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A new statistical software for the estimation of P-S-N curves in presence of defects: statistical models and experimental validation

A. Tridello^{a*}, D.S. Paolino^b

^{a, b} Department of Mechanical and Aerospace Engineering, Politecnico di Torino, 10129 Turin, Italy

*andrea.tridello@polito.it

Abstract. It is well-known in the literature that fatigue failures originate from the weakest element within the component loaded volume. In particular, for metallic materials the fatigue crack typically nucleates from the most critical surface defect in the High-Cycle-Fatigue (HCF) region; whereas, it generally nucleates from the most critical internal defect in the Very-High-Cycle-Fatigue (VHCF) region, at stress amplitudes below the so-called ‘transition stress amplitude’. Therefore, regardless of the fatigue region, the P-S-N curves must necessarily take into account the random distribution of the critical defect size. However, in the literature, there are few statistical models that can model the dependency between the fatigue life and the defect size or that can take into account the presence of different failure mechanisms (e.g., surface crack nucleation in HCF and internal crack nucleation in VHCF). In the present paper, a new software for the estimation of the P-S-N curves is proposed. The statistical P-S-N models recently proposed by the authors and implemented in the software are described in the paper. The procedure for the parameter estimation is also explained in detail and the software is finally validated with experimental datasets collected by the authors or available in the literature.

1. Introduction

The structural integrity of components subjected to mechanical loads is assessed through design methodologies which permit to verify if the applied loads are below the maximum load that can be sustained by the material of the component. For static loads, the yield strength or the tensile strength are generally considered; whereas, in case of cyclic loads, the P-S-N curves are employed [1, 2]. P-S-N curves correlate the fatigue life, in terms of number of cycles to failure, and the applied stress. The fatigue strength at the desired number of cycles to failure is generally used for the design of components: therefore, a proper estimation of the P-S-N curves from experimental results is fundamental for a safe design and to guarantee the structural integrity of components that are to be designed.

It is well-known that fatigue failures originate from the weakest element within the component risk-volume (i.e., the region of material subjected to a stress amplitude close to the maximum applied stress). For example, for metallic materials the fatigue crack typically originates from the specimen surface in the High-Cycle-Fatigue (HCF) region. On the other hand, if large defects form during the manufacturing process, the fatigue crack can also originate from such large defects that are randomly distributed within the risk-volume. For example, surface defects can form during the machining or turning processes [3] or in high carbon steels employed in corrosive environments (corrosion pits [4]) or during the manufacturing processes (e.g., casting process or Additive Manufacturing processes [5]). Moreover, for



metallic materials the fatigue crack generally originates from the most critical internal defect in the Very High Cycle Fatigue (VHCF) region, at stress amplitudes below the so-called “transition stress amplitude”. When the fatigue crack originates from critical defects and the fatigue response is controlled by defects, the fatigue life not only depends on the applied stress amplitude, but also on the random distribution of defect size. However, in the literature, few statistical models can model the dependency between the fatigue life and the defect size or can take into account the presence of different failure mechanisms (e.g., surface crack nucleation in HCF and internal crack nucleation with fish-eye morphology in VHCF region). The defect size is indeed generally neglected, even if it strongly influences the fatigue response.

In the present paper, a new software for the estimation of the P-S-N curves is proposed. The statistical P-S-N models that have been recently proposed by the authors [6, 7] and that have been implemented in the software are described in the paper. Moreover, a general formulation for the duplex P-S-N curves capable of modelling the dependence between the fatigue life and the defect size both in HCF and in the VHCF is proposed. The procedure for the parameter estimation is also explained in detail: both the least square method and the maximum likelihood principle are implemented, depending on the presence of runout specimens. The software is finally validated with experimental datasets collected by the authors or available in the literature.

2. Methods: P-S-N curves in presence of defects

In this Section, the models implemented in the proposed software are analyzed. In particular, in Section 2.1 the models for the fatigue life in presence of defects are described. In Section 2.2 the complete model for the duplex P-S-N curves is analyzed and in Section 2.3 the procedure for the parameter estimation is described.

