10(2013) 845 – 857

Latin American Journal of
Solids and Structures
www.lajss.org

Towards a methodology for the practical applications of the EIFS (Equivalent Initial Flaw Size) concept

Abstract

This work intends to introduce a probabilistic approach for the crack propagation analysis. It presents a methodology that 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.

Juliana Diniz Mattos*,
Carlos Eduardo Chaves

Instituto Tecnológico de Aeronáutica
Pça. Marechal Eduardo Gomes, 50
São José dos Campos - SP
Brazil

Received 22 Nov 2011
In revised form 12 Jun 2012

*Author email: grassiella.hernandez@ig.com.br

1 INTRODUCTION

The life prediction and maintenance planning of aeronautical structures are key questions for the design and certification of aeronautical structures. Considering this, the development of these structures is directly associated to the crack propagation analysis of metallic components, 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. Considering these factors, the definition of the initial flaw size to be assumed in the crack propagation analysis represents not only in an essential step but also a criteria of singular importance for the fatigue and damage tolerance analysis.

Originally, 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 since they have been so far extensively used for damage tolerance analyses of commercial as well as military aircraft. Due to this fact, these values are assumed as reliable ones by the aeronautical certification authorities.

Within the advent of more accurate tests and analysis tools, the USAF proposed later non-deterministic approaches in order to obtain more appropriate values of the initial flaw size (USAF DTD-HDBK, 2006). These approaches depend 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 current 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 approaches, 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.

2 METHODOLOGY

2.1 Summary 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. It is also presented in MMPDS-03, 2006 a procedure to estimate the standard deviation of the numbers of cycles to failure related to a certain load level, as mentioned in Figure 1.

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. Recently some researches (Moreira et. al) were developed considering this approach. In these works the SEM (scanning electron microscopy) is employed to perform the measurements of the fatigue striation spacing. However, it is eventually very expensive and time-consuming.

Alternatively, some works (Liu et. al) were developed applying 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. The methodology proposed in these works is based on the Kitagawa–Takahashi diagram.

In the present work, in order to estimate the crack growth behavior, the Nasgro crack propagation analysis software was used, as mentioned in Figure 1.

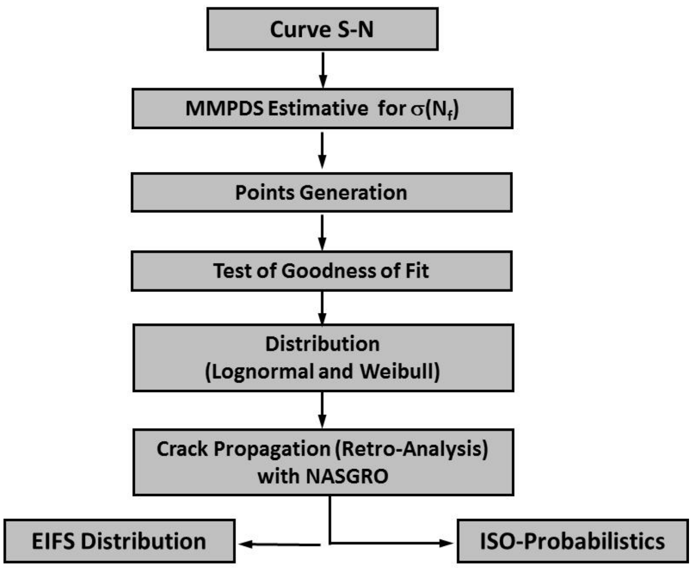

Figure 1 Outline of the Methodology

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 locations where the flaws primarily start to propagate, there will be in fact small defects characterizing surface imperfections that result from the manufacturing quality. It will be shown in both examples that the EIFS curves will be characterized by measurable and “considerably small” flaw sizes, the latter being interpreted as locations where the initial flaw sizes are negligible and crack initiation is occurring during the majority of this “macro” process.

Figure 2 shows schematically the crack propagation “retro-analysis” procedure. Unless an 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.

