NUMERICAL SIMULATION OF DAMAGE IN CERAMIC MATRIX COMPOSITES BASED ON THE BOUNDARY ELEMENT METHOD

H. Maschke, R. Schäuble, S. Wagner*

Based on an advanced BEM-code, a direct approach to damage in ceramic matrix composites was implemented. Damage evolution under the action of external loads is modelled by simulating the formation of micro crack patterns in a piecewise homogeneous, anisotropic, linear elastic material. Local failure is predicted in terms of fracture mechanics concepts taking also into account the stochastic nature of microcrack formation in brittle disordered materials. Thereby - besides the prediction of the macroscopic constitutive response -, an immediate insight is possible into the very complex interactions between the constituents of the hierarchic structure of those composites which govern the features of damage evolution.

INTRODUCTION

Unlike conventional structural ceramics, ceramic matrix composites (CMCs) often exhibit a considerable amount of pseudo-plastic stress-strain-behaviour. This gives this class of materials the potential of attaining toughness values similar to those of metals. In terms of mechanical modelling, CMCs are inhomogeneous materials from brittle constituents. They have a hierarchic structure built up from single fibres (filaments), fibre bundles, and fabrics of a particular texture which are laid up with a certain stacking order. On the other hand, the structure of CMCs usually shows a substantial amount of disorder due to fluctuations in geometric parameters, stiffness values of constituents, and in several strength or toughness values. Thus, ceramic matrix composites can be considered as brittle disordered materials. In contrast to metals, the pseudoplastic behaviour of CMCs is exclusively brought about by a damage evolution which is unique to this class of solids. The investigation of the damage processes and the development of damage-based constitutive models is therefore of primary importance for a substantial understanding of the material behaviour of ceramic matrix composites.

* Fraunhofer Institut für Werkstoffmechanik, Außenstelle Halle, Germany

DAMAGE MECHANISMS IN CERAMIC MATRIX COMPOSITES

In brittle disordered materials damage is generated by the formation of microcracks. Cracking reduces the stiffness and gives rise to various energy-dissipating processes. In the case of ceramic matrix composites the hierarchic structure leads to a corresponding hierarchy of cracks with a great variety both in size and shape. Even in the relatively simple case when load carrying fibres and transverse fibres can be identified in a 2d composite, single fibre failure, longitudinal and transverse cracks in load carrying fibre bundles, normal and transversal cracks in transverse fibre bundles, inter-bundle cracks, and delaminations have to be distinguished for a proper analysis. The extent, the proportions, and the succession of the several classes of crack events are decisive for the global material behaviour. Damage evolution in CMCs is governed by a very complex elastic and fracture mechanical interaction between the constituents of the material which is also influenced by the size, the shape and the loading of the macro-component under consideration.

Traditionally, research in the field of damage theories is focussed on approaches that quantify the amount of damage by the help of one or several continuous damage variables which are introduced on the basis of micromechanical models or phenomonological observations (1). Such a procedure always results in a non-linear constitutive equation providing the basis for numerical calculations and in numerical stability problems at the onset of local failure (2). This kind of approach - when applied to ceramic matrix composites - must take into consideration the different types of crack populations and their interaction which may be very diverse and very strong. First attempts to establish continuum damage theories valid for ceramic matrix composites are meeting these requirements only in parts (3), (4). Whether such an approach will be successful in cases with the characteristic sizes of the crack populations differing by several orders of magnitude and getting near to the components´ extension seems to be undecided up to now. In any case, a link would be desirable intermediate between the phenomena on the microscopic scale and such a homogenization theory which smears the details of damage.