2.1. Fatigue life in presence of defects: statistical models

According to the literature [6], the fatigue life can be considered as normally distributed with mean μ_Y dependent on the logarithm of the applied stress amplitude, s_a ($x = \log_{10}(s_a)$) and constant standard deviation σ_Y . If defects are responsible for the fatigue failures, according to [7], μ_Y is also a function of the characteristic defect size, $\sqrt{a_{d,0}}$ (area of the defect projected in a direction perpendicular to load direction [8]). For defects with irregular morphology, an equivalent defect size can be assessed according to [8, 9]. The fatigue life in presence of defects is therefore:

$$\begin{cases} F_{Y|\sqrt{a_{d,0}}}(y; x, \sqrt{a_{d,0}}) = \Phi\left(\frac{y - \mu_Y(x, \sqrt{a_{d,0}})}{\sigma_Y}\right) \\ \mu_Y(x, \sqrt{a_{d,0}}) = c_Y + m_Y x + n_Y \log_{10}(\sqrt{a_{d,0}}) \\ \sigma_Y = \text{constant} \end{cases} \quad (1)$$

where $F_{Y|\sqrt{a_{d,0}}}(y; x; \sqrt{a_{d,0}})$ is the probability of failure, $\Phi(\cdot)$ is the cumulative distribution function of a standard normal variable, $y = \log_{10}(N_f)$, being N_f the number of cycles to failure and c_Y , m_Y and n_Y are constant coefficients that have to be estimated from the experimental data. By substituting $F_Y(y; x)$ with α_{th} , the α_{th} conditional P-S-N curve can be estimated by solving Equation 1 with respect to x for different values of y . The P-S-N curves estimated from Equation 1 are called “conditional P-S-N curves”, since they are conditioned to the defect size $\sqrt{a_{d,0}}$.

From the conditional P-S-N curves and by taking into account the definition of marginal distribution, the P-S-N curves not conditioned to $\sqrt{a_{d,0}}$ can be also estimated. They are called in the following “marginal P-S-N curves” and are obtained by integrating from 0 to infinite with respect to $\sqrt{a_{d,0}}$ the product of the conditional fatigue life and the distribution of defect size, which is assumed to follow a Largest Extreme Value Distribution (LEVD) [8]:

$$F_Y(y; x) = \int_0^\infty \Phi \left(\frac{y - \mu_Y(x, \sqrt{a_{d,0}})}{\sigma_Y} \right) \frac{\varphi_{LEV} \left(\frac{\sqrt{a_{d,0}} - \mu_{\sqrt{A}}}{\sigma_{\sqrt{A}}} \right)}{\sigma_{\sqrt{A}}} d\sqrt{a_{d,0}}, \quad (2)$$

being $\varphi_{LEV}(\cdot)$ the probability density function of the standardized Largest Extreme Value distribution with parameters $\mu_{\sqrt{A}}$ and $\sigma_{\sqrt{A}}$. By substituting $F_Y(y; x)$ with α_{th} , the α_{th} marginal P-S-N curve can be estimated by solving Equation 2 with respect to x for different values of y . Moreover, according to [10], by expressing the LEVD as a function of the risk-volume, the dependency between the P-S-N curves and the risk-volume can be estimated (size-effect). The models in Equation 1 and 2 are general and can be employed to assess the dependency of the fatigue life with respect to the defect size both in HCF and in VHCF. They are used to model the finite fatigue life, with a continuous decreasing trend; on the other hand, if an asymptotic behaviour is to be modelled at the end of the curve (i.e., a fatigue limit is present), the distribution function of the fatigue limit should be defined. According to [7], the cumulative distribution function of the logarithm of the fatigue limit (X_l) conditioned to the defect size (i.e., $F_{X_l}(y; x; \sqrt{a_{d,0}})$) is given by:

$$\left\{ \begin{array}{l} F_{X_l|\sqrt{a_{d,0}}}(x_l; \sqrt{a_{d,0}}) = \Phi \left(\frac{x_l - \mu_{X_l}(\sqrt{a_{d,0}})}{\sigma_{X_l}} \right) \\ \mu_{X_l}(\sqrt{a_{d,0}}) = \frac{c_{s_l} c_{th,g} (HV + 120)}{\sqrt{a_{d,0}}^{1/2 - \alpha_{th,g}}} \\ \sigma_{X_l} = \text{constant} \end{array} \right., \quad (3)$$

