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Mesoscale modelling and analysis of damage and fragmentation of concrete slab under contact detonation

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It is interesting and important for researchers to understand the damage process in order to reliably predict fragment distribution of concrete material under blast loading. In the present study, a mesoscale concrete model is developed to simulate the dynamic failure process of a concrete slab under contact detonation. In the mesoscale model, the concrete material is assumed to consist of two phases, that is, the high strength coarse aggregates and the low strength mortar matrix, randomly distributed in the structure components. Each coarse aggregate is assumed to be circular with a random radius in a given distribution range following the Fuller's curve. The mesoscale model together with a dynamic plastic damage material model is incorporated into the hydrocode AUTODYN. The dynamic damage process of the concrete slab under contact detonation is numerically simulated. Based on the numerical results, the fragment size distribution is estimated by an image analysis program. Two different random aggregate distributions are assumed in the present simulations. Numerical results from the two different cases are compared, and the results from the mesoscale model are compared with that from the homogeneous concrete material model. The fragment size distributions obtained from numerical simulations are also compared with those from the empirical statistic formulae.

1. Introduction

Concrete as a main structural material has been widely used all over the world. It can be used in not only commercial and residential buildings, but also in industry and military facilities. Some concrete structures during their service life might be subjected to explosive loads. Industrial accidents can be a cause of such events. Some critical infrastructures, such as embassy buildings, bridges and government buildings, might be targets of terrorist attack. Structural damage and personnel injury may be caused by direct blast loading and the flying secondary fragments from the failed structural and nonstructural components. It is of interest for researchers to understand the damage process in order to predict fragments of concrete material under blast loads. Predicting the performance of concrete structures to explosive loading through full-scale tests is often beyond affordability. The majority of blast models today are mainly based on empirical or semi-empirical formulae. They tend to overlook the physical behavior of concrete in the dynamic process in blasting. With the rapid development of computer technology and the advancement of numerical techniques, it makes the predictions through computer simulation viable [1,2]. Different numerical methods have already been reported in the literature to model the damage and fragmentation of concrete materials under blast loading.

1.1. Concrete material model under blast loading

One of the challenges for reliable numerical simulations is to develop a proper material model for concrete. To model concrete damage and fragmentation, its strength criterion is the most important. Based on static tests, many static strength criteria have been proposed in the past [3–6], such as Mohr–Coulomb Criterion, Drucker–Prager Criterion, William–Warnke five parameter Criterion, Ottosen Criterion, Hsieh–Ting–Chen Criterion and the unified twin shear strength model. The dynamic properties of concrete material are different from its static properties. From dynamic experimental tests, it has been found that both the tensile strength and the compressive strength of concrete are highly dependent on the strain rate, i.e., the strain rate effect, which is usually modelled by a dynamic increase factor (DIF) to relate the dynamic strength to the corresponding static strength. The strain rate effect for tensile and compressive strength is also different [7–11]. Usually the DIF is obtained from experimental tests. The dynamic strength criterion is

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also simply obtained by multiplying the static compressive, or tensile strength, by the respective DIF in practice.

Some material models have been constructed to simulate the concrete behavior under dynamic loading conditions [12–20]. In 1993, Johnson and Holmquist [12] developed a brittle damage model for concrete [12]. Based on this model, RHT model [14], Gebbeken's model [15], K&C model [16] and modified Drucker–Prgager model [12,17] were developed. Recently, Leppänen [19] modified the RHT model by using a different DIF for tension and a bi-linear crack softening law. All the above-mentioned models belong to the category of plastic damage model. In addition, some visco-plastic models were also developed for concrete, for example, Gatuingt and Pijaudier-Cabot [21] developed a damage visco-plastic model for concrete. They considered the interaction between the spherical and deviatoric response. The constitutive relation for concrete is based on visco-plasticity combined with the rate-dependant continuum damage. The difference between the plastic damage model and the visco-plastic damage model is that the time history effect is considered in the later model. Theoretically the visco-plastic damage model is more reasonable because it considers the time dependant plastic flow. However, the visco-plastic behavior of concrete is very complicated and it is not well understood yet.

In those models, the concrete material is always assumed to be isotropic, continuous and homogeneous.

1.2. Mesoscale modelling of concrete

As is well known, concrete is a composite material, produced by adding the appropriate portions of coarse and fine aggregates, cement, water and some additives if necessary. Obviously the concrete material is heterogeneous, and its heterogeneity makes the behavior of concrete under blast loads rather complicated. Especially, the heterogeneity of concrete affects the crack pattern and the fragment size distribution when it is under blast loads.

