3D MECHANISM-BASED MODELING OF THE FAILURE OF BRITTLE MATERIALS UNDER DYNAMIC MULTIAXIAL LOADING

Guangli Hu, Leslie Lamberson, K. T. Ramesh
Mechanical Engineering Department, Johns Hopkins university, Baltimore, MD, 21218, USA

Summary A 3D mechanism-based constitutive model is developed to capture the failure of brittle materials under dynamic multiaxial loading conditions. The micromechanics is that of a wing-crack mechanism, assuming a defect density and flaw distributions in both orientation and size. Interactions among cracks are modeled by means of a crack-matrix-effective-medium approach. The tensorial damage parameter, incorporating the anisotropic effects, is calculated based upon the crack length and orientation development under local stress fields. At low confining stresses, the wing-cracking mechanism dominates, leading to the degradation of the modulus and peak strength of the material, whereas at high enough confining stresses, the crack mechanism is completely shut-down and the dislocation mechanism is activated. Effects of loading rates, flaw statistics, confining stress, etc., are explored through parametric studies.

INTRODUCTION & EXPERIMENTAL RESULTS

Defects control the mechanical responses of brittle materials (rocks, glasses, ceramics, etc.), and limit their real applications to a large extent. Pre-existing defects in a brittle material system may be weak grain boundaries, triple junctions, second phases (sintering aids), inclusions, pores, and so forth. These internal flaws generally act as stress concentration sites that nucleate cracks, leading to the catastrophic failure of brittle solids. This paper seeks to understand the dynamic failure of brittle solids.

Over the past decades, extensive experimental and modeling studies have been conducted on the failure of brittle solids. The loading rate and stress state (confining stress) are among the most important parameters affecting the mechanical response of brittle solids. Many ceramic materials, geological materials, and concrete show an increase in strength when deformed at rates larger than a transitional strain rate. In terms of confining stress, Hu et al. [1, 2] conducted dynamic planar confined experiments on aluminum nitride (AlN). The dynamic confined compression experiments were designed to allow visualization of the failure process *during* dynamic compressive loading under high planar confinement. The current apparatus is capable of applying confining stresses as high as 1 GPa. Note that the confining stress is first applied in a quasistatic manner, and the dynamic compressive load is subsequently superimposed. An example of the results of a dynamic confined compression experiment on aluminum nitride is presented in Figure 1 for a confining stress of 780 MPa. Both the stress history (stress along the dynamic loading direction) and the corresponding high-speed photographs are shown. The peak strength is around 3.5 GPa. The big difference is in the process of specimen failure evident in the high-speed photographs, in that no horizontal cracks are observed in the specimen. The high-speed photographs each have an exposure time of 350 ns, and the interframe time is 2 μs. The direction of the static confinement is vertical in these pictures, and the direction of dynamic compression loading is horizontal. A failure zone is first observed in Frame two, corresponding to a stress (in the horizontal direction) of about

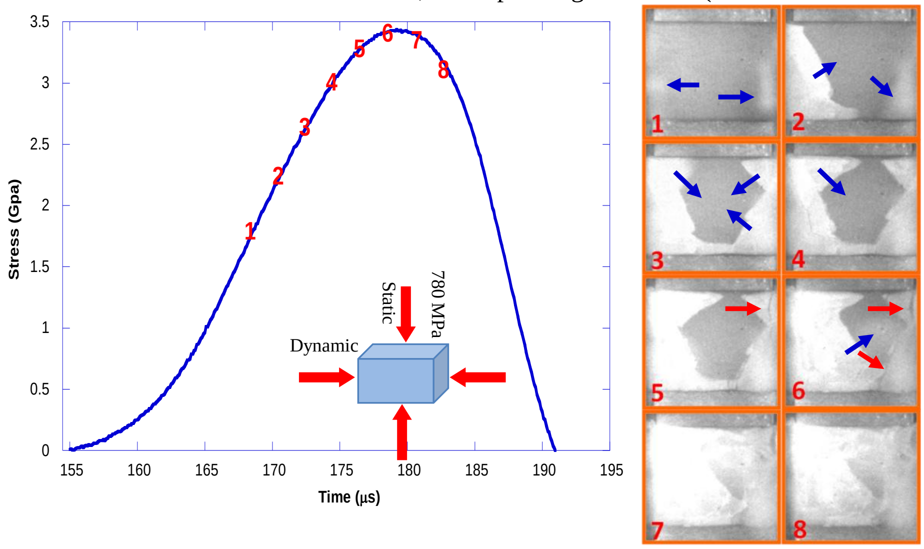

Fig.1 Stress history and high speed camera images of confined dynamic compression with a confining stress of 780 MPa. Note failure patterns under confined dynamic loading are shear dominated, unlike from uniaxial dynamic loading.