being $\mu_{X_l}(\sqrt{a_{d,0}})$ and σ_{X_l} the mean value and the standard deviation of the fatigue limit, respectively, with c_{s_l} , $c_{th,g}$ and $\alpha_{th,g}$ three constant coefficients that have to be estimated from the experimental data and HV the Vickers hardness of material [8]. In particular, the model in Equation 3 is general and can be used to estimate the fatigue limit both for fatigue failures with and without the Fine Granular Area (FGA) morphology. In particular, the constant coefficients $c_{th,g}$ and $\alpha_{th,g}$ are estimated by considering the stress intensity factor threshold as a function of the defect size [7]; whereas the c_{s_l} coefficient accounts for the local reduction of the stress intensity factor threshold in the vicinity of the defect within the FGA. It is generally acknowledged in the VHCF literature that crack can grow within the FGA even though the stress intensity factor associated to the defect is smaller than the threshold for crack propagation [7-8]. It is worth to note that for $c_{s_l} = 1$, $\mu_{X_l}(\sqrt{a_{d,0}})$ corresponds to the well-known Murakami equation for the estimation of the fatigue limit in presence of defects, without FGA; whereas, for $c_{s_l} \neq 1$, it permits to assess the fatigue limit in presence of defects, with FGA formation.

The model for the conditional P-S-N curves in presence of defects and with fatigue limit is given by [7]:

$$F_{Y|\sqrt{a_{d,0}}}(y; x, \sqrt{a_{d,0}}) = \Phi \left(\frac{y - \mu_Y(x, \sqrt{a_{d,0}})}{\sigma_Y} \right) \Phi \left(\frac{x_l - \mu_{X_l}(\sqrt{a_{d,0}})}{\sigma_{X_l}} \right), \quad (4)$$

The model for the marginal P-S-N curves in Equation 2 can be easily modified to take into account the presence of the fatigue limit:

$$F_Y(y; x) = \int_0^\infty \Phi \left(\frac{y - \mu_Y(x, \sqrt{a_{d,0}})}{\sigma_Y} \right) \Phi \left(\frac{x_l - \mu_{X_l}(\sqrt{a_{d,0}})}{\sigma_{X_l}} \right) \frac{\varphi_{LEV} \left(\frac{\sqrt{a_{d,0}} - \mu_{\sqrt{A}}}{\sigma_{\sqrt{A}}} \right)}{\sigma_{\sqrt{A}}} d\sqrt{a_{d,0}}, \quad (5)$$

From Equation 1-5 it is possible to assess the P-S-N curves in presence of defects both in HCF and in VHCF. They represent the starting models for the estimation of the P-S-N curves of the so-called “duplex model”.

2.2. Duplex model: P-S-N curves

According to the literature, the duplex model [11-13] involves a linear trend in the HCF region, a transition stress amplitude, a second linear trend in the VHCF region with a fatigue limit at the end. In its general formulation [14], in the HCF region the fatigue failures originate from the surface, whereas the crack initiation shifts to internal defects in the VHCF region. This is the most general model and is schematically shown in Figure 1:

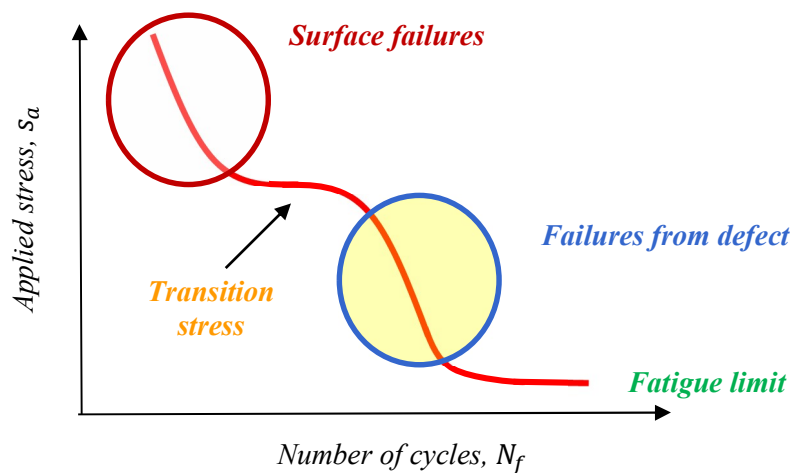


Figure 1: Schematic representation of the duplex P-S-N curve.