To analyze the static heterogeneous behavior of concrete, some mesoscale models for concrete have been developed [22–26]. In most of these mesoscale models, the concrete is assumed consisting of three phases, that is, the coarse aggregates, the mortar matrix with fine aggregate dissolved in it, and the interfacial transition zones (ITZ) between the aggregate and the mortar matrix. Based on the static experimental results, the behavior of ITZ does affect the mechanical properties of concrete. However, it is very difficult to obtain the mechanical parameters of ITZ. Therefore including ITZ in the model introduces some uncertainties. Moreover, considering ITZ in numerical model substantially increases the computational time and computer memory requirement. For these reasons, in some models the ITZs are not included in the numerical simulation [22,25], instead, the ideal bond between the aggregates and the mortar matrix are assumed. To perform the mesoscopic study of concrete material, both discrete element methods, such as lattice model [26] and truss model [27], and continuum finite element methods [22–24] have been used. So far, this kind of mesoscale models has mainly been applied in static numerical simulations.

The present paper aims to construct a mesoscale heterogeneous model for concrete material under blast loading. In the mesoscale model, the concrete material is assumed consisting of two phases, that is, the high strength coarse aggregate and the low strength cement paste, randomly distributed in the structure components. Perfect bond between aggregates and cement paste is assumed. As a numerical example, the dynamic damage process of a concrete slab under blast loads studied by other researchers using a different approach [28] is analysed.

1.3. Concrete dynamic fragmentation

When an explosion occurs, secondary fragments and airborne debris resulting from the damaged structural components may cause serious injury and damage. Therefore, it is of interest to know the fragmentation process of structural components and to predict the size and velocity distribution of the fragments.

The processes of dynamic fragmentation within a concrete member are very complicated since discontinuities such as cleavage cracks and defects with different shapes and orientations are commonly encountered in concrete material and they have significant influence on the failure of concrete. The actual process of dynamic fragmentation is still not well understood, but some theoretical and experimental efforts have provided useful insight regarding the distribution of fragments. Based on energy and momentum balance principles, some models have been developed to predict average fragment size as a function of strain rate and material toughness [29–31]. To determine the distribution of fragment in mass or size, some statistical approaches have been developed [32,33]. In those approaches, the intrinsic failure process leading to fragmentation is not modelled. To understand the mechanisms of fragmentation, some theoretical models have been suggested to correlate the dynamic fracture and fragmentation [34,35]. Recently, numerical modelling has been carried out to simulate the dynamic deformation in the fragmentation process [35–38]. There are mainly three different methods for fragmentation simulation: 1) Interface elements were incorporated between standard finite elements to serve as dynamic fracture paths [35]. The primary drawback of this method is that it cannot give reliable predictions of the fragment size because the size and shape are determined by the pre-defined interface; 2) Damage material model has been put into smooth particle hydrodynamics (SPH method) to simulate the fragmentation process [28,38]. The fragment distribution was obtained by checking the radius of the fully damaged particles. 3) Standard finite element method together with damage mechanics has been employed to model the dynamic deformation and to predict the fragment size [36,37]. The fragment size is predicted by either the energy balance principal or relating the full damage to the fragmentation. All the previous models assumed homogenous material properties. In the present study, the later method is adopted, however, the heterogeneous concrete material properties are considered. The mesoscale concrete model and AUTODYN [2] are firstly employed to model the dynamic deformation of a concrete slab under a contact detonation. The fragment size distributions and ejection velocities are then predicted by relating the full damage to the fragmentation. Next, an image analysis program in MATLAB is used to estimate the fragment size distribution by analyzing the numerical results based on the damage mechanics theory and finite element model.

2. Generation of coarse aggregate particles

The mesoscale concrete model requires the generation of a random aggregate structure in which the shape, size and distribution of the coarse aggregates closely resemble the real concrete in the statistical sense [22]. The coarse aggregates generation method in the present study is the popular "take-and-place" method. Firstly, the size distribution of the coarse aggregate particles is determined by following a certain given grading curve; and then the aggregate particles are placed into the mortar matrix one by one at randomly determined locations in such a way that no overlapping with particles already placed. The similar method was also employed in [22,23,27].

Coarse aggregates are the particles whose diameters are greater than 4.75 mm. For most concrete, the coarse aggregates represent 40–50% of the concrete volume [22]. In the present study, it is