A DIRECT APPROACH TO DAMAGE OF HETEROGENEOUS MATERIALS FROM BRITTLE CONSTITUENTS

In the following, a direct approach to damage of ceramic matrix composites is introduced. It is based on a recently developed model (5) for crack pattern formation in a piecewise homogeneous, anisotropic, linear-elastic material which is accomplished by the help of an advanced boundary element method (BEM) (6). Concisely summarized, the simulation model is constituted by the following elements: 1st: the geometrical arrangement of all potential failure sites (i.e. potential crack paths) which has to be predefined according to the microstructure of the composite within the boundaries of the body under consideration, 2nd: the fracture mechanical concepts (e.g. stress intensity factor concept or alternatively maximum stress concept etc.) according to which the potential failure sites break, 3rd: the according critical values (generalized strength values) of all the potential failure sites, 4th: stochastics which put in appearance as a scattering of geometry parameters and strength values but can also influence the failure process itself via load-dependent failure probabilities. Within each simulation step the complex field of redistributed stresses including the updated fracture mechanical loading quantities of all prospective crack sites is calculated by the help of a linear elastic boundary element code (7). This way, the elastic interaction within the whole system is completely regarded. The development of crack patterns depends not only on the particular choice of different parameters of the simulation model but also on shape, size and loading of the body. With the help of unit cell calculations, where the unit cells are taken to be representative for the material with respect to geometry and loading, macroscopic material properties can be calculated as the result of damage evolution within the cells. Under tensile loading, damage in 0°/90° plain weave fibre composites usually starts by the formation of microcracks in the tranverse fibre bundles. Fig. 1 shows a scheme of the structure of such a material (a), a micrograph of longitudinal bundels embracing two transverse bundles (b), the geometry of a unit cell (c), and the arrangement of potential failure sites (d) for the investigation of this type of damage. The structure of the transverse fibre bundles is reflected by the geometry of potential crack paths which form a slightly irregular honeycomb pattern of straight lines. For the inter-fibre-failure considered here, the loading of the failure sites is reasonably defined in terms of stress components which are averaged over the length of each line. Usually, the load-diplacement-curves which are calculated for one unit cell exhibit a number of sudden drops due to avalanches of failure events which are quite typical for CMCs. In order to get closer to reality in case of a piece of material comprising many cells, a number of single unit cells should be considered under exactly the same loading conditions. Due to its stochastic nature, the evolution of damage in the different cells will exhibit variations. By subsequently applied averaging techniques which are due to parallel connection of cells and/or connection in series the stress-strain-curves are smoothened. For further approximations, the interaction of several cells must be taken into account.

MESOMECHANICAL PARAMETER IDENTIFICATION VIA NUMERICAL SIMULATION COMBINED WITH IN SITU STUDIES OF THE DAMAGE EVOLUTION

The direct approach to damage enables not only the prediction of the macroscopic response of CMC-materials, but also allows an immediate insight into the interaction between their structural constituents. The manner in which properties of the latter which are on the mesoscopic scale govern the damage evolution can be studied in detail. To give an example, the method was applied to 3 different ceramic matrix composites, namely the two carbon fibre reinforced carbons (C/Cs) CF222 and CC1501 and a material of the type C/C-SiC which was made from a C/C precursor by liquid silicon infiltration. First, the evolution of damage in small tensile specimens was investigated experimentally by in situ observation within an environmental scanning electron microscope (ESEM) (8). Thereby it turned out that in the C/C-materials damage starts by longitudinal cracking, in particular within the transverse bundles in the CC1501 but between the normal and transverse bundles in the CF222. On the other hand, in the C/C-SiC transverse cracks within the transverse bundles occured as the first type of damage. Those general features can be reproduced by numerical simulations with the unit cell already introduced (see Fig. 2). To get as close to reality as possible, failure curves valid for combined tensile and shear failure of macroscopic specimens obtained from slant shear experiments (9) were used to predict the failure of the potential crack paths. It turned out by the calculations that the orientation of the initial fibre bundle cracking depends on the ratio of longitudinal and transversal stiffnesses of the bundles. According to a series of simulations (Fig. 3) the transition occurs at a ratio of about 100. Cracking between the bundles (instead of within them) is forced by decreasing the average strength of the potential failure sites located between the bundles down to 60% of the average in the interior at least. This way, parameter identification becomes possible with real composite materials. On the other hand, it can be shown that quite different damage evolution processes may yield macroscopic stress-strain-curves which are practically the same. Further insight into the micro-properties of constituents can be gained by calculationg the effective Poisson´s ratio which often becomes negative with increasing damage in those materials. This was done on the basis of unit cells of the "Type CF222" with 3 different average curvatures of the fibre bundles (Fig. 5). Fig. 6 shows the evolution of Poisson´s ratios versus the accumulated damage, i.e. sum of all crack lengths normalized by the unit cells´ areas.

