International Journal of Fatigue 31 (2009) 1882–1888

Contents lists available at ScienceDirect

International Journal of Fatigue

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

A reliability assessment method for structural metallic component with inherent flaws based on finite element analysis and probabilistic fracture mechanics model

Bo Wu [a,b,*], Anglika Brückner-Foit [b], Qiang Li [a], Lu Chen [a], Jinbiao Fu [a], Chaohui Zhang [a]

[a] *College of Materials Science and Engineering, Fuzhou University, University Park, 350108 Fuzhou, PR China*
[b] *Quality and Reliability Laboratory, Institute of Materials Technology, Department of Mechanical Engineering, Universität Kassel, Mönchbergstr. 3, 34125 Kassel, Germany*

ARTICLE INFO

Article history:
Received 18 September 2008
Received in revised form 2 February 2009
Accepted 7 February 2009
Available online 20 February 2009

Keywords:
Reliability assessment
Lifetime distribution
Finite element analysis
Probabilistic fracture mechanics
Fatigue crack growth

ABSTRACT

Reliability assessment is an essential step to promote advanced materials and components into applications. In this paper, a general reliability assessment framework was proposed to predict the lifetime distribution of a structural steel component with inherent flaws. By combining materials information, finite element analysis of the stress field and probabilistic fracture mechanics model, the distribution of failure probability subjected to fatigue loads was predicted. The local failure probability distributions identify the critical regions of the component visually. Both the global failure probability and the local failure probability distribution can be considered as essential and fundamental data in structure design and system maintenance. Focus was placed on the probabilistic fracture mechanics model and fatigue crack growth model.

1. Introduction

Structural safety and reliability assessment is essential work for design and maintenance of modern engineering systems. The systems range from microelectronic and bio-medical devices to large machinery and structures, as well as civil engineering [1–4]. For example, in a commercial project concerning a high efficient gas turbine rotor in European Union, the full project was subdivided into five work packages, and one of them was to develop a reliability assessment tool for the steel component made from a nano-precipitate hardened high nitrogen steel. The reliability assessment tool integrates material properties, finite element stress analysis and probabilistic fracture mechanics consideration. The probabilistic fracture mechanics model is generally based on the assumption that failure occurs due to the subcritical and catastrophic crack growth of crack-like defects introduced during fabrication. Such defects are initially present with a given probability, and are found during pre- and in-service inspections with a probability depending on their size. The subcritical and catastrophic growth of these defects is governed by fracture mechanics considerations, which may also involve material properties that are randomly distributed. Cracks found by inspection determine the component to be retiring or not.

The basic ideas of the reliability assessment tool are presented in this paper. The probabilistic fracture mechanics model is described in Section 2. In Section 3, a semi-elliptical surface crack growth model subjected to fatigue load is discussed and programmed. The demonstration of the reliability assessment tool is given in Section 4 with a four-point-bending bar. A summary and outlook are presented in Section 5.

2. The framework of reliability assessment tool and probabilistic fracture mechanics model

2.1. The framework of reliability assessment tool

The framework of the reliability assessment tool is sketched in Fig. 1. The ABAQUS, PATRAN and ANSYS represent the commercial finite element analysis software packages, and any of them can be employed depending on the availability. The ginput.for file is an interface program developed in the current work to extract the data of the geometry model and the stress field from the finite element analysis, which coincides with the commercial finite element analysis package mentioned above, and the STAUF is a finite element analysis post-processor developed in the current work based on the probabilistic fracture mechanics method.

---

[*] Corresponding author. Address: College of Materials Science and Engineering, Fuzhou University, University Park, 350108 Fuzhou, PR China. Tel.: +86 591 38725008; fax: +86 591 22866537.

E-mail addresses: wubo@fzu.edu.cn (B. Wu), a.brueckner-Foit@uni-kassel.de (A. Brückner-Foit), qli@fzu.edu.cn (Q. Li), cliiverson@sina.com (L. Chen), fujinbiao0114@yahoo.com.cn (J. Fu), arbor4388@sina.com (C. Zhang).

0142-1123/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijfatigue.2009.02.013

