called "manufacturing quality flaw") for secondary cracks in multiple load path structures. Despite the fact that this rule has been later discontinued, most of the aircraft manufactures still rely on these values that have been so far extensively used for damage tolerance analyses of commercial as well as military aircraft.

Later, the USAF proposed non-deterministic approaches in order to obtain more appropriate values of the initial flaw size (USAF DTD-HDBK, 2006), which depends not only on the manufacturing quality, but also on characteristics of the structural detail itself. One of these approaches is based on the concept of EIFS, the "Equivalent Initial Flaw Size".

In the present work, the fundamentals of the EIFS methodology are presented. Departing from *S-N* curves corresponding to two specific aircraft components, lugs and fastened shear joints, two different statistical distributions (Log-normal and Weibull) are applied into these curves and a retro-analysis in terms of crack propagation is performed in order to obtain the EIFS distribution for each of these components. A discussion is presented on various ways that the EIFS concept could be applied as a function of the load spectra or material variability.

Further, the actual results of these two examples are compared to the deterministic approachs, which rely on the a_0 values previously outlined, and as a result the possibility to introduce a more realistic approach, relying on EIFS distributions, which is based on component characteristics and actual manufacturing quality, will be proposed in this work.

2. BACKGROUND

2.1. Outline of the EIFS methodology

The concept of Equivalent Initial Flaw Size (EIFS) was introduced after the works of Rudd and Gray (1977). The motivation for such approach was the conclusion that the application of NDT methods for obtaining statistical distributions of flaw sizes was a time consuming and sometimes non-reliable approach. On the other hand, fatigue cracks obtained in laboratory coupon tests could also be used for determination of EIFS distributions in actual structures (Provan, 1987).

Most of the probabilistic analysis methods, when applied to failure problems related to fatigue, aim to supply boundary values that will assure that the structure will survive to a certain number of cycles (i.e., the probability of survival) with a certain level of confidence. Two widely used statistical distributions often applied to failure problems are the Weibull and the Log-normal distributions (Schijve, 2005).

Hence, if there is a structural component subject to fatigue conditions whose EIFS distribution can be obtained by means of coupon tests, it becomes necessary to define a methodology in order to accomplish it. The flowchart presented in Figure 1 is suggested as a roadmap for application of the methodology.

Initially, the only information requested is the *S-N* curve, characterizing the full life of the component. The number of specimens to be tested must be sufficient to assure an appropriate fitting of the experimental data. The Metallic Materials Properties Development and Standardization – (MMPDS-01, 2003) supplies guidelines with respect to data requirements and the "quality" of the distribution obtained.

From the failure event at a certain load or stress level, it is necessary to infer the distribution of flaws that lead to these failures. This task can be accomplished by various ways, experimentally or analytically. The MIL Damage Tolerance Design Handbook (USAF DTD-HDBK – Section 3.2, 2006) suggests the estimation of initial flaw sizes by counting the number of fatigue striations through a fractographic test, and then extrapolating the crack growth curve trend to time zero. Such approach may lead to very consistent results, mainly when the so-called "marking spectra" are used, allowing more visible striations for counting. However, it is eventually very expensive and time-consuming. Alternatively, the use of a crack propagation analysis, coupled with suitable crack propagation data, where the threshold behavior is well characterized, is also a good approach. In the present work, the Nasgro crack propagation analysis software (Southwest Research Institute, 2009) was used, as mentioned in Figure 1.

One common question about the methodology is that departing from fatigue test results and performing a crack propagation time encompassing the full failure event (i.e., nucleation plus propagation) means to neglect the crack initiation period. First, it should be emphasized that the EIFS methodology intends to characterize an "equivalent" initial flaw", and not to fully describe the processes of initiation and crack propagation. There are many metallurgical effects, such as slipping bands and fretting, that will be involved by a macroscopic process, and it is assumed here that such process may be described uniquely by the crack propagation event. A second argument, as it will be shown later through practical examples, is that the for first locations where the flaws start to propagate, there will be in fact small defects characterizing surface imperfections that result from the manufacturing quality.

