Systematic analysis of fracture in two-phase materials at all stages

Citation for published version (APA):
SYSTEMATIC ANALYSIS OF FRACTURE IN TWO-PHASE MATERIALS
AT ALL STAGES

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Summary. Although multi-phase materials are widely used, the micro-mechanisms dominating fracture are only partially understood. This paper systematically investigates this topic using computational models. An idealized microstructure is employed wherein a brittle hard phase and a ductile soft phase are randomly distributed. The idealization facilitates transparent analyses with well controlled variations. Three topics are considered: the competition between fracture initiation in either of the phases, and the effect of the local phase distribution on fracture initiation and on propagation. The results indicate that, depending on the macroscopic stress state, one of the phases dominates the fracture initiation. The local phase distribution determines where fracture initiates. Regions of hard phase in the tensile direction intersected by bands of the soft phase in the shear directions promote damage for both mechanisms. Voids then link-up through the soft phase, strongly influenced by the amount of hard phase and the phase contrast.

COMPETITION BETWEEN DUCTILE AND BRITTLE FRACTURE

A simple microstructural model is employed in which the microstructure is modeled using a periodic volume element comprising square cells representing individual grains or particles. Each cell is randomly assigned the properties of the hard or the soft phase according to a certain volume fraction of hard phase – which is also varied. To obtain a statistically representative set, a large ensemble of random volume elements is used. The two phases are modeled using isotropic elasto-plasticity, whereby damage indicators signal fracture initiation in the individual cells. For the hard phase the quasi-brittle Rankine criterion is used, whereas for the soft phase the ductile Johnson-Cook criterion is used. Macroscopic fracture is predicted once 1% of the cells have failed. Because of all these idealizations the computations remain cheap, allowing an extensive parameter study.

The predicted macroscopic fracture initiation strain, ⟨\bar{\varepsilon}_f⟩, as a function of applied stress triaxiality \bar{\eta} is shown in Figure 1(a) using a black curve. As observed the fracture strain decreases with increasing triaxiality, as is common for ductile materials. However, around a critical triaxiality of approximately 0.5 a sharp decrease in fracture strain is observed. This is understood by considering fracture in the soft phase only (blue curve) and in the hard phase only (red curve). At low triaxiality the fracture is dominated by the soft phase while above the critical value it is dominated by the hard phase. Around the critical value the two mechanisms are in competition. It is found that the transition point, is a function of the hard phase volume fraction and the contrast in mechanical properties between the phases (not shown).

INFLUENCE OF LOCAL MICROSTRUCTURE ON FRACTURE INITIATION

The influence of the arrangement of the phases on fracture initiation is quantified using the hard phase probability as a function of position relative to the fractured cells [1]. As the microstructure consists of only two phases, the soft phase probability is contained in this quantity. For two values of applied triaxiality, \bar{\eta} = 0 and 1, the results are shown in Figures 1(b,c). To interpret the result, the hard phase probability, ⟨I_D⟩, must be compared to the hard phase volume fraction, in this case \varphi^{\text{hard}} = 0.25. A value ⟨I_D⟩ > \varphi^{\text{hard}} (red in the figures) corresponds to an elevated probability of the hard phase, and ⟨I_D⟩ < \varphi^{\text{hard}} (blue) to that of the soft phase. Both figures are for loading in plane strain pure shear, with extension in

Figure 1. (a) Predicted macroscopic fracture initiation strain, ⟨\bar{\varepsilon}_f⟩, as a function of applied stress triaxiality \bar{\eta}, for fracture in both phases (black), in the soft (blue) or hard (red) phase only. (b,c) Hard phase probability around fracture initiation, ⟨I_D⟩, for two values of applied triaxiality; the colors may be interpreted as an elevated probability of the soft phase (blue) and of that of the hard phase (red). Pure shear is applied: horizontal extension and vertical compression.

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horizontal direction and compression in vertical direction. Each cell in the diagram corresponds to a position relative to the fracture initiation sites in the center.

From Figure 1(b), in the regime where fracture in the soft phase dominates, bands of hard phase are observed in horizontal direction, the direction in which the extension is applied. Under ±45 degree angles with respect to this axis, bands of soft phase are observed that interrupt the band of hard phase in the fracture initiation sites. By simple mechanical arguments it can be understood that the band of hard phase provides a high hydrostatic tensile stress, while the bands of soft phase provide significant plastic deformation, which are together critical for fracture. Remarkably, Figure 1(c) – taken in the regime where hard phase fracture dominates – is qualitatively very similar to Figure 1(b) outside the fractured cell in the center. This means that the microstructural features that are responsible for the initiation of fracture are identical, regardless whether fracture initiates in the hard phase or in the soft phase.

This is further investigated by extending the analysis to three-dimensions [2]. To overcome computational limitations a solution scheme that uses the Fast Fourier Transform is employed. Different loading paths are considered from which only one result, in pure shear, is included in Figure 2 – which shows the arrangement of phases around fracture initiation. It is observed that the basic features are the same as predicted by the 2-D analysis.

**PROPAGATION OF FRACTURE**

The analysis is extended beyond regime of fracture initiation. In the spirit of the idealized model used above, propagation is modeled using a simple a cell erosion technique. Once the damage indicator in a cell has exceeded a critical value it is completely removed and thus no longer carries load. This corresponds to a non-local damage criterion as the underlying numerical discretization is finer than the cells. A typical result is shown in Figure 3, the homogenized macroscopic response in (a) and the local incremental damage indicator in (b). As observed, fracture initiates in a couple of locations in which the local arrangement of phases is similar to Figure 1(b). Above a threshold, initiation sites start to link up along a shear band, macroscopically observed as fracture. These observations are confirmed by a statistical analysis. Furthermore it is observed that fracture is accelerated for higher hard phase volume fraction, whereby the microstructure has a stronger influence on both void nucleation and the localization path.

**References**