Nomenclature

a	the crack size, in the semi-elliptical crack, a represents the minor semi-axis (in depth)
a_0	the initial crack size
a_c	the critical size of crack
$a_{(c,0)}(x,\omega)$	the critical initial crack size,
c	the major semi-axis of the semi-elliptical crack (on surface)
a_0/c_0	the aspect ratio of the cracks at the beginning of the lifetime
a/c	the crack aspect ratio during the fatigue process
d	the diameter of the precipitate particles
w	the width of the plate
t	the thick of the plate
A	the surface of the component under consideration
dA	the surface elements under consideration
M	the average number of crack on the surface area A of the component
M_0	the mean density of surface crack on the component
n	the statistically independent cracks on the surface elements dA of the component
N	the cycle number
N_n	the corresponding cycle numbers of crack size a_n
N_f	the lifetime (the cycle numbers to failure)
C, m	the parameters of the Paris law of the fatigue crack growth
σ	the applied stress field
σ_{eq}	the equivalent stress
$\sigma_{\max}$	the maximum fatigue load
$\sigma_{\min}$	the minimum fatigue load
σ_n, τ_{II}, τ_{III}	the projections of the stress tensor on the crack plane
K_I, K_{II}, K_{III}	the stress intensity factors with the mode *I*, *II*, *III*
Y_I, Y_{II}, Y_{III}	the geometric correction factors with the mode *I*, *II*, *III*
ω	the orientation of the crack plane
$g(K_I, K_{II}, K_{III})$	the failure criterion
g_c	the critical value of the failure criterion
$K_{I_{eq}}$	the equivalent mode *I* stress intensity factor
K_{Ic}	the mode *I* fracture toughness of the material
x	the location of the cracks
f_A	the probability density functions of the location
P_x	the probability of a surface crack having the location x
Ω	the orientation of the crack relative to a pre-defined coordinate system
f_Ω	the probability density functions of the orientation
P_ω	the probability of a surface crack having the orientation ω relative to the global coordinate system
$f_{a_0}(a)$	the probability density function of the initial crack size
P_{F_a}	the probability of a crack size exceeding the critical value
$P_F^{(1)}, Q_F^{(1)}$	the failure probability of a component containing exact one crack
$P_S^{(1)}$	the survival probability of a component containing exact one crack
$P_F^{(n)}$	the failure probability of a component containing n statistically independent cracks
$P_S^{(n)}$	the survival probability of a component containing n statistically independent cracks
$P_{S,A}$	the survival probability of a component containing an arbitrary number of surface cracks
$P_{F,A}$	the failure probability of a component containing an arbitrary number of surface cracks
P_n	the probability of having exact n cracks on the surface A of a component with an average number M of cracks
$F_{a_0}(a_{(c,0)})$	the cumulative probability distribution function of the initial crack size $a_{(c,0)}$
ΔK, ΔK_A, ΔK_c	the stress intensity factor range in general, in deepest point A and on surface point C, respectively
K_A, K_C	the stress intensity factor in deepest point A and on surface point C, respectively
$E(k)$	the second elliptical integral
z	the vector of all random variables
$Z_1, \ldots, Z_k$	the random variables of type (1)
ABAQUS, PATRAN, ANSYS	the commercial finite element analysis software packages
ginput.for	the interface program between the finite element analysis and finite element analysis post-processor
STAUF	a finite element analysis post-processor
GUI	the graphical user interface

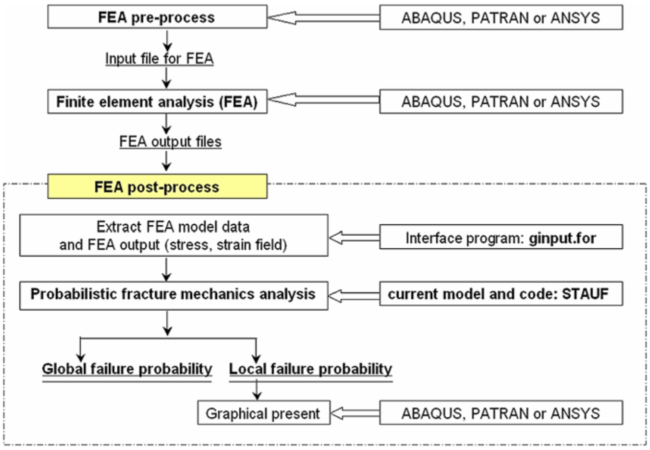

Fig. 1. The framework of the reliability assessment tool.

Generally, the procedure of the reliability assessment can be subdivided into the following steps:

(1) Finite element analysis (FEA) pre-process.
(2) Finite element analysis (FEA).
(3) Finite element analysis (FEA) output data extract and rearrangement.
(4) Probabilistic fracture mechanics computation.
(5) Result graphical presentation.
(6) Graphical user interface (GUI).

Steps (3–6) are the so-called finite element analysis post-processor. In the present paper, the emphasis is put on the probabilistic fracture mechanics model.

2.2. Probabilistic fracture mechanics model

Compared with the volume flaws, the surface flaws are believed to be more dangerous in metallic materials, so the surface cracks are considered as the risk inherent flaws in this work.

Probabilistic fracture mechanics [5–7] is used to describe the failure behaviour induced by inherent cracks. Unstable propagation, i.e. spontaneous failure, occurs if the crack size exceeds a certain critical value a_c. The random orientation of a crack in the applied stress field σ in general leads to a mixed-mode load of