Engineering Fracture Mechanics 76 (2009) 1437–1449

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

Triple-scale failure estimation for a composite-reinforced structure based on integrated modeling approaches. Part 2: Meso- and macroscopic scale analysis

J.H. You *

Max-Planck-Institut für Plasmaphysik, Euratom Association, Boltzmannstr. 2, 85748 Garching, Germany

ARTICLE INFO

Article history:
Received 26 September 2007
Accepted 31 October 2008
Available online 17 November 2008

Dedicated to Professor Wolfgang Brocks on the occasion of his 65th birthday.

Keywords:
Metal matrix composite
Finite element analysis
Probabilistics
Weibull theory
Shakedown
Failure assessment

ABSTRACT

In this article, the meso- and macroscopic failure features are discussed considering the identical composite component as in the foregoing article. In the meso-scale failure analysis, the risk of plastic instability of the composite tube was estimated considering the shakedown boundary as a failure criterion. The meso-scale stresses of the composite tube were computed using micromechanical homogenization and compared with the shakedown boundary of the composite obtained from the direct shakedown analysis. The stress states were close to the shakedown boundary indicating no critical danger of plastic failure. In the macro-scale failure analysis, the mechanical influence of the local composite integration was investigated with regard to the brittle failure risk of the neutron-embrittled component. To this end, a probabilistic failure analysis code was applied which was based on the fracture mechanics and the weakest-link failure theory. Various fracture criteria were considered. It was found that the failure risk of the tungsten block was strongly reduced by the composite reinforcement of the tube due to the intensification of compressive stress fields.

1. Introduction

In the foregoing companion article (part 1), the microscopic failure features of a composite component was treated. A plasma-facing component for fusion reactors was considered whose cooling tube was locally reinforced with fiber metal matrix composite (FMMC). The focus of the microscopic failure analysis was placed on the estimation of the fiber fracture risk and the plastic damage of the ductile matrix. Non-linear triple-scale FEM was applied using the micromechanics-based homogenization algorithm.

In the present article (part 2), meso- and macroscopic failure features of the same FMMC component are discussed (see Fig. 1). The failure problems are treated in two lines, that is, plastic instability of the FMMC tube (meso-scale) and brittle failure of the tungsten armor block (macro-scale).

1.1. Meso-scale failure analysis: shakedown behavior

This issue is related to the plastic flow in the ductile matrix which is locally concentrated near the fibers. The plastic behavior of the FMMC is detrimentally affected by variation of the applied loads. Although major plasma instability will

* Tel.: +49 89 3299 1373.
E-mail address: you@ipp.mpg.de

0013-7944/$ - see front matter
doi:10.1016/j.engfracmech.2008.10.017

Nomenclature

Latin symbols

a	crack size
a_c	critical crack size
b	Weibull parameter (scale parameter)
$[B]$	matrix of partial derivatives of the shape function
$[J]$	Jacobian transformation matrix for the shape function of an element
$f(\sigma^s, x)$	von Mises yield function
$g(K_{Ieq}, 0, 0)$	effective failure criterion
$g(\sigma_n, \tau_{II}, \tau_{III})$	mixed-mode failure criterion
J_V, J_Ω	Jacobians of variable transformation
K	stress intensity factor
K_{Ic}	mode I fracture toughness
K_{Ieq}	equivalent mode I stress intensity factor
m	Weibull modulus (shape parameter)
N_e	number of elements of the FEM model
P	elastically admissible domain
$P_{F,A}$	failure probability due to unstable propagation of surface cracks
$P_{F,V}$	failure probability due to unstable propagation of volume cracks
V_e	volume of the eth element
dV	infinitesimal volume element
X	coordinate for macroscopic length scale
x	coordinate for microscopic length scale
Y	geometric correction factor

Greek symbols

θ	element coordinate in the reference configuration
Σ	macroscopic stress tensor
σ	microscopic stress tensor
σ^c	elastic stress field in virtual elastic matrix
σ^e	microscopic elastic stress state
σ_{eq}	equivalent stress
σ_n	normal projection of stress tensor on crack plane
σ_o	material parameter in a 2-parameter Weibull distribution
$\hat{\sigma}^r$	time-independent periodic residual stress field
σ^s	safe states of stress
σ^*	reference stress characterizing a load level
τ_{II}, τ_{III}	shear projection of stress tensor on crack plane
ξ	element coordinate in the reference configuration
Ω	domain occupied by the unit cell

be suppressed in fusion power plants, unexpected minor plasma instability may possibly appear generating heat flux fluctuations [1]. This thermal load perturbation will lead to a thermal stress variation in the plasma-facing component.

Depending on the stress state and loading history, the plastic response of a FMMC under variable loads will show one of the following behaviors: elastic shakedown, alternating plasticity (low cycle fatigue) or progressive straining (ratcheting). Such plastic responses can be most suitably described on a mesoscopic length scale (e.g. length scale of a unit cell or a representative volume element) [2].

According to the cyclic plasticity FEM study of a conventional plasma-facing component, low cycle fatigue of the softened copper alloy cooling tube can be a critical failure problem [3]. Hence, shakedown limit may be regarded as an appropriate failure criterion in the context of failure assessment of the FMMC tube under variable loads. The FMMC, which was initially loaded in a plastic regime, eventually reach elastic state under arbitrarily varying load, provided that the peak load is bounded within the shakedown limit. In this circumstance the plastic strain ceases to develop and overall FMMC response is confined within safe elastic regime regardless of the loading path thereafter. When maximum load is located beyond this limit, the FMMC component will undergo either low cycle fatigue or incremental plastic collapse (ratcheting) [4–6].

Recently, several theoretical works were reported in the literature in which shakedown boundaries of FMMC under various loading conditions were computed using the FEM-based direct shakedown analysis method [7–12]. On the other hand, theoretical study to investigate the shakedown behavior of a composite component is not found yet.