The models in Equations 1-5 must be modified in order to take into account the presence of two different decreasing trends and of a transition stress amplitude. The logarithm of the transition stress amplitude (X_t) is assumed to be normally distributed [6], with constant mean μ_{X_t} and standard deviation σ_{X_t} :

$$\begin{cases} F_{X_t}(x) = \Phi\left(\frac{x-\mu_{X_t}}{\sigma_{X_t}}\right) \\ \mu_{X_t} = \text{constant} \\ \sigma_{X_t} = \text{constant} \end{cases}, \quad (6)$$

being $F_{X_t}(x)$ the cumulative distribution function of the logarithm of the transition stress amplitude. By modifying the formulation in [6] to take into account the crack initiation from defects in the VHCF region, the general model for the marginal duplex P-S-N curve becomes:

$$F_Y(y; x) = \Phi\left(\frac{x-\mu_{X_t}}{\sigma_{X_t}}\right) \Phi\left(\frac{y-\mu_{Y,s}(x)}{\sigma_{Y,s}}\right) + \left(1 - \Phi\left(\frac{x-\mu_{X_t}}{\sigma_{X_t}}\right)\right) \int_0^\infty \Phi\left(\frac{y-\mu_{Y,i}(x, \sqrt{a_{d,0}})}{\sigma_{Y,i}}\right) \Phi\left(\frac{x-\mu_{X_t}(\sqrt{a_{d,0}})}{\sigma_{X_t}}\right) \frac{\varphi_{LEV}\left(\frac{\sqrt{a_{d,0}}-\mu_{\sqrt{A}}}{\sigma_{\sqrt{A}}}\right)}{\sigma_{\sqrt{A}}} d\sqrt{a_{d,0}}, \quad (7)$$

with the quantities with subscript s ($\mu_{Y,s}(x)$ and $\sigma_{Y,s}$) referring to the surface failure mode and the quantities with subscript i referring to the internal failure mode ($\mu_{Y,i}(x, \sqrt{a_{d,0}})$ and $\sigma_{Y,i}$). This is the complete and most general model and by substituting $F_Y(y; x)$ with α_{th} and solving Equation 7 with

respect to x for different values of y it is possible to assess the α_{th} quantile of the P-S-N curve. It is worth to note that with $\Phi\left(\frac{x-\mu_{X_t}}{\sigma_{X_t}}\right) = 1$, Equation 7 reduces to the case of finite fatigue life with linear decreasing trend and failures originating from the surface; whereas, with $\Phi\left(\frac{x-\mu_{X_t}}{\sigma_{X_t}}\right) = 0$, Equation 7 models a linear decreasing trend with fatigue limit in case of failures from defects. Moreover, if a clear fatigue limit is not evident from the experimental data, $\Phi\left(\frac{x_l-\mu_{X_l}(\sqrt{a_{d,0}})}{\sigma_{X_l}}\right) = 1$ and the curve in the VHCF region has a continuous monotonic decreasing trend.

If the fatigue crack originates from defects also in the HCF region, Equation 7 can be modified by replacing $\Phi\left(\frac{y-\mu_{Y,s}(x)}{\sigma_{Y,s}}\right)$ with $F_Y(y; x)$ in Equation 5:

$$F_Y(y; x) = \Phi\left(\frac{x-\mu_{X_t}}{\sigma_{X_t}}\right) \int_0^\infty \Phi\left(\frac{y-\mu_{Y,i1}(x,\sqrt{a_{d,0}})}{\sigma_{Y,i1}}\right) \frac{\varphi_{LEV,1}\left(\frac{\sqrt{a_{d,0}}-\mu_{\sqrt{A_1}}}{\sigma_{\sqrt{A_1}}}\right)}{\sigma_{\sqrt{A_1}}} d\sqrt{a_{d,0}} +$$

$$+ \left(1 - \Phi\left(\frac{x-\mu_{X_t}}{\sigma_{X_t}}\right)\right) \int_0^\infty \Phi\left(\frac{y-\mu_{Y,i2}(x,\sqrt{a_{d,0}})}{\sigma_{Y,i2}}\right) \Phi\left(\frac{x_l-\mu_{X_l}(\sqrt{a_{d,0}})}{\sigma_{X_l}}\right) \frac{\varphi_{LEV,2}\left(\frac{\sqrt{a_{d,0}}-\mu_{\sqrt{A_2}}}{\sigma_{\sqrt{A_2}}}\right)}{\sigma_{\sqrt{A_2}}} d\sqrt{a_{d,0}}, \quad (8)$$

and the superscript 1 and 2 discriminates between HCF (superscript 1) and VHCF (superscript 2). In general, $\varphi_{LEV,1}$ is equal to $\varphi_{LEV,2}$, but this must be experimentally validated.

