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A methodology for probabilistic prediction of fatigue crack initiation taking into account the scale effect

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ABSTRACT

An approach for probabilistic prediction of fatigue crack initiation lifetime of structural details and mechanical components is presented. The methodology applied is an extension of the generalized local model (GLM) to the fatigue case using the fatigue Weibull regression model proposed by Castillo-Canteli. First, the primary failure cumulative distribution function (PFCDF) of the generalized failure parameter is derived from experimental results for a given reference size, taking into account the non-uniform distribution of the generalized parameter (GP) the specimens are submitted to. The adequacy of the GP is presumed, ensuring uniqueness of the derived PFCDF as a material property, irrespective of the specimen shape and size, and the test chosen to this end. Next, the GP distribution is obtained by a finite element calculation and the PFCDF is applied to each finite element, considering the scale effect, to derive the probability of failure for the whole component. The suitability of the proposed approach is illustrated twice: first, assessing simulated data in a theoretical example, and second, evaluating experimental fatigue life results for riveted joints from the historical Fão Bridge. The PFCDF for the puddle iron from the bridge is calculated from standard tensile specimens, from which the initiation fatigue lifetime of the riveted connections is predicted and compared with the experimental results. In this way, the transferability from standard tests to real components is demonstrated.

1. Introduction

Probabilistic fatigue models are indispensable to take into account the different sources of uncertainty inherent to fatigue lifetime analysis, which become apparent as scatter of the experimental data. Contrary to deterministic models, probabilistic ones provide the solution to extrapolate fatigue data from simple uniaxial tension or bending tests to predict lifetime of components or even large engineering structures, such as bridges, ensuring transferability, in which the scale and shape effect are important issues to be considered. It is worth mentioning that, besides probabilistic models, there are also deterministic models based on fractal theories that allow the scale effect to be taken in a natural way [1–3].

During the last decades, different probabilistic fatigue models have been proposed in the literature to derive probabilistic S-N fields. Already in 1972, Bastenaire [4] proposed a method for the statistical evaluation of constant stress amplitude fatigue test results. After that, different models and improvements have been developed, such as the study of cumulative damage developed by Bogdanoff (1985) [5] based on the so-called B-model, or the inclusion of censored life data proposed by

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Nomenclature

B	threshold number of cycles of the Castillo-Canteli model
C	fatigue limit of the Castillo-Canteli model
CDF	cumulative distribution function
EFCDF	experimental failure cumulative distribution function
GLM	generalized local model
GP	generalized parameter
N	number of cycles
N_{ini}	lifetime to crack initiation
PFCDF	primary failure cumulative distribution function
P_{fail}	probability of failure
P_{int}	integrated probability of failure
S	stress
S_{ref}	reference size
SWT	Smith-Watson-Topper parameter
V	normalized variable of the Castillo-Canteli model
λ	Weibull location parameter
β	Weibull shape parameter
δ	Weibull size parameter
ε	strain

Escobar and Meeker (1999) [6]. Furthermore, other relevant examples of probabilistic fatigue models are presented by the works of Pascual and Meeker [7], Spindel and Haibach [8], and Schijve [9]. The Weibull fatigue approach proposed by Bolotin [10,11], denoted "half phenomenological" by the author, is derived from scalar damage measures, and deserve special recognition since it anticipates the Weibull regression model for the S-N and ε-N fields as proposed by Castillo and Canteli [12]. The latter merges as the solution of a functional equation, resulting from the necessary compatibility condition to be accomplished along the whole S-N field between both distributions, that of lifetime for given stress (or strain) range and that for stress (or strain) range for given lifetime. An interesting point is that the Bolotin model fulfils the above mentioned compatibility condition, without being contemplated as an initial requirement of the model by the author [10,11].

Subsequently, Correia et al. [13] have extended this model to more general damage criteria, by considering the Smith-Watson-Topper (SWT) parameter as a reference for the fatigue damage, thus leading to the probabilistic SWT versus number of cycles field (p-SWT-N). An extension to more general parameters of energetic character is justified in Ref. [14].

Usually, the p-S-N field (probabilistic stress versus number of cycles field), resulting from probabilistic Weibull fatigue models, is applied without considering the influence of the reference parameter distribution due to the geometry and size of the specimens tested and loading conditions. This even hinders a comparison between different testing programs. Occasionally, the length effect on the fatigue lifetime of long elements has been explicitly investigated [15], but generally the influence of the varying distribution of the reference parameter over the specimen (usually referred to stress or strain) is neglected, leading to an erroneous cumulative distribution function (CDF) of failure or mistaking the reference specimen size. This limitation in previous models impedes a correct transference of the fatigue characterization resulting from small-scale specimens tested in the laboratory to the practical design, so that the prediction of the fatigue crack initiation life of real components and structures will be unreliable.

To proceed to the fatigue lifetime forecasting of real components, the so-called primary failure cumulative distribution function (PFCDF) must be derived by applying the "generalized local model" (GLM), developed in previous works of the authors for quasi-static failure predictions [16–18]. The PFCDF characterizes the material failure in a probabilistic way representing the probability of failure for a given reference size of the material as a function of the generalized parameter, this being uniformly distributed over that size. The PFCDF could be derived from any specimen geometry and size even in the case of non-uniform distribution of the selected reference parameter along the specimen, so that any type of test may be adopted to characterize the material. In this way, the assessment of the probabilistic failure of a real component for any geometry, size and loading conditions is possible.

The GLM, initially developed to predict the quasi-static failure of components made of brittle materials such as structural members of glass, may be extended to fatigue lifetime prediction based on the normalizing property of the Weibull fatigue model proposed by Castillo-Canteli [12], assuming validity of the weakest link principle. In particular, a probabilistic prediction of the fatigue crack initiation of structural details or mechanical components of engineering structures is feasible, taking into consideration the specimen shape and size, and the distribution of the critical fatigue damage parameter. The combination of both models (GLM and Weibull fatigue model) ensures the uniqueness of the PFCDF, which can be derived irrespective of the test selected to this aim. As a consequence, assuming adequacy of the fatigue damage parameter adopted, the probabilistic methodology proposed in this paper guarantees the transferability of the fatigue test results from laboratory