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Cementitious material models for simulating projectile impact effects ☆

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ABSTRACT

Digital simulation of structural components of brittle cementitious materials like concrete subjected to blast and/or high-velocity impact are problems of high complexity. In the current asymmetric war environment around the globe, there is significant interest to study the performance of concrete panels as armor material in resisting the ballistic impact of projectiles of different types and impact velocities. Extensive experimental solution to the problem is not realistic, because it can be very expensive and highly time consuming. To be able to predict the behavior corresponding to the myriads of possibilities, reliable numerical simulations by a discrete numerical method is the sensible alternative. Different material models have been used over the past two decades to realistically simulate the behavior of concrete under dynamic, highly localized, high-velocity impact conditions. The present study gives an overview of the mechanics of such effects, identify the most popular material models that have been tried recently to properly predict the behavior through finite element simulations, present an improved model for superior prediction of response, and validate the proposed model using example problems for which experimental results are generated by way of actual impact tests.

1. Introduction

The response of a concrete target under impact depends upon numerous variables, including but not limited to geometry of both target and projectile, material of projectile, impact velocity and angle of incidence of projectile. Due to low cost, reduced areal density, significant hardness, and ease of onsite manufacture, the use of high strength concrete as armor material for temporary, short- to medium-term protection against small arms fire and shell fragments has been found to be an attractive possibility. For inducing higher ductility to enhance energy absorption capacity, a layer of some backing material like carbon or Spectra fiber reinforced composite, or incorporation of short steel whiskers, polypropylene fibers, or other high strength low-density fibers in the concrete mix may help increase effectiveness of protection provided by the armor. Understanding the response of such armors to blast effects and ballistic impact is crucial to ensure effective protection. Under ballistic impact, concrete structures experience various states of stress leading to different failure modes. The worst case scenario for a single projectile occurs when it strikes the armor normal to its surface. In the case of a concrete panel or plate subjected to such loading, a crater is formed in the front surface and a strong compressive shock wave is created, attenuating as it traverses through the plate thickness and is reflected off the back surface [1]. In addition, this compressive shock wave reflection generates a tensile shock wave, which when interacting with the compressive waves, lead to fracture on the rear face of the panel accompanied by spalling of the material in the back face behind the point of impact [2].

Significant advancements in phenomenological and experimental characterization of complex materials, numerical modeling and simulation techniques, and computational speed capabilities of modern computers, is enabling analysts to more accurately study the dynamic effects of structures subjected to blast and high-velocity impact. Accurate simulation of the structural response to such dynamic loads is a useful way to drastically cut down the cost of R/D efforts related to new materials and applications. The availability of powerful general purpose modeling and simulation codes like Abaqus/CAE and LS/DYNA with ability to incorporate new material models developed by the user have given added boost to this effort. After discussing the merits and demerits of popular material models for cementitious material targets subjected to impact effects, this paper presents an improved model for such materials, applies it to some typical ballistic impact problems and verifies with results of experiments especially undertaken for the purpose.

1.1. Nature of dynamic effects

The response of a structure due to an intense, impulsive loading is very complex. Over the years, sophisticated mathematical solutions have been created for various loading conditions, but most

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are for semi-infinite bodies. As a projectile or blast wave impacts a solid target normal to its surface, the governing equations for both bodies should satisfy: (a) conservation of mass, (b) conservation of momentum, and (c) conservation of energy. These equations are commonly summarized in the Rankine–Hugoniot relations [3], the compact forms of which are shown in Eqs. (1)–(3) for a compressible plate with initial uniform pressure p_o and density ρ_o and one face suddenly exposed to a uniform pressure p_1. The applied pulse travelling with a velocity U_s compresses the material in front of it to a new density ρ_1 accelerating the compressed material to a velocity U_p. These relations, commonly known as "jump" equations, do not describe the properties of a specific material, but relate the change in variables across a shock front. For application to a specific material, it is necessary to generate curves (or Hugoniots) depicting the locus of states achievable by shock transition from a given initial state. For instance, in a particular case, the final pressure and relative volume reached depend on the initial conditions present when the shock arrives [4]. A Hugoniot curve contains the minimally required information about a material to adequately solve the shock-propagation problem, consistent with a given set of variables. In order to determine all the parameters associated with the shock front, it is, sometimes, necessary to append the stated equations with an experimentally determined equation of state.

$$\rho_0 U_s = \rho_1 (U_s - U_p) \tag{1}$$

$$p_1 - p_0 = \rho_0 U_s^2 - \rho_1 (U_s - U_p)^2 \tag{2}$$

$$E'_1 - E'_0 = \frac{1}{2}\left(\frac{1}{\rho_0} - \frac{1}{\rho_1}\right)(p_1 + p_0) \tag{3}$$

Eq. (3) assumes the impact process to be adiabatic. E'_1 and E'_o represent the specific internal energies in front and behind the shock front, respectively [5].

