

Recent Advances in First-Principle Simulation of the Transition from Continuous to Discontinuous Failure under Impact

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Extended Abstract

Summary

By discretizing wave, diffusion and instantaneous response equations in a single computational domain, a computer test-bed is being developed for the first-principle simulation of multi-scale structural failure under blast and impact loads. Based on the previous work [Chen, 2000; Chen et al., 2001; 2002 and 2003], recent advances in model-based simulation of the transition from continuous to discontinuous failure modes are discussed in this presentation. The failure transition is identified through the discontinuous bifurcation analysis of the acoustic tensor governing rate-dependent damage. A discrete constitutive model is then used to predict material failure as a decohesion or separation of continuum. To accommodate the multi-scale discontinuities and different material phases involved in structural failure under blast and impact loads, the Material Point Method is being developed to be a robust spatial discretization tool for the computer test-bed. As a result, the model parameters could be calibrated based on experimental data available, and routine simulation could be performed with limited computational resources. Sample problems are considered to illustrate the potential of the proposed procedure.

Introduction

The ability to design and construct blast-resistant buildings depends on an understanding of how such buildings behave under blast loads. Here, the blast resistance refers to the ability of a building to withstand an explosion event with minimum loss of life or property. In recent years, engineers and scientists have developed a better understanding of building performance under the dynamic horizontal and vertical forces associated with earthquakes. Due to the large cost, impact on the environment and other collateral factors involved, however, it is not feasible in many cases to conduct the real-time field tests to verify new design concepts for blast-resistant structures. Hence, a computer test-bed could be very valuable in testing a wide range of building types and structural details over a broad range of hypothetical blast events.

Modeling and simulation of blast effects can be divided into two groups: first-principle and semi-empirical. In first-principle-based approaches, mathematical equations are formulated that describe the basic principles of physics governing a particular problem. These principles are the conservation of mass, momentum and energy. In addition, constitutive models, that describe the physical behaviors of different materials, are needed to formulate a complete set

of governing equations. If the governing equations are solved accurately for given boundary and initial data, they should be able to predict the structural response under blast loads. However, accurate constitutive models are not available for the building materials, since the structural failure due to explosion involves localized large deformations, inelasticity, thermal softening, phase transition, fragmentation and other complicated mechanisms. The failure wave phenomena, which were observed in shocked brittle solids, might provide a key to understand the failure mechanisms due to blast loads, and to better assess the energy dissipation associated with the failure evolution process.

Based on the recent research results on the failure wave phenomena and impact responses [Chen et al., 2003; Chen and Xin, 1999], it appears that the formation of localization represents the onset of material failure evolution. The onset of localization can be identified via the transition among three basic types of governing differential equations; i.e., hyperbolic (wave), parabolic (thermal diffusion) and elliptic (instantaneous response), which represents the transition among different physical phenomena. Furthermore, the evolution of localization can be described by a diffusion equation. The failure wave phenomenon could be considered as a practical and illustrative example. It appears that the inelastic deformation can be described as a prompt stress-controlled process if the deformation process can occur in a nearly point-wise manner such as the dislocation motions. However, the evolution of inelastic deformation appears to be a diffusion process if the deformation involves a length scale and can only occur in an essentially random-walk manner. The challenging questions are how to identify the physics behind the transition from the stress-wave propagation to a diffusion-controlled process and subsequent fragmentation in the evolution of impact failure, and how to simulate, in a single computational domain, the multi-physics involved in multi-scale structural failure evolution.

Many approaches have been proposed in the open literature to model the evolution of localization and the subsequent transition from continuous to discontinuous failure modes. However, there are certain kinds of applicability and limitation for different approaches, depending on the scale of the problem and the degrees of discontinuity considered. Since a complete failure process involves different degrees of discontinuity and every physical phenomenon must obey the conservation laws, the jump forms of conservation laws might provide a useful tool to link continuous approaches with discontinuous ones [Chen, 1996]. In fact, the transition from continuous to discontinuous failure modes could be identified through the bifurcation analysis of the acoustic tensor governing inelasticity. If the initiation and orientation of localized failure mode is identified via the bifurcation analysis, continuous and discontinuous approaches could be combined to model and simulate the evolution of material failure, based on the physics involved.