If the transition stress is not evident (i.e., a bilinear trend is present with an abrupt change of the slope, as for some Aluminium alloys [15]), Equation 7 can be easily modified as follows:

$$F_Y(y; x) = \left(\int_0^\infty \Phi\left(\frac{y-\mu_{Y,i1}(x,\sqrt{a_{d,0}})}{\sigma_{Y,i1}}\right) \frac{\varphi_{LEV,1}\left(\frac{\sqrt{a_{d,0}}-\mu_{\sqrt{A_1}}}{\sigma_{\sqrt{A_1}}}\right)}{\sigma_{\sqrt{A_1}}} d\sqrt{a_{d,0}} \right) \cdot$$

$$\left(\int_0^\infty \Phi\left(\frac{y-\mu_{Y,i2}(x,\sqrt{a_{d,0}})}{\sigma_{Y,i2}}\right) \Phi\left(\frac{x_l-\mu_{X_l}(\sqrt{a_{d,0}})}{\sigma_{X_l}}\right) \frac{\varphi_{LEV,2}\left(\frac{\sqrt{a_{d,0}}-\mu_{\sqrt{A_2}}}{\sigma_{\sqrt{A_2}}}\right)}{\sigma_{\sqrt{A_2}}} d\sqrt{a_{d,0}} \right), \quad (9)$$

The model in Equation 7 is very general and can be easily adapted to different fatigue models available in the literature: duplex without fatigue limit, linear with or without fatigue limit, bilinear with or without fatigue limit.

2.3. Parameter estimation

The models described in previous Sections depend on many constant parameters that must be estimated from the experimental data. Figure 2 shows schematically the procedure for the estimation of the parameters involved in the general model in Equation 7 (superscript s refers to surface failures, whereas the superscript i refers to internal failures from defects):