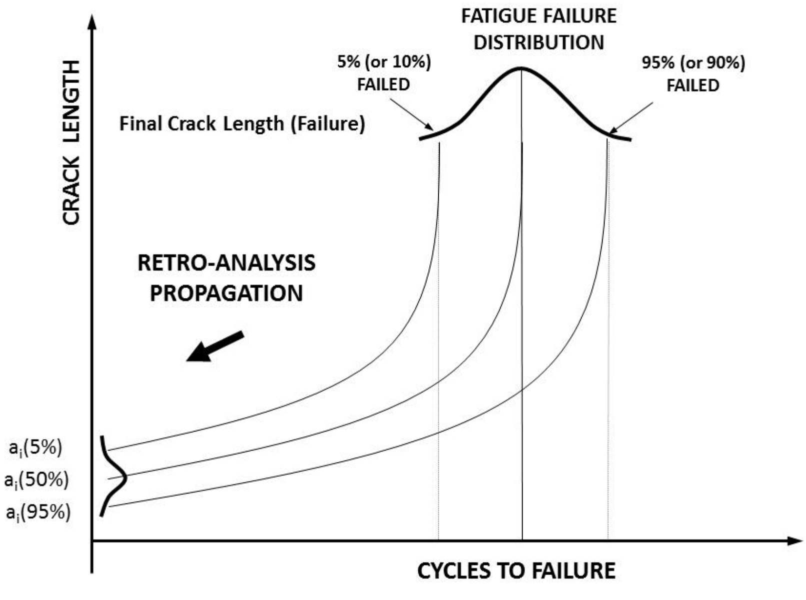

Figure 2 Schematic representation of inverse crack propagation analysis in order to obtain the EIFS distribution

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 physical 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:

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

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:

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

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:

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

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 RESULTS

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. 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.

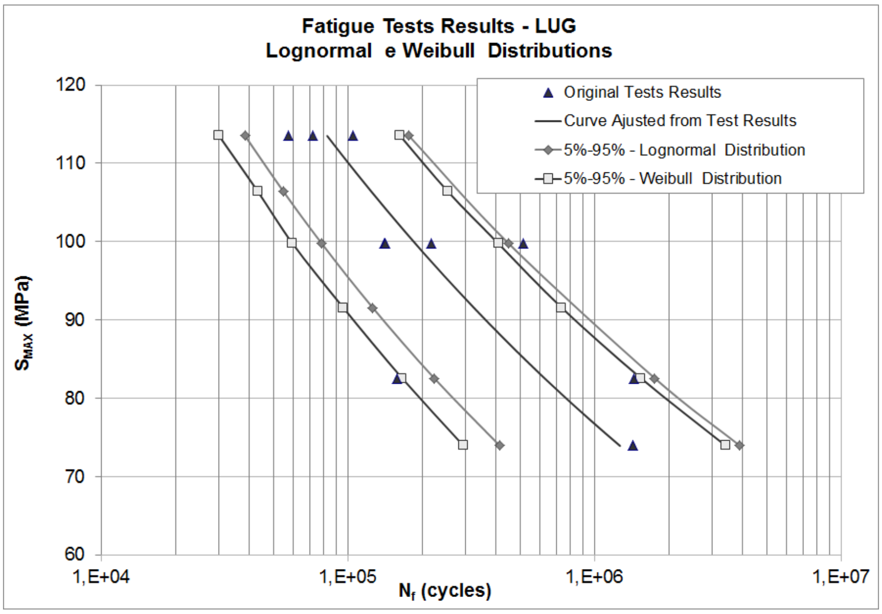

Figure 3 Application 1 (lug analysis) – *S-N* curve with the results of Weibull and Log-normal distribution.

Taking the Log-normal distribution as an example, a set of design tension levels was chosen for evaluation, corresponding to 82.56; 91.61; 99.73 and 113.51 MPa (i.e., the same tension levels used for the tests). Then, following the flowchart previously described, it was applied the procedure described in the MMPDS to estimate the standard deviation of the number of cycles required to failure for each load level considered. From this point it was possible to generate points that could represent the distribution of the number of cycles required to failure. It was applied a goodness of fit test to these points and it was verified that they exhibit a good enough fit to represent Log-normal and Weibull distributions. These points were applied to a reverse crack propagation analysis, performed with Nasgro software, applying the appropriate material da/dN vs. DK curve available in Nasgro material database. Then it was obtained the initial crack sizes related to the tension level considered and it became possible to determine the EIFS distribution.

Figure 4 shows the probability density functions for the initial flaw size a0 obtained for each load level (except for 82.56 MPa), 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 90% probability of occurrence varies from 0.11 mm (for P = 82.56 MPa) up to 0.44 mm (for P = 113.51 MPa). Returning to the actual crack propagation analysis for this component and at a certain tension level, it was verified through this analysis that departing from $a_0 = 0.127$ mm, the deterministic value previously discussed, for a tension level of 82,56 MPa it will be necessary 360,500 cycles to failure, in contrast with nearly 594,000 cycles verified for the value of $a_0 = 0.11$ mm obtained from the statistical evaluation. That is roughly fifty percent of increase from the life obtained by means of the deterministic approach.