Figure 2 shows schematically the crack propagation "retro-analysis" procedure. Unless a optimization strategy is applied, this task needs to be performed by trial and error. The test loading level is a design choice. However, it must be assured that if the component is subjected to variable amplitude loading, such level will be sufficient to envelope the loading spectra. Hence, for this loading level, the distribution of failure is obtained, and the numbers of cycles that will correspond to probabilities of failure of 5% and 95% (or to any other design criteria, say 10% of failure) are known. Departing from the distribution of the numbers of cycles to failure, it is possible to perform a retro-analysis to determine the equivalent initial flaw size distribution.

Then, once the equivalent initial flaw size distribution is achieved, the flaw size that corresponds to 95% of occurrences is known. This value may be first compared with the deterministic values currently used. Usually, as it will be shown later through the examples, the actual initial flaw sizes will be significantly smaller, what shows that the present deterministic approaches are often conservative.

The following section will bring more details about the statistical distributions to be applied, which are an essential tool for the appropriate application of this methodology.

2.2. A review of statistical distributions

Many improvements in fatigue and damage tolerance analyses may be obtained by means of statistical analyses, that will allow to quantify the structure reliability, as well as to know the sensitivity of all parameters that are involved in the structure analysis. Statistical information, if available, supplies stronger background for decision taking.

Certain statistical distributions have been widely used for fatigue and fracture analysis, and the Weibull distribution is probably the most adequate. Weibull distributions are often used for modeling the time to failure of many phisical system of different nature. The parameters of this distribution have a flexibility that allows to model systems where the number of failures increase with time (such as wearing), decreases with time (such as certain semi-conductors) or remain constant with time (Rao, 1992).

The Weibull distribution with two parameters (Montgomery and Runger, 1999) is given by the following equation:

$$f(x) = \begin{cases} \dfrac{k}{\lambda}\left(\dfrac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k} & if\ x \geq 0 \\ 0 & if\ x < 0 \end{cases} \qquad (1)$$

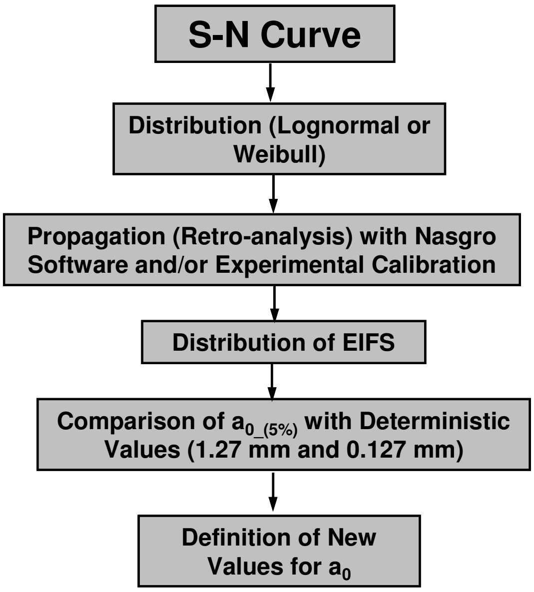

Figure 1. Outline of the methodology

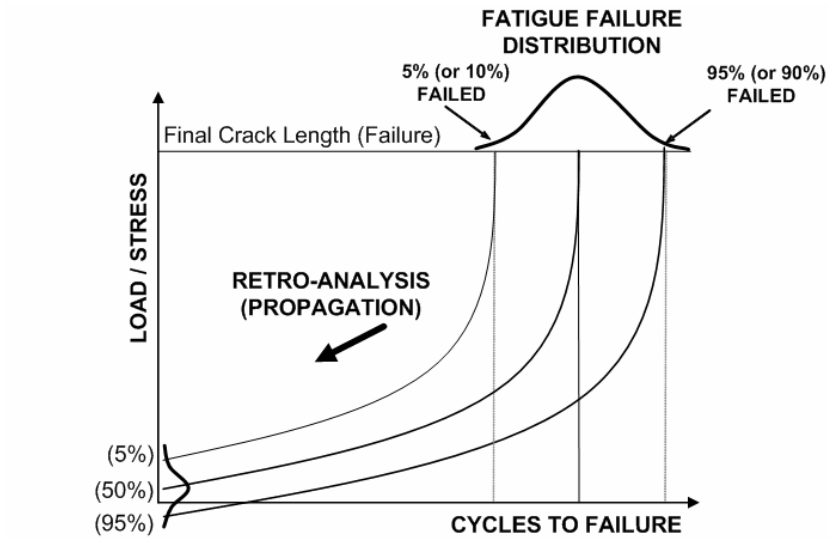

Figure 2. Schematic representation of inverse crack propagation analysis in order to obtain the EIFS distribution

where $k > 0$ is the shape parameter and $\lambda > 0$ is the scale parameter of the distribution. The cumulative distribution function for the Weibull distribution is:

$$F(x) = 1 - e^{-(x/\lambda)^k} \qquad (2)$$

for $x \geq 0$, and $F(x) = 0$ for $x < 0$.