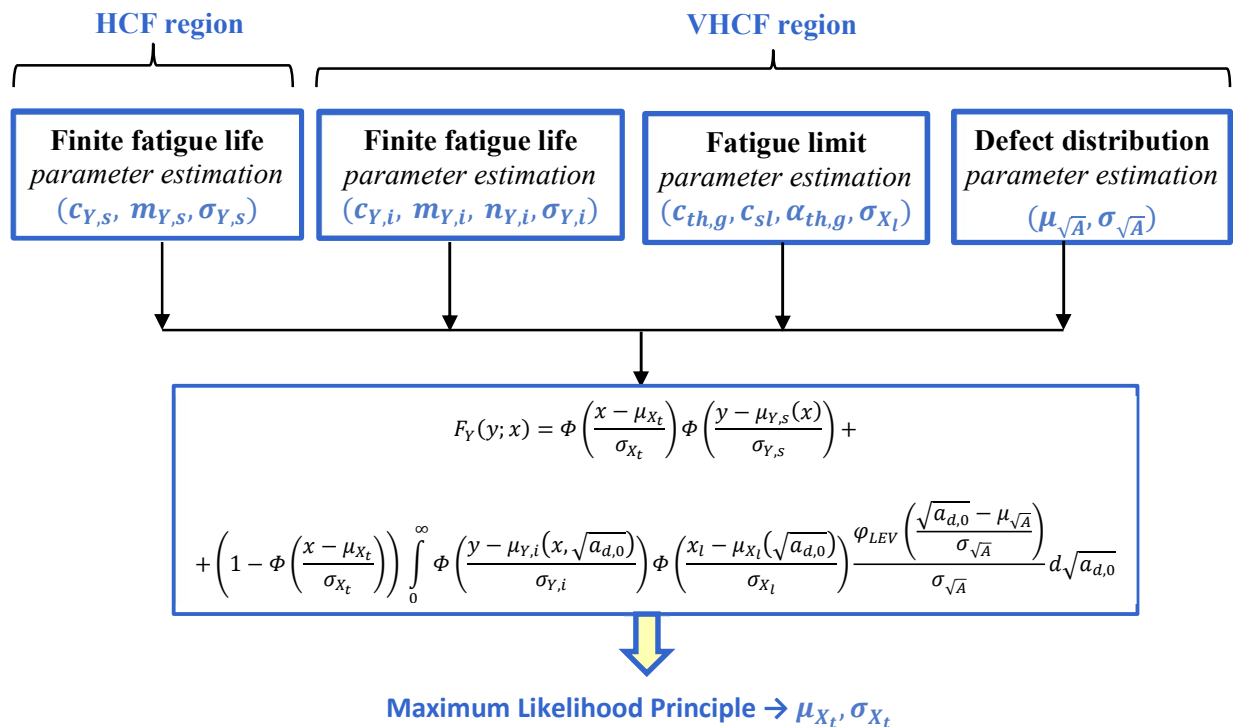


Figure 2: Schematic representation of the procedure for the parameter estimation of the duplex P-S-N curves

According to Figure 2, the constant parameters of the distribution of the finite fatigue life in HCF and VHCF regions are estimated concurrently. In particular, they are estimated through the application of the Least Squares Method or of the Maximum Likelihood Principle by considering the model reported in Equation 1 (i.e., $n_Y = 0$, for surface failures). For failures from defects, the LEVD distribution parameters are estimated again through the application of the Least Squares Method or of the Maximum Likelihood Principle by considering the defect size measured on the fracture surfaces [7]. For the fatigue limit, the procedure for parameter estimation is described in detail in [7]. In particular, the $c_{th,g}$ and $\alpha_{th,g}$ parameters are estimated through a linear regression between the stress intensity factor associated to the size of the defect originating the fatigue failures (or the FGA size) and the defect size (or the FGA size); whereas the c_{sl} parameter is estimated through the application of the Maximum Likelihood method of the model reported in [7] and describing the probability of having a failure and runout for the experimental data. Following the scheme in Figure 2, once the parameters for the finite fatigue life and the fatigue limit are estimated, the mean value and the standard deviation for the transition stress amplitude become the only unknown parameters, which are estimated through the application of the Maximum Likelihood Principle of the model reported in Equation 7. In the proposed software this procedure is implemented and carried out automatically, providing the unknown parameters in few seconds.

3. Experimental validation

In this Section, the models and the procedure for parameter estimation are experimentally validated. In particular, in Section 3.1 the graphical user interface is briefly presented; in Section 3.2 the models are experimentally validated by considering the experimental results obtained by the authors or taken from the literature.

3.1. Graphical user interface

The software Matlab is used for the implementation of the models described in previous Section. In particular, a Matlab code is written for the automatic parameter estimation. In Figure 3, the graphical user interface is shown:

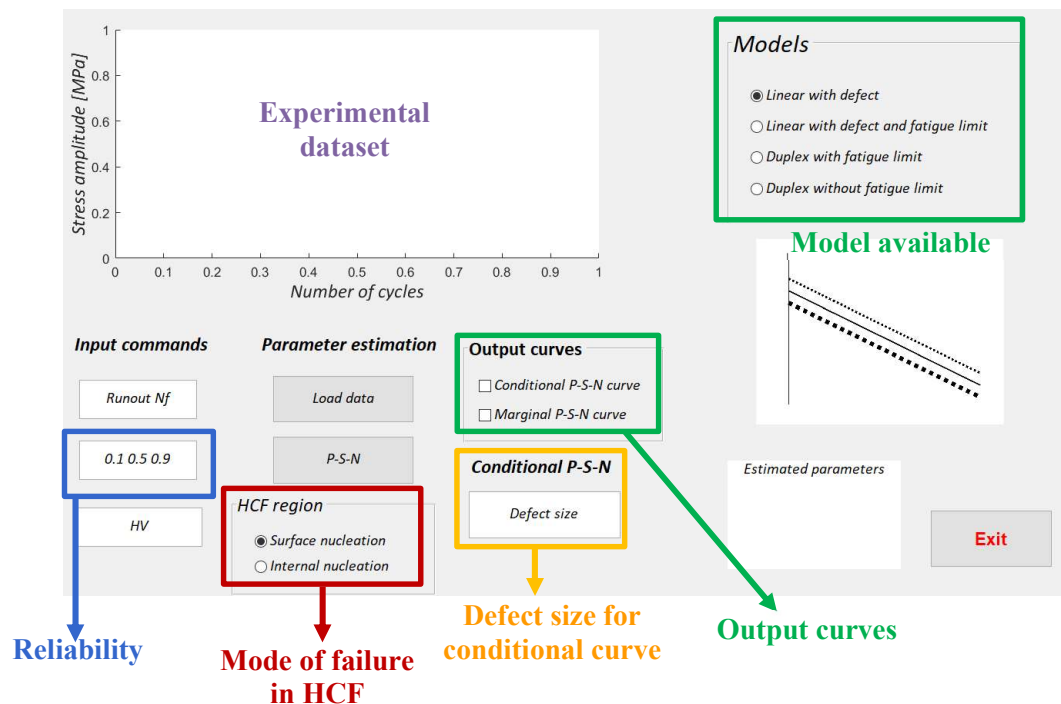


Figure 3: Graphical user interface for the parameter estimation and for the assessment of the P-S-N curves.

According to Figure 3, the developed graphical user interface permits to select the reliability of the P-S-N curves in output, to select the mode of failure in the HCF region (above the transition stress) for the duplex model and, for the conditional P-S-N curves, the defect size. The models currently available are those described in previous Section and the analysis can be run by uploading a text file and with the button “P-S-N”. The software provides in output the P-S-N curves and the estimated parameters in a text file. The graphical user interface is currently under development.

3.2. Model validation

The models implemented and the procedure for parameter estimation are finally validated. The simplest model, i.e. the marginal P-S-N curves without fatigue limit, is validated at first. In particular, the experimental data reported in [16] (experimental tests on as-built AISi10Mg specimens obtained through a Selective Laser Melting process) are considered for the validation. The parameter estimation is carried out by applying the Maximum Likelihood Principle and by considering both failures and runout. Figure 4 shows the marginal P-S-N curves for the experimental data in [16]: the median, the 90-th and the 10-th marginal curves are shown, together with the experimental data.

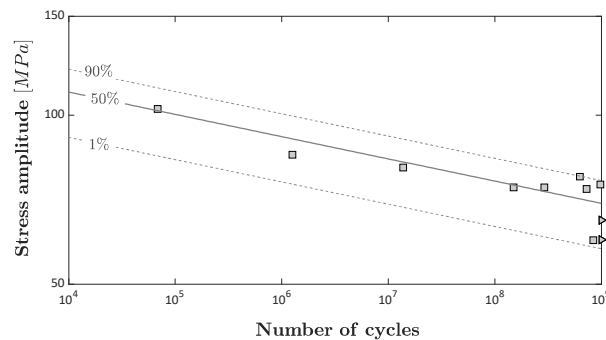


Figure 4: Marginal P-S-N curves estimated through tests on AlSi10Mg specimens produced through SLM [16].

According to Figure 4, the marginal P-S-N curves are in agreement with the experimental data: about the 50% of the experimental failures are above the median curve and about the 89% are within the 80% confidence interval, thus validating the proposed model.

The case of experimental failures in VHCF with FGA morphology and fatigue limit is also validated. The experimental data reported in [17] (ultrasonic fatigue tests on H13 tool steel) are considered. The resulting marginal P-S-N curves (median, 10% and 90%) are shown in Figure 5.

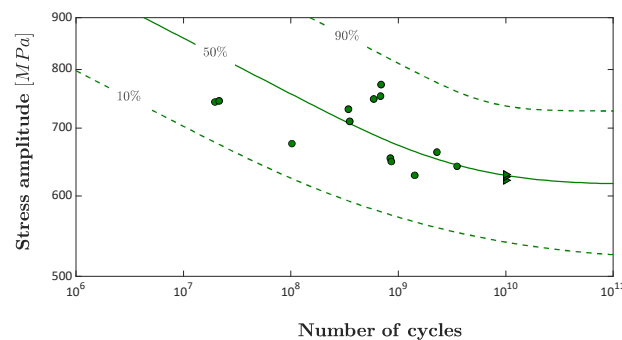


Figure 5: Marginal P-S-N curves estimated from tests on H13 specimens [17]: finite fatigue life (with FGA morphology) and fatigue limit.