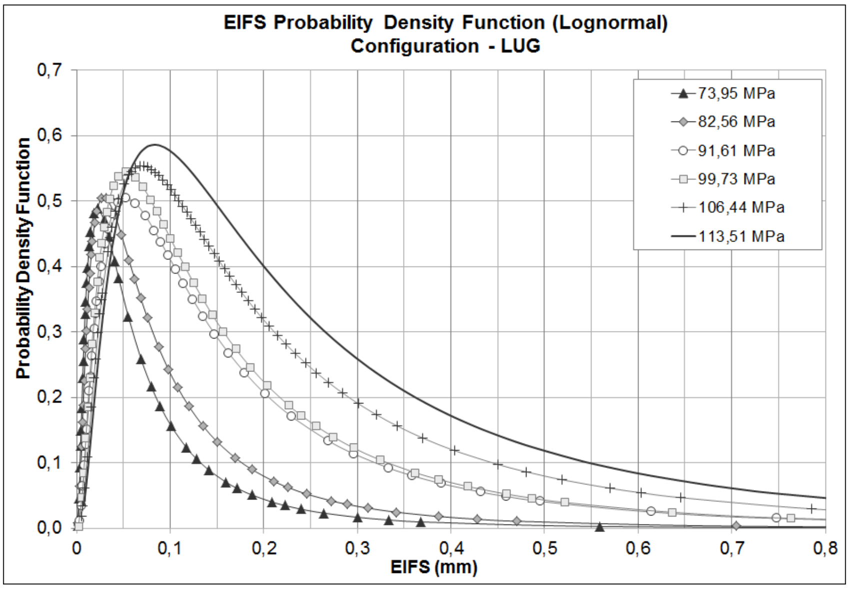

Figure 4 Application 1 (lug analysis) – Log-normal distribution– probability density function for initial flaw size a_0

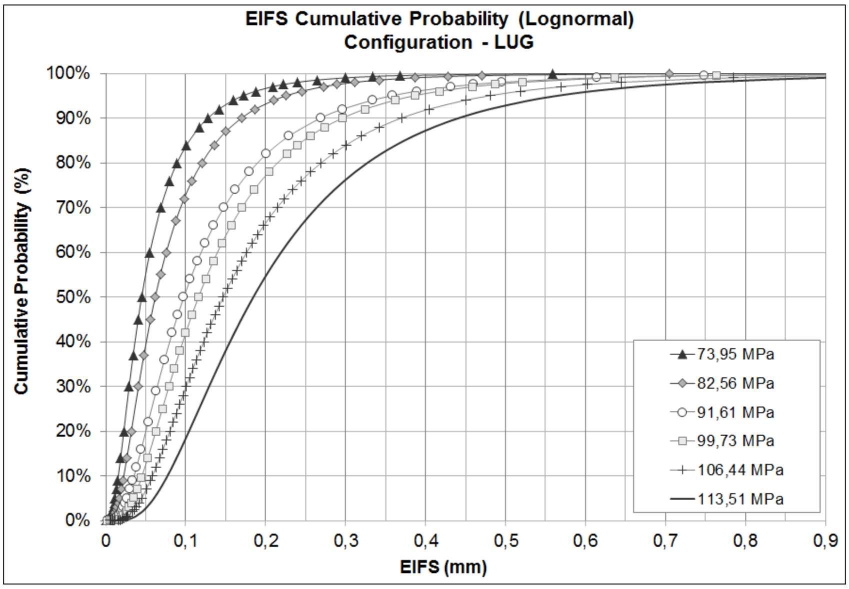

Figure 5 Application 1 (lug analysis) – Log-normal distribution– cumulative probability for initial flaw size a_0.

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, 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 Lognormal and Weibull distributions. It is observed from this figure that the Weibull distribution has a larger scatter, and will consequently lead to more conservative results.

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 7 shows such correlation, obtained from the data of Figure 6 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 6.

The information compiled in Figure 7 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.