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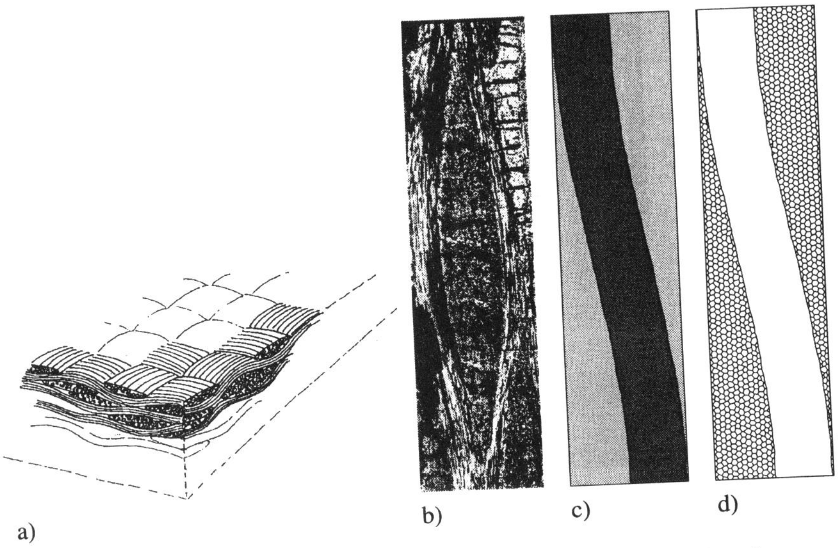
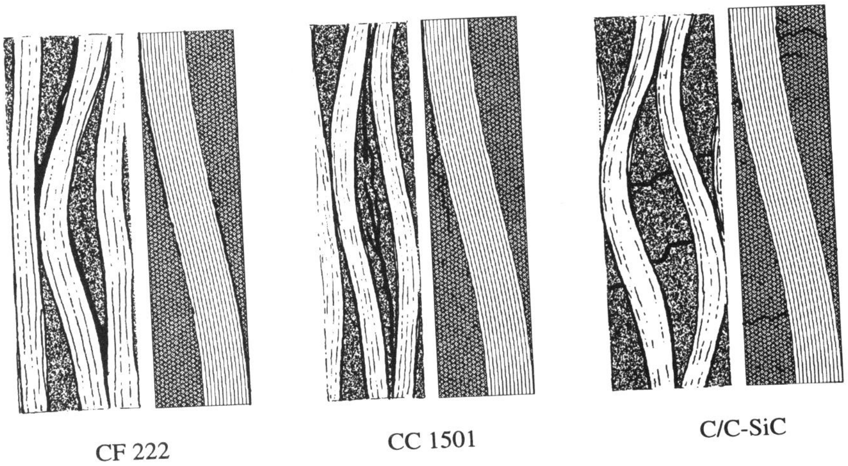


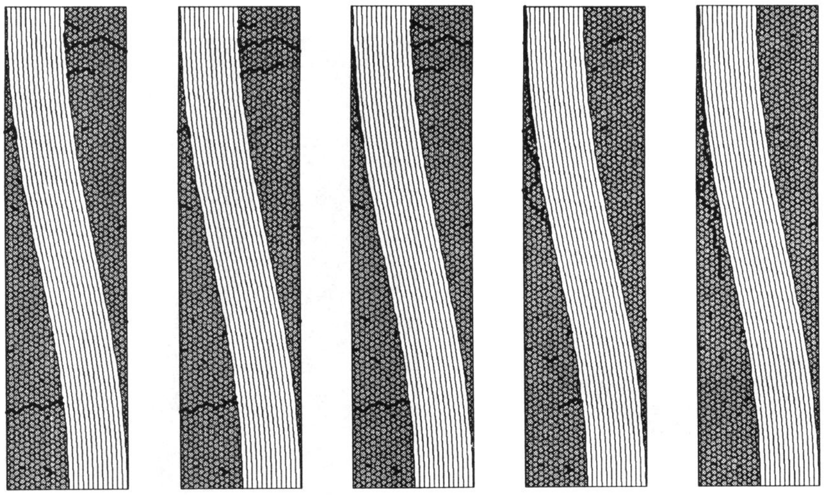
a) b) c) d)

Figure 1 Derivation of a representative unit cell with potential crack paths according to the structure of a 0°/90° plain weave CMC



CF 222 CC 1501 C/C-SiC

Figure 2 Typical damage patterns in 3 different CMC materials and corresponding crack patterns from simulations



$E_L/E_T = 4$ $E_L/E_T = 20$ $E_L/E_T = 50$ $E_L/E_T = 100$ $E_L/E_T = 500$

Figure 3 Crack patterns from simulations with different ratios E_L/E_T of longitudinal and transversal Young´s moduli

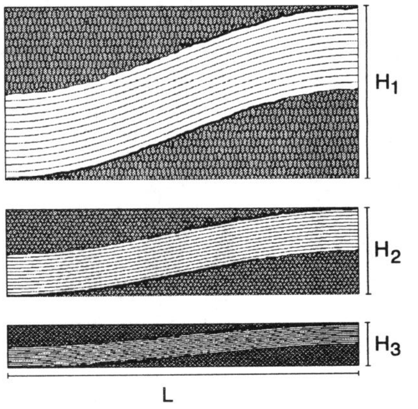


Figure 4 Simulated damage patterns in unit cells with different fibre bend

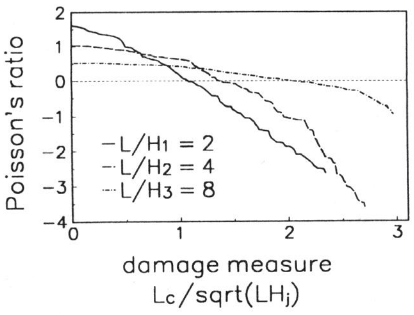


Figure 5 Evolution of Poisson´s ratio in unit cells with different fibre bend