2.2 GPa. Failure zones have nucleated from all the corners by the time of Frame 4. The peak strength occurs at the time of Frame 6, and significant failure has occurred throughout the specimen by Frame 8. However, no horizontal cracks are observed in any of these frames, and indeed no identifiable cracks are visible. The damage appears to develop in diffuse zones that propagate across the specimen along failure fronts that are inclined at about 45° to the dynamic loading direction. This apparently shear dominated failure mode is observed in all of the dynamic confined compression experiments. Thus the presence of the confining stress appears to have dramatically changed the failure mode in this material. The confining stress appears to have suppressed the axial splitting mode, a phenomenon that has been studied in terms of wing crack micromechanics. What is observed at the macroscale in our experiments is a macroscopic change in failure mode because of the change in the collective response of the microcracks under the confining pressures. A similar behavior has been postulated after post-mortem examination of sleeve-confined specimens [3], but this is the first direct in situ observation of the dynamic evolution of this anisotropic failure process under multiaxial loading, indicating that microcrack interactions were important to the global failure process. The experiments also demonstrated that dislocation mechanisms were active in the ceramic under confined dynamic loading conditions.

Even higher strain rates are developed in shock experiments, together with high pressures. Chen et al. [4] observed twin formation in alumina, suggesting another plastic deformation mechanism besides slip. Other ceramic systems, such as, aluminum oxynitride (AlON), boron carbide (B_4C), silicon carbide (SiC), and titanium diboride (TiB_2), have also been studied, and various inelastic deformation mechanisms have been suggested under shock loading, including amorphization [5], slip [1], and phase transformations. These inelastic deformation mechanisms, activated at different length scales and different time scales, should therefore be incorporated into constitutive models for these materials.

Mechanism-based modeling is preferred over phenomenological modeling since different failure and deformation mechanisms are involved in impact applications. Phenomenological models may be efficient for computation, but are generally unable to capture the different mechanisms, and therefore can predict qualitatively unreasonable behaviors. Furthermore, a generalized 3D model is required to handle the damage anisotropy, multiaxial stress states, and loading path (no-monotonic loading) effects. This naturally requires the detailed micromechanical description of each operative mechanism under general stress states. In the following, a 3D mechanism-based constitutive model for brittle materials under dynamic multiaxial loading conditions is constructed. The mechanisms involved in the model have been presented in the previous paper [6].

THEORETICAL FRAMEWORK

The theoretical framework for the model development is briefly discussed due to space limitation. Detailed simulation results and discussion will be presented at the meeting. This constitutive model is composed of three mechanism-based regimes: crack growth under local tension, crack growth under local compression, and plastic flow due to lattice plasticity. At low confining stress, the cracking mechanism dominates, leading to either the tensile or compressive crack growth to accumulate the damage based upon the local tractions along the crack surface. The micromechanics is that of a wing-crack mechanism. The damage, defined as equation (1), is calculated based upon the crack size and orientation, which takes the damage anisotropy into account. Internal flaws are assumed to be planar cracks being characterized into families based upon the crack size and crack normal. Crack size is described through distribution function g(s) and normal n is determined through distribution functions h(φ) and f(θ). For each family of cracks, the interactions are accounted for by means of a crack-matrix-effective-medium approach [7]. Among different crack families, the interactions are accounted for through the tensorial damage parameter.

$$\Omega_0 = \frac{1}{V}\sum_k \left((2s)^3 \underline{n} \otimes \underline{n}\right)^{(k)} \tag{1}$$

where Ω_0 is the damage tensor defined by the crack normal and crack size. V is the volume and k the number of flaws for the current family. The global stiffness degrades as a function of damage accumulation in both tension and compression, leading to the peak strength of the brittle solids. Crack growth dynamics are also incorporated to account for the loading rate dependence. Whereas at high enough confining stress, the cracking mechanism is completely shut-down and the lattice plasticity is activated. The plastic strain rate accounted for through the classic plastic rule.

SUMMARY

A physics-based model is constructed based upon the operative mechanisms (tensile crack growth, compressive crack growth and plasticity seen in experiments [1, 2, 6]), incorporating the flaw statistics, crack growth dynamics, and plastic flow rule. It can be applied to investigate the responses of structural ceramics under a wide range of loading rates and multi-axial stress states. Furthermore, through systematic parameter study of this 3D model, constructive feedback can be provided to the manufacturing process (by tailoring the microstructural features) to obtain improved material systems.

References

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