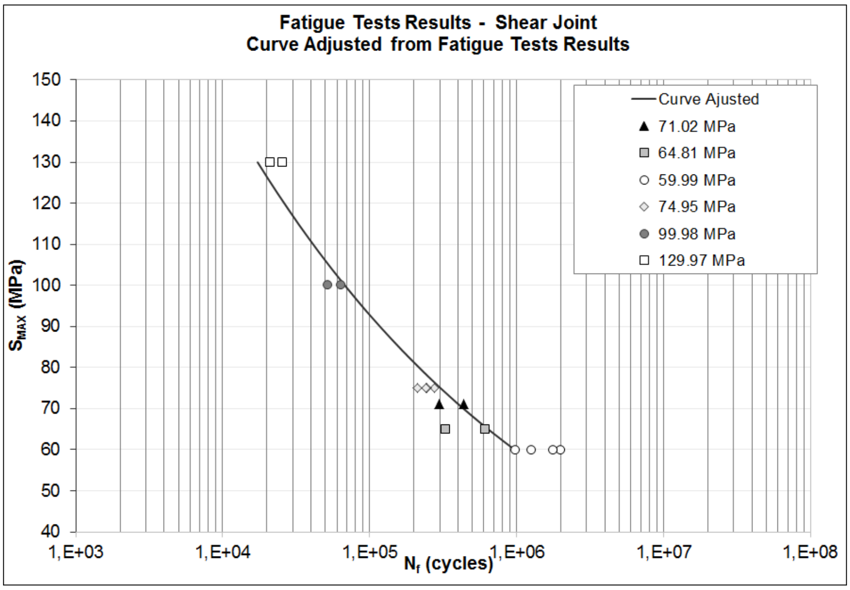

Figure 6 Application 2 (shear joint analysis) - S-N curve with original data

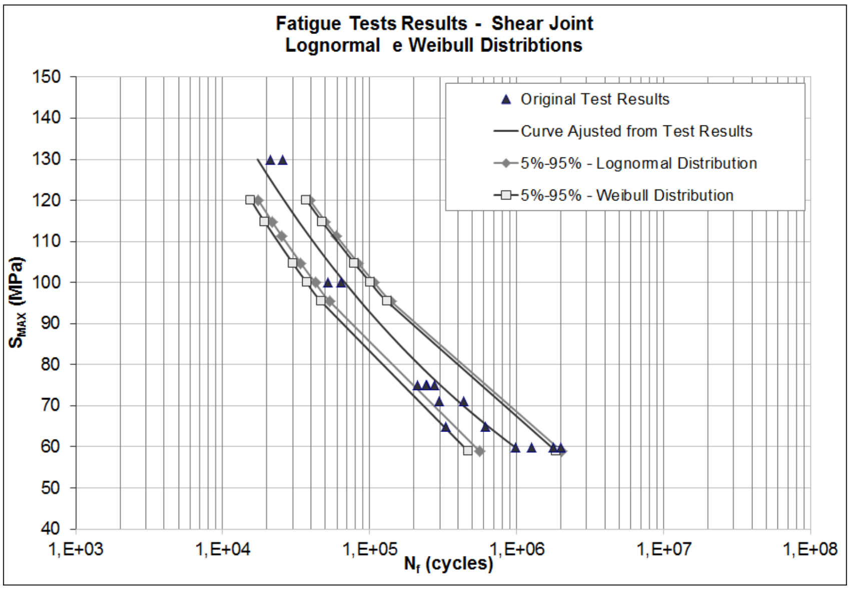

Figure 7 Application 2 (shear joint analysis) - S-N curve with inserted data and results of Weibull and Log-normal distributions

4 COMENTS AND CONCLUSIONS

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 tension 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.

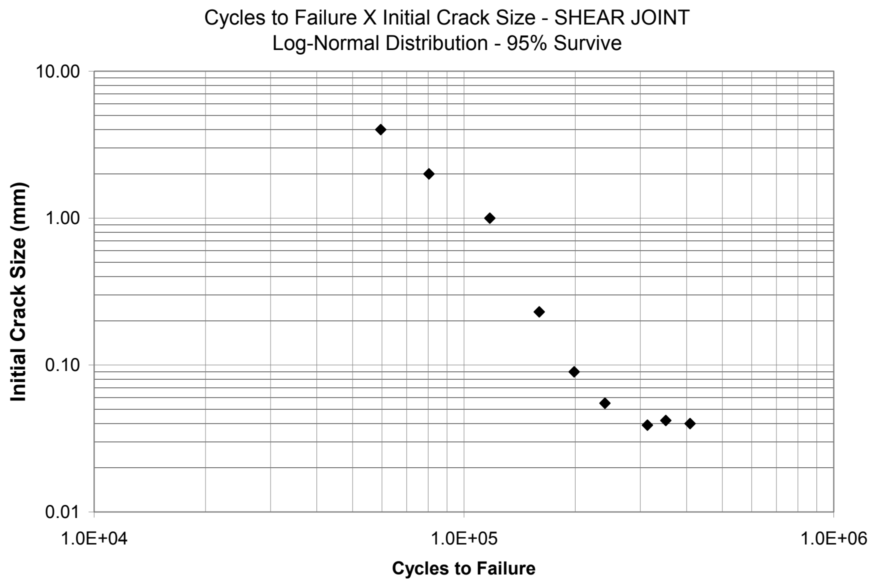

Figure 8 Correlation between initial flaw size and cycles to failure for the shear joint, obtained from the Log-normal distribution (POF = 5%)