The Log-normal distribution has been also extensively used for failure analysis. This distribution is given by:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln(x)-\mu)}{2\sigma^2}} \qquad (3)$$

for $x > 0$, where μ and σ are the mean and standard deviation of the variable's natural logarithm (by definition, the variable's logarithm is normally distributed).

3. APPLICATIONS

3.1 Lug Analysis

The first example presented is the analysis of a lug configuration. Lugs are components widely used for aircraft structures such as rudder and elevator hinge supports, flap and aileron support fittings, door hinges etc., where the total load is transferred by means of a connection pin. These components are often subjected to cyclic loads and are prone to fatigue failure. Fretting fatigue is one of the main causes of failure for such components, and the actual fatigue life for lugs is usually much shorter than predicted by the simple application of stress concentration factors. While fatigue life is difficult to predict, mainly due to fretting (what suggests tests in actual components), the crack propagation description is straightforward.

A certain amount of aluminum lugs with the same characteristics was tested up to failure under four load levels with stress ratio R = 0.1. The original data is as presented in Figure 3. Additionally, some points were inserted into the distribution in order to improve its quality. The data corresponding to all load levels was used to generate a Weibull and Log-normal distribution for each load level.

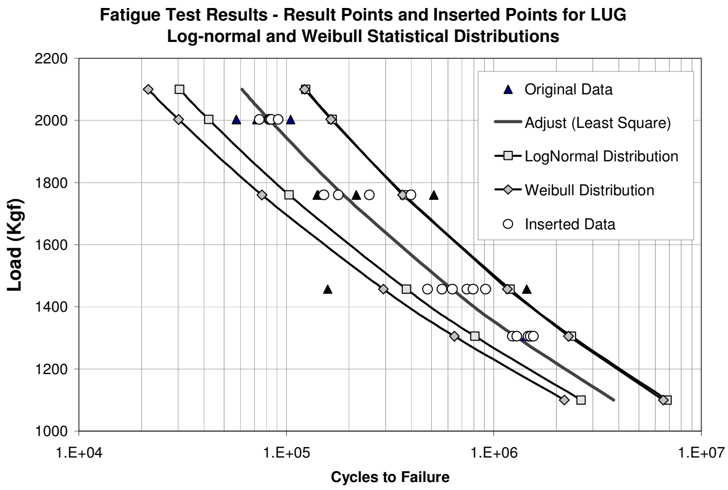

Figure 3. Application 1 (lug analysis) – *S-N* curve with the results of Weibull and Log-normal distribution

Taking the Log-normal distribution as an example, a set of design load levels was chosen for evaluation, corresponding to 1305, 1457, 1760 and 2003 Kgf (i.e., the same load levels used for the tests). Then, the numbers of cycles related to 5% and 95% of probability of failure were determined for the four load levels. Departing from these values, two 'boundary' curves (probability of failure = 5% and 95%) were obtained. With these two curves, it becomes possible to estimate the distribution for any load level. Then, following the flowchart previously described, a reverse crack propagation analysis was performed with Nasgro software, applying the appropriate material da/dN vs. ΔK curve available in Nasgro material database.

Figure 4 shows the probability density functions for the initial flaw size a_0 obtained for each load level (except for 1305 Kgf), while Figure 5 presents the corresponding cumulative probability density functions.

It is observed from Figure 5 that the value of a_0 which corresponds to a 95% probability of occurrence varies from 0.07 mm (for P = 1305 Kgf) up to 0.37 mm (for P = 2003 Kgf). Returning to the actual crack propagation analysis for this component and at a certain load level, it was verified through this analysis that departing from a_0 = 0.127 mm, the deterministic value previously discussed, for a load level of 1305 Kgf it will be necessary 306,500 cycles to failure, in contrast with nearly 569,000 cycles verified for the value of a_0 = 0.07 mm obtained from the statistical evaluation. That is roughly twice the life obtained by means of the deterministic approach.