To accommodate the multi-scale discontinuities and different material phases involved in structural failure under impact and blast loads, a robust simulation tool is a necessity without invoking fixed mesh connectivity. As one of innovative spatial discretization methods, the Material Point Method (MPM) is an extension to solid mechanics problems of a hydrodynamics code which, in turn, evolved from the Particle-in-Cell Method. The motivation of the development was to simulate those problems with history-dependent internal state variables, such as contact/impact, penetration/perforation and solid-fluid

interaction, without invoking master/slave nodes and remeshing. The essential idea is to take advantages of both Eulerian and Lagrangian methods. Although the MPM is still under development, sample calculations have demonstrated the robustness and potential of this method for the challenging problems of current interests, as reviewed recently by Chen et al. [2002].

Proposed Approach

Based on the recent research results as discussed above, a simple numerical procedure is proposed here to simulate the rate-dependent evolution of material failure under impact and blast loads. The transition from continuous to discontinuous failure modes is identified via the bifurcation analysis of continuum damage, and a discrete rate-dependent constitutive model is formulated to predict decohesion or separation of continuum. To accommodate the multi-scale discontinuities and different material phases involved, the MPM is modified to solve the differential equations governing different physical phenomena in a single computational domain.

Demonstration

The failure patterns of a concrete wall due to the impact of the steel flyer are shown in Fig. 1 and Fig. 2, respectively, by using continuum damage with decohesion, and continuum damage only. Initially the concrete wall is at rest. As the flyer approaches the concrete target, contact/impact between the flyer and wall produces acceleration of the concrete wall and deceleration of the steel flyer. As can be observed, the impact induces significant material failure close to the middle section of the concrete wall, but the failure patterns are different for different constitutive models. The synergistic effect of blast and fragments on a concrete wall is shown in Fig. 3. A parametric study will be presented to demonstrate the effects of controlling parameters on the structural failure responses under impact and blast loads.

References

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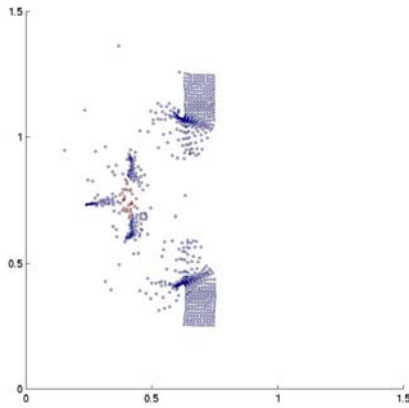


Figure 1. The use of damage/decohesion for impact problem.

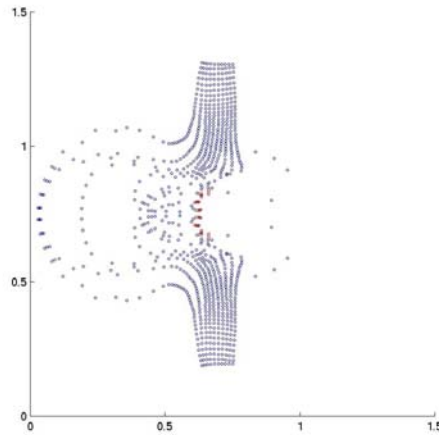


Figure 2. The use of continuum damage for impact problem.

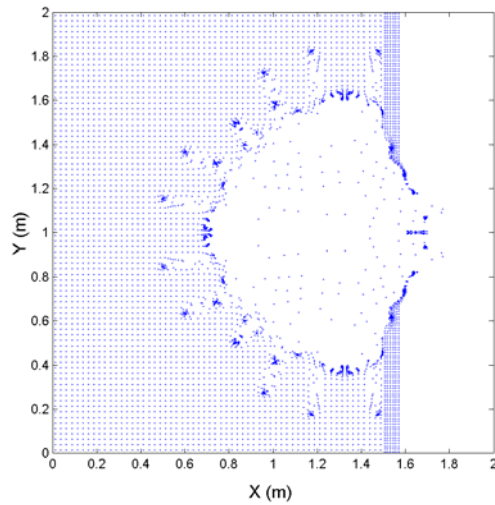


Figure 3. Synergistic Effect on Blast Response.