Engineering Fracture Mechanics 121–122 (2014) 40–66

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Reliability assessment of high cycle fatigue under variable amplitude loading: Review and solutions

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ARTICLE INFO

Article history:
Received 22 January 2013
Received in revised form 15 February 2014
Accepted 22 February 2014
Available online 3 April 2014

Keywords:
Reliability
Fatigue crack growth
Damage tolerant
High cycle fatigue
Variable loads

ABSTRACT

In fatigue reliability assessments, the random load process is commonly represented by its marginal distribution (load spectrum) only. However, as shown in this paper, the correlation characteristics of the load process can have a strong influence on the fatigue reliability and should be accounted for. The paper reviews the modeling of random fatigue crack growth under variable amplitude loading for reliability analysis. Solutions for fatigue crack growth evaluation at different levels of detailing are described and a fatigue crack growth and failure evaluation algorithm, based on a discretization of the random stress process, is presented. As an alternative, a mean approximation is described. Finally, effective computational methods for assessing the fatigue reliability under variable amplitude loading are introduced and applied exemplarily to a case study. The solutions are based on the first-order reliability method FORM and the subset simulation. Using a Markov process model of the loads, the influence of different types of service histories is investigated, by varying the correlation length of the stress cycle process. The results show that the correlation length of the load process has significant influence on the resulting reliability; the resulting probability of failure can vary up to several orders of magnitude for the same marginal probability distribution of stress amplitudes. Based on the results of the case study, the influences of the stress process correlation and of the adopted failure criteria on the reliability are discussed. The mean approximation and the random variable model of the random load process are demonstrated to be applicable under specific conditions.

1. Introduction

The reliability of mechanical and structural components subjected to high cycle fatigue can be ensured with a safe-life approach, a damage tolerant design or a fail-safe approach. The safe-life approach requires that the fatigue reliability is sufficiently high over the entire service life, which is typically achieved by ensuring that no or only small crack growth occurs [1]. Damage tolerant design ensures that the component does not fail between inspection intervals with a sufficiently high reliability [2]. The fail-safe approach ensures that damages are limited in case of fatigue failure. In many applications, the fail-safe approach is ruled out, and it is necessary to demonstrate sufficient reliability, with or without inspections. Thereby, the uncertainties in fatigue crack growth must be considered, which are associated with the presence and size of initial flaws or cracks, the mechanical properties of the material, the fatigue crack growth models and its parameters, and the stress

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http://dx.doi.org/10.1016/j.engfracmech.2014.02.023
0013-7944/

Nomenclature

a	crack depth
a_0	initial crack depth
a_{cr}	critical crack depth
b	number of cycles in a block
c	crack semi-length
$\frac{dx_i}{dn}$	general expression of the crack growth rate in direction x_i
$h_a = \frac{da}{dn}$	fatigue crack growth rate in a-direction
$h_c = \frac{dc}{dn}$	fatigue crack growth rate in c-direction
h_x	fatigue crack growth rate
$f_{\Delta\sigma,R}$	is the joint CDF of $\Delta\sigma(n)$ and $R(n)$
$g(\mathbf{X})$, $g(\mathbf{X}, N)$	limit state function
k_0, k, k_{min}	parameters of the toughness distribution
n	number of fatigue cycles
m, p, q, C, C_{th}, A_0	Forman–Mettu equation parameters
n_F	number of failures
n_s	number of samples
p_F	probability of failure
x	generic crack length
z	correlation length of the stress range process
CDF	cumulative density function
E	Young's modulus
F	cumulative density function
$F_{\sigma_{max,i}}$	CDF of the maximum stress range in b cycles
FORM	first order reliability method
$G(\mathbf{U})$	limit state function in the standard normal space
J	J-integral
J_e	elastic J-integral
J_{mat}	fracture toughness expressed as J-integral
K	stress intensity factor
K_{mat}	fracture toughness expressed as K-factor
K_{max}	maximum stress intensity factor
L	length of the tubes
L_r	ligament yielding factor
$L_{r,max}$	critical value of the ligament yielding factor
MCS	Monte Carlo simulation method
MA	mean approximation
N	number of cycles (fixed value)
N_{fail}	number of cycles at failure
N_{target}	target number of cycles
N_{stop}	number of cycles at which the crack growth algorithm stops
NDT	non-destructive tests
P	load
POD	probability of detection
R	stress ratio
$\{R(n)\}$	random process of the stress ratio
RV	random variable
RP	random process
SuS	subset simulation method
UTS	ultimate tensile strength
WT	wall thickness
X	vector of random variables
U	vector of standard normal uncorrelated random variables
V	vector of standard normal correlated random variables
$\{X(n)\}$	general expression for a random process
γ	vector of parameters related to the geometry of the component containing the crack
δ	vector of parameters related to the material properties
θ, ζ	parameters of the POD distribution
φ	standard normal probability density function
ν	Poisson's ratio