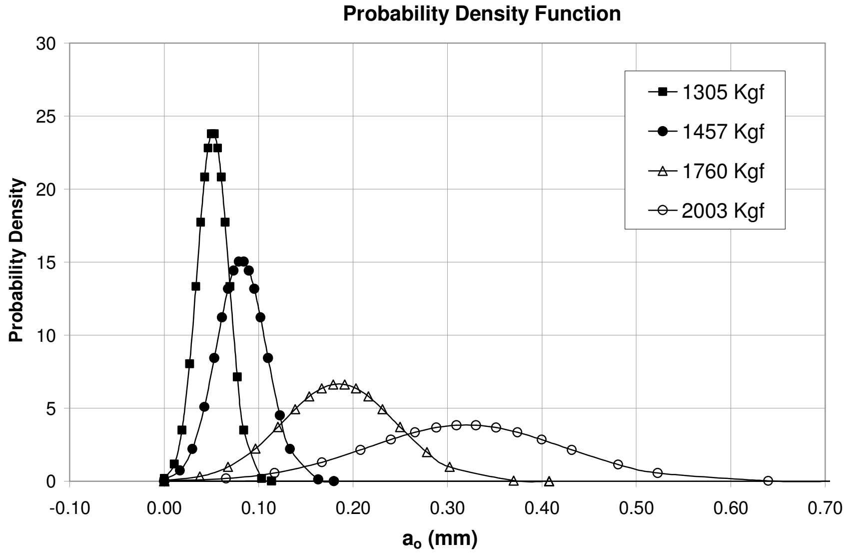

Figure 4. Application 1 (lug analysis) – Normal distribution– probability density function for initial flaw size a_0

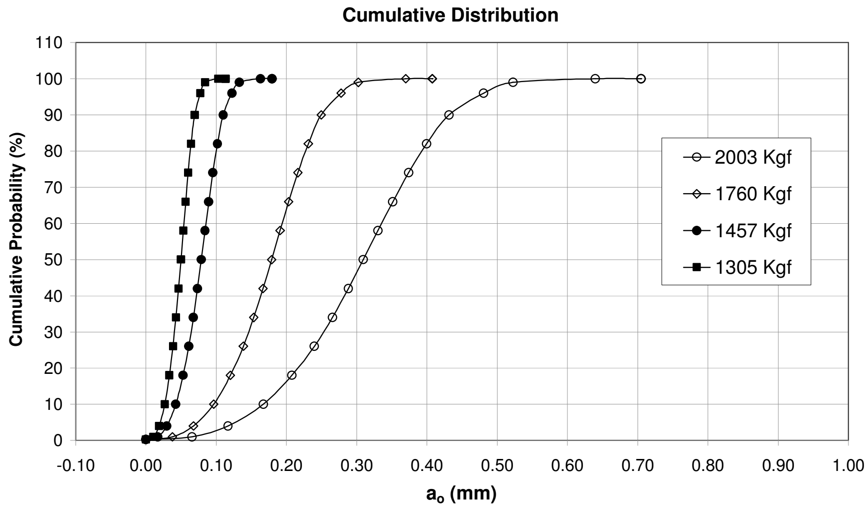

Figure 5. Application 1 (lug analysis) – Normal distribution– cumulative probability density function for initial flaw size a_0

3.2 Shear Joint Analysis

The second example presented corresponds to the analysis of a fastened aluminium shear joint. This configuration has similar characteristics with the previous one, in terms of load transfer through fasteners (i.e., bearing load) and fretting to a certain extent. As in the previous case, a certain amount of test specimens were subjected to various cyclic load levels for R = 0.1, such that an *S-N* curve could be generated, which is shown in Figure 6.

In order to improve the quality of the distributions, a data insertion procedure was adopted. These new points do not change the shape of the statistical distributions, which are obtained by analyzing all data points (i.e., for all load levels) simultaneoulsly. Figure 7 presents the same curve with the inserted data and after the adjust to the Log-normal and Weibull ditributions. It is observed from this figure that the Weibull distribution has a larger scatter, and will consequently lead to more conservative results.