1.2. Nature of cementitious materials

Analytical and theoretical studies of the non-linear response of reinforced concrete structures have been, for the most part, focused on the behavior of isolated, simple structural elements. Availability of meaningful quantitative data on failure processes of concrete paved the way to increased effort for accurate prediction of response of concrete structures under complex loading conditions, like blast and impact. Although currently available commercial finite-element software packages have a wide range of capabilities for many areas of mechanical stress analysis, inadequate material models is a major crippling factor in the case of structures made of brittle, geologic materials like concrete and ceramics. The currently incorporated material models can, in a general way, describe the elastic–plastic behavior of reinforced or unreinforced concrete under simple, quasi-static loading conditions. However as advances in concrete and ceramic mixes are made to improve performance under extreme loading conditions, the generally accepted constitutive equations that describe the basic characteristics of concrete no longer apply [6].

Problems of material failure near a free surface some distance away from the localized area of application of an impulsive load have been studied extensively. In the case of ceramic or cementitious materials that have high compressive strengths but relatively weak tensile strengths, spalling at the free surfaces is a phenomenon to be expected, due to reflection of incident-compressive impulses generated by high-velocity ballistic impact [7]. Fig. 1 illustrates the progressive effects that take place during high velocity impact and penetration event for a thin panel. In the first few microseconds of impact, local material cratering takes place. Directly in front of the projectile, the material then undergoes local material compaction. Due to the high rate of loading, Poisson effects do not have time to occur, which would normally allow for some of the material in front of the projectile to expand outward radially. Therefore, such behavior essentially characterizes radially confined compression. As described later, this is the rationale for using a material model that has been calibrated using triaxial compression experiments. As an aftermath of these effects, the strong compressive shock wave gets weakened as it traverses through the plate thickness and gets reflected off the back surface. This reflecting shock wave causes a tensile shock wave, which when interacting with the compressive waves, will lead to cracking on the rear face of the target panel causing fragmentation (or spalling) of the material.

2. Existing models

Over the past few years, a number of material models have been developed by Johnson, Holmquist, and their coworkers to characterize the behavior of concrete and other brittle geologic materials under large strain, high-strain rate, and high-pressure impact conditions. Three of these models are the HJC model [8], the JHB/JH-1 model [9], and the JH-2 model [10]. It has also been found that a similar material behavior can be customized using a combination of the Drucker–Prager plasticity model and an equation of state [11]. Each of these models contain the same three basic elements: (1) an equation of state (EOS) for the pressure–volume relation that includes the non-linear effects of compaction, (2) a representation of the deviatoric strength of the intact and fractured material in the form of a pressure-dependent yield surface, and (3) a damage model that transitions the material from the intact state to the fractured state. Treating as the starting point of the present effort, these existing models were thoroughly evaluated, shortcomings were identified, and necessary improvements were made.

3. Proposed improved model

The constitutive model proposed in this paper takes advantage of certain aspect of the previously mentioned models, improving upon them as needed based upon new developments. Outlined in the following are the same three principal components of the material model along with the associated equations. The proposed model also builds upon the basic considerations associated with the Advanced Fundamental Concrete (AFC) model proposed by Adley and coworkers [12]. It accounts for processes like irreversible hydrostatic crushing, material yielding, plastic flow, and damage evolution. The model is based upon a non-linear pressure–volume relationship, a linear shear relationship (constant shear modulus, G), and incorporates a failure surface that is strain-rate dependent. As with most of the simplistic models for geomaterials, the proposed model uncouples the hydrostatic and deviatoric responses, so that no volumetric strain due to purely deviatoric loading may develop.

In the case of HJC, JHB/JH-1, and JH-2 models, the hydrostatic and deviatoric behaviors are completely decoupled and therefore independent of each other. As a result, the hydrostatic (pressure–volume relation) part of the model is a function of only the first

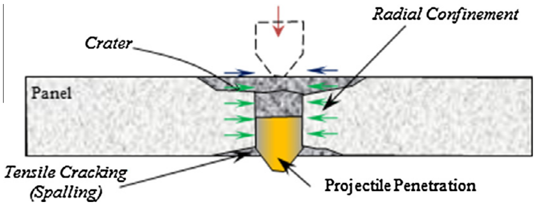

Fig. 1. Physical characteristics of high-velocity penetration of brittle panel.