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A GENERAL FRAMEWORK FOR CRITICAL PLANE METHODS BASED ON THE MICROMECHANISMS OF HIGH CYCLE FATIGUE

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ABSTRACT

Over the years, different approaches for fatigue strength predictions under multiaxial loading conditions have been favored in the scientific and engineering community, with the various forms of critical plane methods attracting most interest. If one regards the critical plane method as a model reflecting the actual physical mechanisms of fatigue failure, the method and its modifications have to be judged by two criteria, namely, (i) in how far the model approach depicts the underlying physical mechanisms, and (ii) how accurately the predictions compare with experimental findings. Whereas in the literature the second point has been given ample consideration, the first point has thus far not received any systematic treatment. This is the aim of the present contribution. After a short review of the main influence factors and basic experimental findings, the underlying micro-/mesomechanical setting and the possible physical mechanisms of fatigue failure are discussed. Within this setting, a general modular continuum mechanics framework able to represent these geometrical and physical features is proposed. For the sake of systematics, several specific implementations of critical plane methods in the present general framework are discussed. It is found that the framework proposed is able to accommodate most of the existing models. Finally, a new critical plane method is synthesized which incorporates, in a modular manner, the features that are most promising from a micro-mechanical point of view.

Most metals and alloys in engineering use show significant impurities, inclusions or similar features acting as weak spots where microcracks may nucleate even in the bulk of the material. Grain boundaries, oxide skins and gas pores may also be viewed as such weak spots. Therefore, the *basic microstructural features* to be taken into account in any general model are the material's grain structure, together with any flaws or weak spots. In the present framework, this will be modeled by means of the spatial distribution of grain sizes and orientations and/or by the spatial distribution of flaw sizes and orientations. If the spatial fluctuations of the applied stress field in the critical region of interest are one length scale above the grain size, instead of the spatial distributions the size and orientation distribution functions with respect to the ensemble of grains and/or flaws may be used.

The *basic mechanisms of fatigue damage* are cyclic plasticity on the one hand and crack nucleation and growth on the other hand. For the vast majority of cases with engineering relevance, one may assume that initial flaws (inclusions, precipitates, weakened grain boundaries, oxide skins, or gas pores) are present, so that fatigue resistance is equivalent to crack arrest. However, in some cases the concept of elastic shakedown may be applicable: it precludes cyclic plasticity, a precursor of fatigue crack nucleation, and should therefore give more conservative results compared to crack arrest concepts.

Assuming that the spatial fluctuations of the applied stress field are one length scale above the microstructural length scale, a certain number of neighboring grains or flaws are subjected to the same loading. Macroscopic fatigue strength at a certain point means that all grains/flaws contributing on the microscale to that point's behavior must be safe against fatigue. The two extreme viewpoints are given by two classical hypotheses: according to the weakest link hypothesis, the macroscopic point fails if any single grain/flaw at the microscale fails; according to the critical distance concept, a certain number of grains/flaws must fail for macroscopic failure, which corresponds roughly to the concept of successive microstructural barriers.

Therefore, a statistical treatment of the microstructure at a macroscopic material point leads directly to its fatigue assessment: in the simplest case, the local grain/flaw ensemble is sufficiently large, so that all sizes and orientations are represented as they are in the total ensemble. This means that locally the size and orientation distribution functions are identical to those of the total ensemble. For macroscopically isotropic materials, all orientations are distributed homogeneously across the hemisphere. In this case, the weakest link hypothesis leads to the classical critical plane concepts; the critical distance hypothesis leads to integral methods (such as the effective shear stress hypothesis and the shear stress intensity hypothesis, cf. [1]), where an average over a range of microscopic orientations is used to assess macroscopic failure.

Based on the aforementioned considerations, a critical assessment of some more prominent criteria [1] [2] is performed. It is most interesting to note that, from a micromechanical point of view, the integral shear stress hypotheses [1] [2] may be interpreted, depending on their treatment of superimposed normal stresses, either as elastic shakedown criteria (without accounting for normal stress components) or as Mode II crack arrest criteria (accounting for crack closure due to normal stresses). An extended version of the integral shear stress hypothesis [1] fits well into the framework presented above and has improved predictive capabilities, notably for anisotropic materials.

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