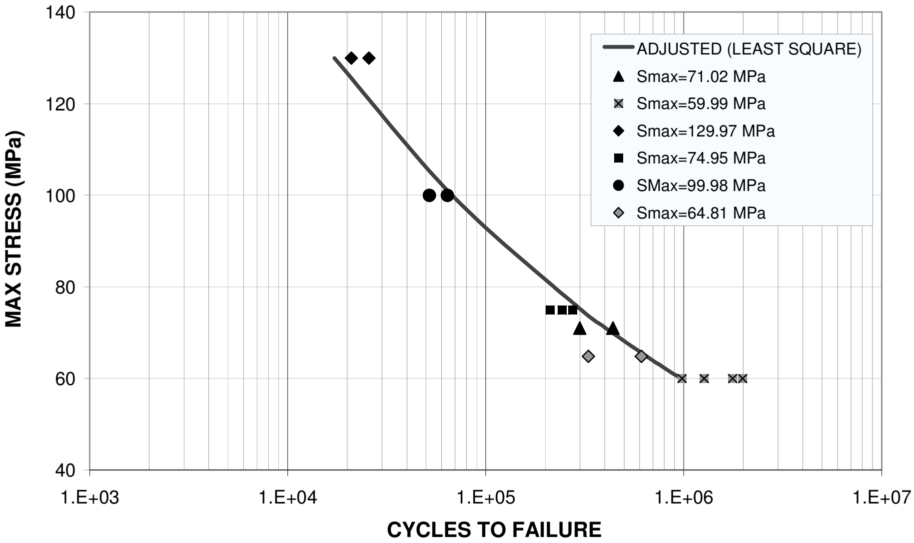

Figure 6. Application 2 (shear joint analysis) - *S-N* curve with original data

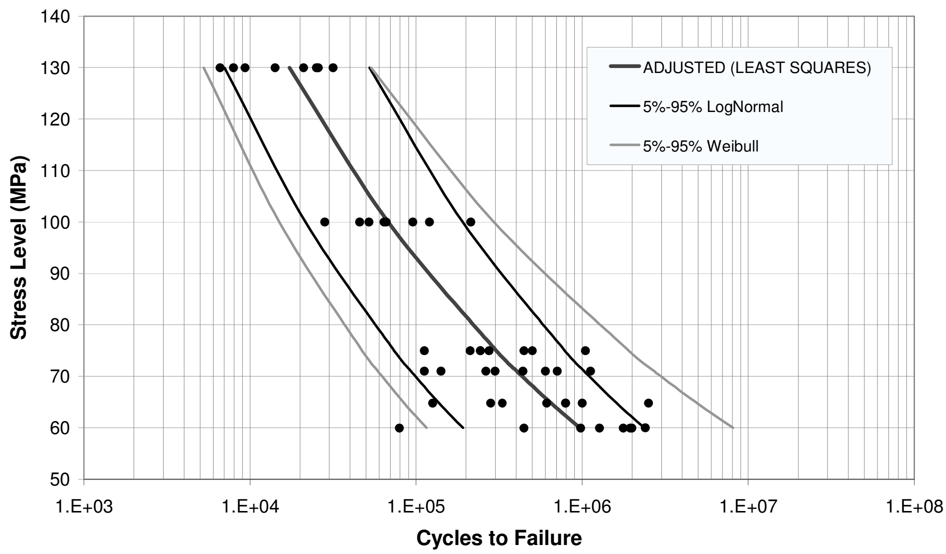

Figure 7. Application 2 (shear joint analysis) - *S-N* curve with inserted data and results of Weibull and Log-normal distributions

From this point, instead of choosing a certain stress level and then determining the distribution of EIFS for this specific level, it is supposed that the user does not know *a priori* which level to use. If one of the 5% failure probability curves is selected, say the one from the Log-normal distribution, it is possible to correlate the initial flaw size with the number of cycles that lead to failure when departing from this value of a_0. Figure 8 shows such correlation, obtained from the data of Figure 7 through the retro-analysis procedure discussed in the previous example, for a range of load levels. Further, Figure 9 presents the correlation between the initial flaw size and the corresponding stress level, for the range observed in Figure 7.

