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The immersed-body gas-solid interaction model for blast analysis in fractured solid media

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ABSTRACT

Blast-induced fractures are simulated by a novel gas-solid interaction model, which combines an immersed-body method and a cohesive zone fracture model. The approach employs a finite element fluid model and a combined finite-discrete element solid model. This model is fully coupled and simulates the whole blasting process including gas pressure impulse, shock wave propagation, gas expansion, fragmentation and burden movement phases. In the fluid model, the John-Wilkins-Lee equation of state is introduced to resolve the relationship between pressure and density of the highly compressible gas in blasts and explosions. A Q-scheme is used to stabilise the model when solving extremely high pressure situations. Two benchmark tests, blasting cylinder and projectile fire, are used to validate this coupled model. The results of these tests are in good agreement with experimental data. To demonstrate the potential of the proposed method, a blasting engineering simulation with shock waves, fracture propagation, gas-solid interaction and flying fragments is simulated.

1. Introduction

Explosives have played an important role in rock blasting, cutting, mining and tunneling industries for centuries. In such applications, the damage and other effects due to blasts are mainly predicted by experiments and numerical analysis. The earliest developments in the numerical analysis of how to use explosives began with very simple formulae. These primitive formulae date back to the nineteenth century[1,2] and more or less depend on users' experience. However, they are very efficient for obtaining a realistic estimate for engineering use.

A large number of models have been developed for modelling blast-induced fracture processes. They can be divided into two groups: the distinct phase models and the complete blast models[3]. For the distinct phase models, there are two phases: the fragmentation phase with shock waves[4–6] and the burden movement phase[7–9]. Fragmentation models only simulate the beginning stage of explosions, which is mainly the fracture propagation and shock wave reflection. After the first stage, the fracture extension and fragmentation movements are described by the burden movement models. The distinct phase models are easily built, but they are not able to simulate blasting processes realistically. In order to resolve this problem, several complete blast models[3,10,11] have been developed to simulate the fragmentation and burden movement phases in one model. The ultimate goal of the complete models is to simulate the entire blasting process including detonation, shock waves, compressible flow, fracture propagation and gas-solid interaction in one model.

In blast-induced fracture modelling, there are three parts involved: gas modelling, solid fracture modelling and the gas-solid coupling. In simple gas models, user-defined or empirical pressure profiles are applied on the cracks and the walls of blasting holes.[12,13] In sophisticated gas models, pressure distributions in the blast process are determined by solving the fluid governing equations. Munjiza et al.[14,15] proposed a gas model based on a combined finite-discrete element method (FEMDEM) for accurate simulation of pressure within cracks and fractures. The gas flow in this model is assumed as an equivalent one-dimensional duct flow with a constant duct area. Based on this idea, Mohammadi et al.[16] further applied the model to non-uniform isentropic gas flows [3]. From a different point of view, Preece et al.[8] and Taylor[17] proposed gas models based on porous media flows. In these models, the fractured rock mass is replaced with an equivalent porous medium. This type of models was further developed by Mohammadi et al.[16,3] and Su et al.[18]. Mohammadi et al.[16] first introduced a non-uniform isentropic gas model, and used a two-mesh

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method[3] to couple porous media flows and FEMDEM. Su et al.[18] extended this method to multiphase flows.

As far as fracture models are concerned, a variety of numerical methods have been developed. The earliest are continuum-based fracture models, which are used at the starting stage of an explosion. Firstly, cracking models, which depend on stress wave propagation, were introduced into the finite element or finite difference methods to resolve small fractures inside solids.[19–21] Continuum fracture models were then developed to adapt to various rock blasting problems.[22–25] Despite the widespread use of continuum damage models, they are not suitable for simulating extensive solid cracks and fragmentation since there are significant discontinuities in the solid mass. To resolve intense fractures, discontinuum based methods were introduced into the burden movement models. These methods treat the fractured solids as discontinuous separate smaller parts, which impact each other via contacts and collisions.[10,26–29] In order to simulate complete blasting processes, FEMDEM was proposed by Munjiza.[30] FEMDEM has been used recently in complete blast models.[15,14,31,32]

With regard to the gas-solid interaction modelling, two types of numerical methods have been developed. One is local influence gas flow modelling, whilst the other group is general gas flow modelling in porous media. In local gas flow models, flow in cracks and fractures is simulated as a uniform gas flow in pipes and channels.[14] On the other hand, porous media models treat the gas flow in cracks and fractures as flow in equivalent porous media.[16,3] In the coupled gas-solid interaction model developed by Mohammadi et al.,[3] two separate meshes were introduced for representing the rock and gas, respectively. These two meshes were coupled to each other to complete the simulation of the entire blast process. In this model, the porous, media gas flow was coupled with the FEMDEM[33] to resolve both the gas flow behaviour and the solid fracturing process. However, there is a gap between the model and real blasting problems, most notable being the simplified gas equation of state and the structured coarse gas mesh used in this model. Recently, an advanced three mesh fluid-structure interaction model via an immersed-body method was developed by Viré et al.[34] In this model, a finite element based fluid model was coupled with a FEMDEM solid model. A coupling term is used in the third mesh, a thin shell mesh surrounding the solid surface, to complete the coupling process. This method was further developed by Yang et al.,[35] where fluid stresses were introduced into the coupling term. The modified coupling term enables the fluid viscous behaviour to be well represented in numerical simulations involving fluid-structure interaction (FSI). This model was developed for rigid or deformable solids coupling with incompressible flow and is not suitable for the blasts and explosions/compressible flow.