As for Figure 5, also the model with fatigue limit is in good agreement with the experimental data, with all the data within the 80% confidence interval and the median curve below and above the 50% of the experimental failures.

The duplex model without fatigue limit is also validated. The experimental dataset reported in [11] and obtained by testing a High-Strength-Low-Alloy (HSLA) steel is considered: in particular, surface failures are found above the transition stress; whereas failures originating from defects are experimentally found in the VHCF region. The experimental data and the estimated marginal P-S-N curves (95%, median and 5%) are shown in Figure 6.

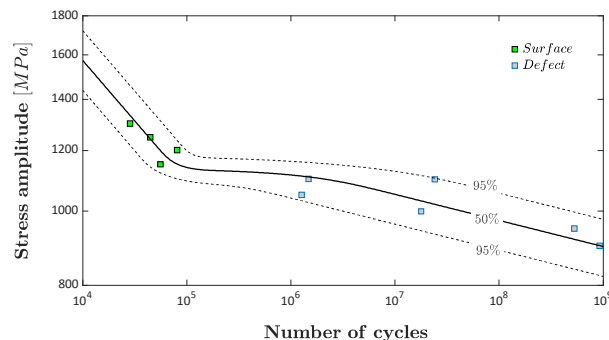


Figure 6: Marginal P-S-N curves estimated through tests on HSLA specimens [11]: duplex model without fatigue limit.

According to Figure 6, even if the number of experimental data is limited, the model is capable to properly fit the two trends and the transition stress. The median curve is capable to equally subdivide the experimental failures and all the data are within the 90% confidence interval.

Finally, the complete duplex model is validated by considering the fatigue response of a H13 tool steel. In particular, for the HCF region the experimental results are taken from the literature [18] and the fatigue failures originated from the specimen surface. On the other hand, the experimental data for the VHCF are collected by the authors [17]. Even if the data are obtained by different authors and by considering different manufacturing processes, they can be used for a qualitative validation of the proposed duplex model. Figure 7 shows the experimental data together with estimated P-S-N curves (5%, median and 95%).

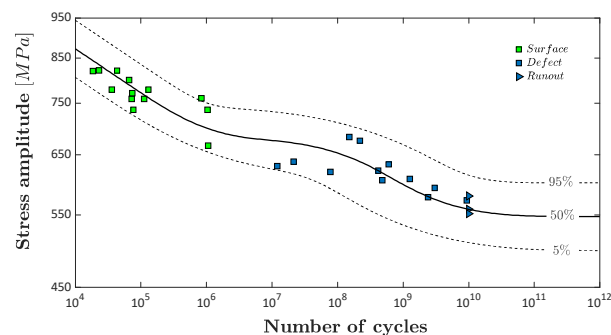


Figure 7: Marginal P-S-N curves estimated through tests on H13 tool specimens [17, 18]: duplex model with fatigue limit.

As shown in Figure 7, the estimated model for the complete duplex curve well fits the experimental data and is capable of properly modelling the occurrence of two failure modes, a transition between them and a final asymptote. 96% of the experimental data are within the 90% confidence interval and the median curve equally subdivides the experimental dataset, proving the validity of the model and of the procedure for the parameter estimation even in presence of different failure modes.

4. Conclusions

In the present paper, a new software for the estimation of the P-S-N curves in case of failures originating from defects has been proposed. The models implemented in the software have been described and validated by considering the experimental data collected by the authors and taken from the literature. In particular, a general model for the estimation of the duplex curve with fatigue limit has been proposed.

Differently from the literature, the influence of defects on the fatigue life in the HCF and in the VHCF region can be taken into account with the proposed formulation.

The experimental validation has confirmed the validity of the implemented models and also of the procedure for the parameter estimation, which takes a limited time even for the most complex models (less than 1 minute). The proposed software has been implemented by writing a Matlab code. It would permit to reliably assess the P-S-N curves when defects are at the origin of the fatigue failures and would help designers in assessing the fatigue strength of components both in HCF and in the VHCF region and in presence of different failure modes.

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