The information compiled in Figure 8 stands for the number of cycles that will lead this specific shear joint configuration to failure, with 5% of probability, as function of the corresponding initial flaw size. From the plot presented in this figure, it is possible to affirm that, departing from a_0 = 0.1 mm, after 85,000 cycles the joint will fail, and returning to Figure 6, the corresponding stress level will be 76 MPa. Hence, departing from a_0, the stress level that the structure withstands for a certain life will be known, and any design stress level below this one will be safe. It should be noticed that even for a_0 = 0.127 and a_0 = 1.27 mm, the number of cycles to failure and the corresponding load level may be easily obtained.

Another important conclusion is that the EIFS does not only depend on the detail surface characteristics, but also on loading severity.

4. DISCUSSION

The methodology presented in this paper leads to more quantitative information and therefore to more consistent data to be used as input for damage tolerance analysis. However, some points deserve attention and will be discussed in this section. These points will be separated in short topics, as follows, for purposes of clarity.

Shape of the *S-N* curve: it is usually observed that for lower load levels, the scatter of data is larger, and therefore the statistical distributions will reflect such experimental behavior. The curves presented in this study do not reflect this change of shape, because due to the limited number of data for both cases presented, it was preferred to use all data points to obtain the distribution. Ideally, the larger is the number of data, the best will be the distribution, such that different fits may be done for different load levels.

Scatter in crack propagation: the variability that occurs during the crack propagation event was not accounted for for this study. However, it is well known that crack propagation presents significantly lower variability when compared to crack nucleation.

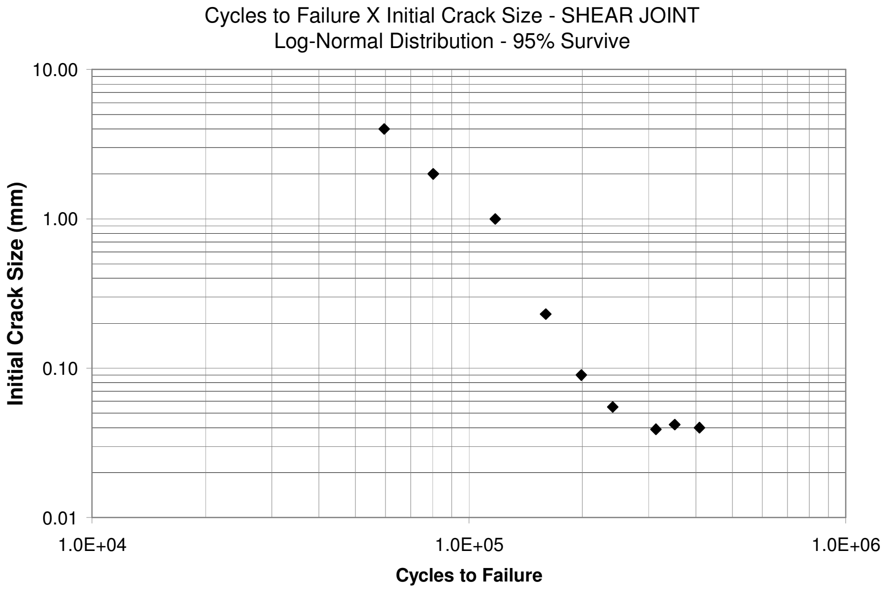

Figure 8. Correlation between initial flaw size and cycles to failure for the shear joint, obtained from the Log-normal distribution (POF = 5%)