This paper extends the immersed-body approach[35] to rock blasting simulations. In the present model, compressible flow with the John-Wilkins-Lee (JWL) equation of state is used to close the gas system of equations. In order to stabilise the gas model when solving extremely high pressure situations, a Q-scheme is used. A fracture model using a Mohr-Coulomb failure criterion with a tension cut-off[36] is employed to define the cracking and fragmentation within the solid. The fracture model employs a discontinuous mesh to simulate fracture initiation and propagation. On fluid side, a continuous representation of the pressure field is used. In order to link these two different kinds of meshes, we implement a new mesh conversion algorithm to convert discontinuous meshes to continuous meshes.

The remainder of this paper is organised as follows. Section 2 details the governing equation for discontinuum fractured solids, together with the fracture model. Section 3 presents the governing compressible fluid equations with the JWL equation of state. The theory behind the gas-solid interaction model is detailed in Section 4. The accuracy of this method is evaluated using a blasting cylinder test, and a projectile fire test in Section 5. A practical complicated blasting engineering simulation with shock waves, fracture propagation, gas-solid interaction and flying fragments is also presented in Section 5. We discuss the strengths and weaknesses of this approach and draw conclusions in Section 6.

2. Fractured solid model

2.1. Equations for solid dynamics

The combined finite-discrete element method (FEMDEM)[31] is used to model the structural dynamics. The FEMDEM model developed by Xiang et al.[37] is used here in combination with a fracture model developed by Guo et al. [36] and a fracture network model developed by Lei et al.[38] The resulting FEMDEM model has the ability to compute the stresses and fracture networks of any shape and stiffness. The dynamics of fracturing solids on the solid mesh are given by[37]:

$$\boldsymbol{F}_{ext} - \boldsymbol{F}_{int} + \boldsymbol{F}_c + \boldsymbol{F}_f = \boldsymbol{M}_s \frac{\partial \boldsymbol{u}_s}{\partial t}, \tag{1}$$

where, $\boldsymbol{M}_s$ denotes the mass, $\boldsymbol{F}_{ext}$ and $\boldsymbol{F}_{int}$ are the external and internal force, respectively, $\boldsymbol{F}_c$ stands for the contact force when multiple solids contact each other, $\boldsymbol{F}_f$ is the exchange force between the solid and gas due to the gas pressure and viscosity. More details about the exchange force $\boldsymbol{F}_f$ can be found in Section 4.

2.2. Fracture algorithm

The fracture model used here is based on the FEMDEM method, which was first proposed by Munjiza.[31] This model treats each solid body as a single discrete element and discrete solid motions are modelled by the discrete element method (DEM), whilst deformable fracturing arbitrary-shaped solid body interaction (stress, velocity and deformation) is modelled by finite-element method (FEM). The stresses are computed by the FEM before fracture initiation. Once the stress state meets a failure criterion, discrete fractures are generated and the DEM is used to explicitly model the discontinuous interaction between discrete surfaces. By combining the FEM and DEM parts, the fracture model is able to accurately capture the transition from continuum to discontinuum behaviour.

2.2.1. Joint element

A modified 3-noded triangular element mesh is introduced to complete the 2D fracture model. Initially, the whole solid domain is discretised by 3-noded triangular elements, and 4-noded joint elements are inserted between these triangular elements. Six adjacent discontinuous elements sharing one centre point (see Fig. 1 left) is taken as an example to describe the joint element method. According to the joint element method mentioned in Ref. 36, for these six adjacent discontinuous elements (element 1–6), there should be six unbroken joint elements (element 7–12) among them (see Fig. 1 right).

2.2.2. Combined tensile and shear failure criterion

The constitutive model is a combined single and smeared crack model equivalent to a cohesive zone model[36,15] Both the tensile stress σ and shear stress τ in joint elements are calculated according to the basic law shown in Fig. 2. In Fig. 2, G_f is the fracture energy, which is a material property; δ_c is the critical displacement when the joint element breaks; and δ_p is the maximum elastic displacement corresponding to the peak stress f. The peak stress f is the material strength. It becomes tensile strength f_t and shear strength f_s when it represents tensile stress σ and shear stress τ, respectively. Tensile strength f_t is assumed to be constant. However, shear strength f_s is given by the Mohr-Coulomb criterion with a tension cut-off:

$$f_s = \begin{cases} \sigma_n tan\phi + c, & when \quad \sigma_n < f_t; \\ f_t tan\phi + c, & when \quad \sigma_n \geq f_t, \end{cases} \tag{2}$$

where σ_n is the normal stress, ϕ is the angle of internal friction and c is