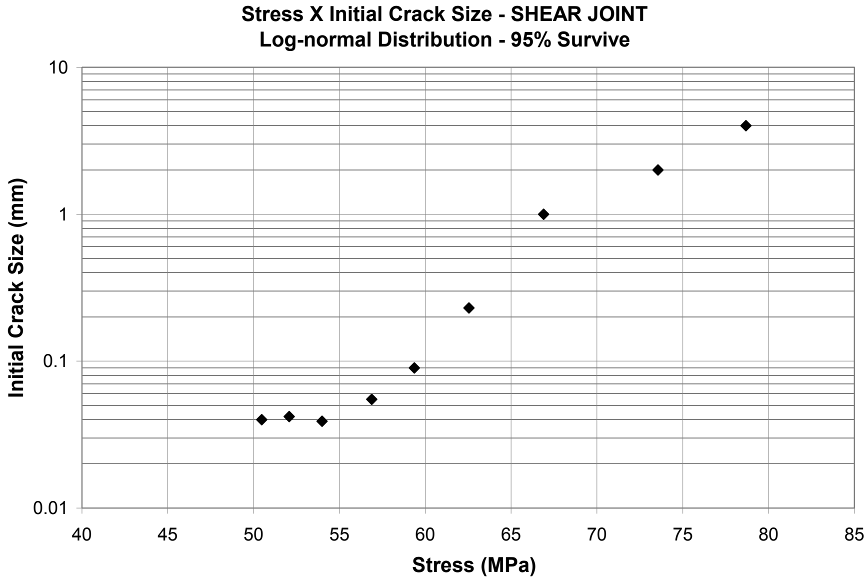

Figure 9 Correlation between initial flaw size and stress level for the shear joint, obtained from the Log-normal distribution (POF = 5%)

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 envelopes the spectrum or has an 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.

4.1 Conclusions

A simplified methodology for determination of a parameter called "equivalent initial flaw size" was presented in this work. The application of this methodology to the tests results of two configurations, 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.

Some points should be observed. The fatigue tests results related to the shear joint configuration conducts to EIFS distributions that increase the structure lifetime in a higher range of application, when compared to the lug ones. Such differences occur not only due to the tension levels of applications, but also due to the propagation characteristics related each configuration. It should be noticed that the methodology here presented is associated to one EIFS concept which is not a material property, but also a characteristic of the configuration itself and of the tension level considered.

References

LIU, Y, MAHADEVAN, S, Probabilistic fatigue life prediction using an equivalent initial flaw size distribution, International Journal of Fatigue, pp 476-487,

MANNING, S.D., YANG, J.N., RUDD, J. L., Durability of Aircraft Structures, in Probabilistic Fracture Mechanics and Reliability, Martinus Nijhoff Publishers, 1987.

MIL A-83444 (USAF), Military Specification – Aircraft Damage Tolerance Requirements, 2 July 1974.

MOLENT, L, SUN, Q, GREEN, A, Characterisation of equivalent initial flaw sizes in 7050 aluminium alloy, J. Fatigue Fracture Engineering Material Structure 2006; 29: 916-37

MOREIRA, P.M.G.P. MATOS, P.F.P , CASTRO, P.M.S.T., Equivalent Initial Flaw Size in AL 2024-T3 Riveted Specimens, 9th Portuguese Conference on Fracture, 2004.

MMPDS-01, 2003, Metallic Materials Properties Development and Standardization, U.S. Department of Transportation, Federal Aviation Administration., 1974

MONTGOMERY, D.C., RUNGER, G.C., Estatística Aplicada e Probabilidade para Engenheiros, Segunda Edição, Editora LTC, 1999.

Nasgro Crack Propagation Analysis Software – Southwest Research Institute, San Antonio, Texas, 2009.

PROVAN, J.W., Probabilistic Fracture Mechanics and Reliability, Martinus Nijhoff Publishers, 1987.

RAO, S., Reliability Based Design, McGraw-Hill, Texas, June 1992.

RUDD, J.L., GRAY, T.D., 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., Statistical Distribution Functions and Fatigue of Structures, International Journal of Fatigue, pp. 1031-1039, 2005.