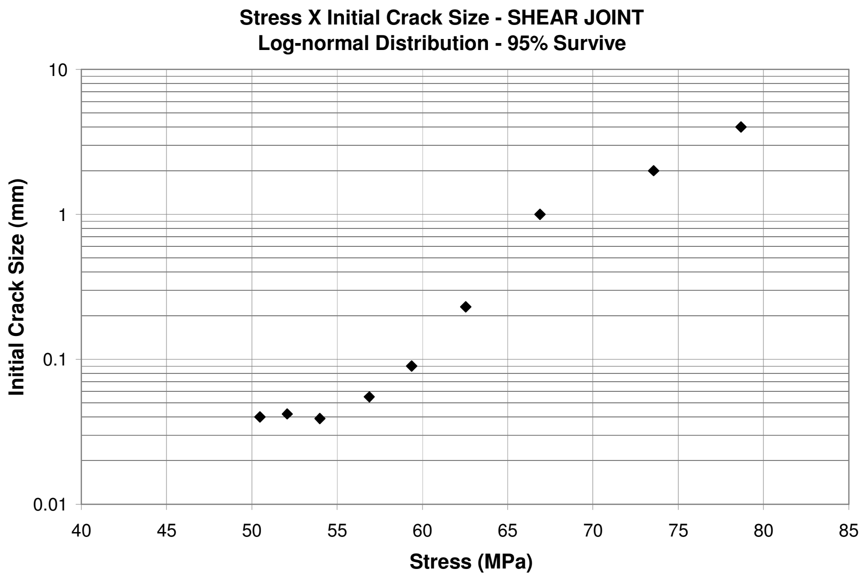

Figure 9. Correlation between initial flaw size and stress level for the shear joint, obtained from the Log-normal distribution (POF = 5%)

Constant vs. variable amplitude loading: except for locations subjected to prevailing pressurization loading, the majority of the aircraft structure will be subjected to variable amplitude loading due to continuous turbulence, manouvers, landing and ground conditions. However, the *S-N* curve as proposed is based on constant amplitude loading. It is believed by the authors that, assuming a certain loading level with constant amplitude, that will envelope the spectrum or will be with equivalent severity, constant amplitude loading may be applied without restrictions. It should be reminded that most of the influence of variable amplitude loading is due to aspects associated to the plastic zone size in the crack tip, and consequently most of these effects will lead to longer lives than constant amplitude loading.

The application of loading spectra into the test campaign for components in the scope of the proposed methodology can be also considered. Furthermore, there is an alternative approach for estimation of the EIFS distribution, described by Manning, Yang and Rudd (1987), where in Figure 2 previously presented the number of cycles to failure will be fixed while the load level will vary according to the statistical distribution. Such approach may be more suitable for a variable amplitude loading problem.

Concept of "equivalent" initial flaw size: as previously mentioned, it becomes apparent through the methodology that the crack initiation event, which is usually responsible for the majority of the component life, is being neglected. It should be stressed that the equivalent initial flaw size is an equivalent parameter that expresses the full set of events by means of a simple crack propagation event, as discussed in Manning, Yang and Rudd (1987). Further, it is believed that for the 5% POF upper bound, that is the subject of the analysis, there will be in fact small defects that originate cracks.

Different values of EIFS distributions for different components or details: the EIFS distribution reflects the quality of the manufacturing process. Hence, it is expected that different components, materials, material interfaces and other factors will result in different distributions. When a detail is selected and a set of tests is performed in order to obtain a *S-N* curve, aspects such as the applicability of this approach along the full aircraft structure are important. Critical details and widespread details are the main candidates for the application of this methodology.

5. CONCLUSION

The following conclusions can be drawn from this work:

- A methodology for determination of a parameter called "equivalent initial flaw size" was presented in this work.

- Two examples of application, corresponding to lugs and fastened shear joints applied in aircraft structures, showed that such methodology can bring some advantages when compared to the deterministic approach that has been used by manufacturers.

6. REFERENCES

Manning, S.D., Yang, J.N., Rudd, J. L., 1987 "Durability of Aircraft Structures", in Probabilistic Fracture Mechanics and Reliability, Martinus Nijhoff Publishers.
MIL A-83444 (USAF), 1974, "Military Specification – Aircraft Damage Tolerance Requirements, 2 July 1974.
MMPDS-01, 2003, "Metallic Materials Properties Development and Standardization", U.S. Department of Transportation, Federal Aviation Administration.
Montgomery, D.C., Runger, G.C., 1999, "Estatística Aplicada e Probabilidade para Engenheiros", Segunda Edição, Editora LTC.
Nasgro Crack Propagation Analysis Software, 2009 – Southwest Research Institute, San Antonio, Texas.
Provan, J.W., 1987, "Probabilistic Fracture Mechanics and Reliability", Martinus Nijhoff Publishers.
Rao, S., 1992, "Reliability Based Design", Mcgraw-Hill, Texas, June 1992.
Rudd, J.L., Gray, T.D., 1977, "Quantification of Fastener Hole Quality", Procedures of AIAA/ASME 18th Structures, Structural Dynamics and Materials Conference, San Diego, California, March 21-23, 1977.
Schijve, J., 2005, "Statistical Distribution Functions and Fatigue of Structures", International Journal of Fatigue, pp. 1031-1039.

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