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Triple-scale failure estimation for a composite-reinforced structure based on integrated modeling approaches. Part 1: Microscopic scale analysis ☆

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ABSTRACT

The structural reliability of a composite component locally reinforced with a fibrous metal matrix composite is essentially affected by the micro-scale failures. The micro-scale failures such as fiber fracture or matrix damage are directly governed by the internal stress states such as mismatch thermal stress. A proper computational method is needed in order to obtain micro-scale stress data for arbitrary thermo-mechanical loads. In this work a computational scheme of microscale failure analysis is presented for a composite component. Micromechanics-based triple-scale FEM was developed using composite laminate element. The considered composite component was a plasma-facing component of fusion reactors consisting of a tungsten block and a composite cooling tube. The micro-scale stress and strain data were estimated for a fusion-relevant heat flux load. Ductile damage of the matrix was estimated by means of a damage indicator. It was shown that the risk of micro-scale composite failure was bounded below an acceptable level.

1. Introduction

Nowadays fiber-reinforced metal matrix composites (FMMC) are considered as promising materials for high-temperature structural applications. Examples of potential application are aircraft engine turbine, heat sink of power electronics and plasma-facing component of nuclear fusion reactors [1–4]. The essential advantage of FMMCs is that high thermal conductivity and toughness of a metallic matrix can be combined with excellent strength and creep resistance of strong fibers [5,6]. Further, small coefficient of thermal expansion (CTE) and high elastic modulus of the fibers can be utilized to tailor the corresponding composite properties.

In design practice of a composite component, structural reliability is usually evaluated in terms of composite failure on a macroscopic scale. For instance, some commercial FEM codes provide failure estimation postprocessors in which stresses are averaged for each element by means of elastic homogenization method and compared directly with the macroscopic strength data of the composite according to various composite failure criteria such as Tsai-Hill [5,6]. Although the spatial resolution of the prediction can be arbitrarily improved by mesh refinement, this approach has a macroscopic nature since the stress state is averaged in each finite element. In the framework of an empirical failure criterion it is tacitly assumed that the composite failure is controlled solely by macroscopic stress.

In reality, the situation is more complex because of internal stress and matrix plasticity. It should be noted that FMMCs are fabricated usually at high temperatures and used also at elevated temperatures. Due to the mismatch of CTE between the

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

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Nomenclature

Latin symbols

$\bar{A}_t^{(p)}$	instantaneous mean field strain concentration tensor of phase p
$\bar{B}_t^{(p)}$	instantaneous mean field stress concentration tensor
C	global elastic compliance matrix
D_p	Rice–Tracey damage indicator
E	global elastic stiffness matrix
E_t	global instantaneous tangent stiffness
I	fourth rank identity tensor
S_t	instantaneous Eshelby tensor

Greek symbols

$\langle\varepsilon\rangle$	global volume averaged stress tensor
$\langle\varepsilon\rangle_{tot}^{(p)}$	phase averaged total stress tensor in phase p
$d\langle\varepsilon\rangle_{mech}$	far-field global averaged mechanical strain rate
$\Delta\varepsilon_c$	global strain increment
$\Delta\varepsilon_{mech}$	global strain increment from purely mechanical contribution
$\Delta\varepsilon_{EB}$	Euler-backward strain
$\varepsilon_{e,pl}$	equivalent plastic strain
${}^{n+1}\Delta\varepsilon$	applied global strain sub-increment
$\Delta\langle\varepsilon\rangle_{mech}^{(m)}$	phase averaged mechanical strain increment in matrix
η	stress triaxiality
σ_e	von Mises equivalent stress
σ_h	hydrostatic stress
$\langle\sigma\rangle$	global volume averaged stress tensor
$\langle\sigma\rangle_{tot}^{(p)}$	phase averaged total stress tensor in phase p
$\Delta\langle\sigma\rangle_{tot,el}^{(m)}$	elastic predictor

matrix and the fibers considerable internal thermal stress fields may appear [6,7]. In the absence of applied load this mismatch stress is a kind of residual stress. The characteristic fluctuation length of the internal stress fields spans typically over the length of a fiber diameter.

In the residual stress state, tensile stress prevails in the matrix whereas the fibers are stressed compressively [7,8]. During subsequent thermo-mechanical loading, the applied mechanical stress and the mismatch thermal stress are superposed on micro-scale. As a result of superposition, the matrix and the fibers experience completely different evolution of the internal stresses. Hence, the actual internal stress state is determined by previous thermal load history as well as by currently applied load.

The structural reliability of a FMMC component is essentially affected by the micro-scale failures such as fiber fracture or matrix damage. On the other hand, these micro-scale failures are directly governed by the internal stress states [9]. Hence, accurate estimation of the internal stresses is a primary design concern. In this context, a computational method is needed which is able to provide with the micro-scale data of the composite related to the micro-scale failure mechanisms. There are also failure features which can be better assessed and interpreted on higher length scales, for example, plastic instability of FMMC or stress perturbation effect in the vicinity of the embedded FMMC.

The correlation between micro- and macro-scale field quantities can be established by means of micromechanics-based homogenization methods [10–12]. One of the most widely used methods is the mean field theory of Mori and Tanaka [13]. This method enables to identify the local stress (strain) state of each phase (i.e. matrix and inclusions) via stress (strain) concentration tensor which is a function of the elastic stiffness tensor of the local phases and the Eshelby tensor [14–16]. The original elastic formulation was extended to a non-linear rate form to consider matrix plasticity [17]. This scheme was initially restricted to uniformly applied loads. Afterward, it was formulated as a constitutive equation and was further implemented into a commercial FEM code as a material law subroutine [18]. It was demonstrated that this implemented algorithm worked successfully for a hierarchic stress analysis of a particulate composite [19].

The algorithm was further applied to a FMMC laminate system by the author for which the micromechanical material subroutine was combined with the 3-dimensional composite laminate element of the ABAQUS code [20]. This approach allowed elasto-plastic FEM analysis of a FMMC laminate system on three different composite length scales. Stress and strain data were estimated for matrix and fiber (micro-scale), for lamina layer (meso-scale) and for laminate element (macro-scale). In the following we call it triple-scale analysis.

Considering that FMMC is often locally integrated into a complicated component system, it is highly desired to establish a scale-bridging failure analysis methodology for industrial composite component systems. The aim of present work is to illustrate a scale-dependent failure estimation methodology for a FMMC component on the basis of the nonlinear triple-scale