

Fracture of Solids Based on Deformation Wave Dynamics

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Abstract. Fracture of solids is considered from the viewpoint of wave dynamics derived from a field theory. Based on the principle known as the symmetry of physical laws, the present field theory describes deformation and fracture on the same theoretical basis. From experimental observations, fracture is classified into two types; the first type characterized by decaying displacement waves that initially travel and eventually become stationary, and the second type characterized by shear bands that are initially dynamic and eventually become stationary. The field theory interprets that the decaying displacement wave represents elasto-plastic deformation dynamics and that the shear band indicates solitary wave dynamics associated with strain concentration. In either case, the theory explains that the termination of wave propagation causes infinite volume expansion that generates material discontinuity. From the wave dynamical viewpoint, fracture is a self-driving phenomenon where the decrease in the elastic constant in a late stage of deformation induces instability in oscillatory dynamics which leads to exponential increase in the volume expansion with time. The theory indicates that in this mechanism fast pulling rate enhances the instability. Simple numerical analysis with finite element modeling supports this argument of instability and its association with the pulling rate.

INTRODUCTION

Conventionally, elastic deformation, plastic deformation and fracture of solids are treated as separate phenomena. Consequently, fundamentally different approaches are applied to the respective regimes. In the elastic regime, continuum mechanics [1, 2] is used to describe reversible deformation based on the linear constitutive relation. Various theories [3, 4, 5, 6, 7, 8] are available for the plastic regime, and these theories can be generally classified into two groups. The theories classified in the first group [3, 4, 5, 6] are based on certain physical processes such as dislocation dynamics and thermodynamic processes. Those classified as the second group [7, 8] describe deformation based on nonlinear constitutive relations that are empirically known or mathematically modeled. In the regime of fracture, a number of theories [9, 10] have been developed as well. They mostly describe crack propagation based on various underlying physics such as energy argument near the crack tip to evaluate the crack resistance of the material under given conditions.

Although these are established theories and work well in the respective regimes, there are limitations in the use of them for some areas of engineering for two main reasons. The first reason is that in reality elastic and plastic deformations are not separate events but they coexist. Metal specimens freshly taken out from an annealing oven always have a number of dislocations. The existence of dislocations and other defects makes the elastic theory less accurate when the object is in the micro or nano-scale level. The second reason is that often the analysis of the transition from one regime to another is important in engineering. For instance, fracture mechanics cannot describe when a fatigued metal fractures. On the other hand, a deformation theory cannot describe crack generation or propagation. The use of a deformation and fracture theory separately is not practical to predict fracture accurately.

In this study, we discuss a physics-based approach to describe deformation and fracture of solids on the same theoretical basis. The present approach is based on a fundamental physical principle known as the symmetry in physics [11], which in short, states that the laws of physics are independent of the choice of the coordinate system. In other words, the physical laws do not change where, when and how (still or in motion, or in which orientation in space) you make the experiment, although the obtained data are completely different depending on the way the experiment is conducted. In the present case, we request the symmetry in Hooke's law in local regions of the object under plastic deformation. The request of this local symmetry requires the introduction of a compensation (gauge) field. We can

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