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The 3D meso-scale model and numerical tests of split Hopkinson pressure bar of concrete specimen

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HIGHLIGHTS

- A 3D meso-scale model of concrete is constructed based on the grid mapping method.
- Material parameters of HJC model for mortar, ITZ and aggregate are determined based on tests.
- The meso-scale model is reliably validated both in the aspects of waveform data and specimen deformation process.
- The SHPB tests of concrete specimen under various strain rates are successfully simulated.
- The cracking mechanism of concrete in the SHPB test is revealed.
- The formation mechanisms of different failure modes of the concrete specimen are revealed.

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ABSTRACT

In the present study, a 3D meso-scale model of plain concrete has been developed with consideration of the aggregates, mortar and interface transition zone (ITZ) between them. Firstly, the generation methods of the random polyhedron aggregate and ITZ are introduced, as well as the process how to create the meso-scale finite element (FE) model of the concrete specimen through grid mapping method. Then, based on the experiment data and repeated numerical simulations, the appropriate material parameters of HJC model with respect to each ingredient in concrete are determined. Based on the waveform data and the specimen deformation and failure process in the split Hopkinson pressure bar (SHPB) test of the concrete specimen, the validation of the numerical model is well verified. Subsequently, the numerical SHPB tests of concrete specimen with the experiment size of $\Phi 120 \times 100$ mm under various strain rates are performed. The formation processes of four typical failure patterns of the concrete specimen in the experiment are well reproduced, i.e. "slight-spalling", "breaking", "fragmentation" and "comminution". What's more, the cracking mechanism of concrete specimen in SHPB test is revealed. The formation mechanisms of various failure modes of the concrete specimen under different strain rates are further investigated. The research results show that the failure process of the concrete specimen in the SHPB test can be well simulated by the 3D meso-scale model developed in this paper. Furthermore, the accumulation of the tension strain damage in concrete is the main reason to initiate the cracks in the loading process. Under different loading conditions, due to the crush failure and the tension breaking failure derived from the compression expansion effect play different roles, the specimen deformation and failure processes of different modes will be exhibited.

1. Introduction

Concrete is a kind of material widely used in the civil and protective engineering, i.e. bridges, high-rise buildings, protective structures, etc. These structures should have the capability of resisting the high-rate loads, i.e. earthquake, impact, explosion, etc. Under these loading conditions, the concrete easily exhibits as brittle failure since it is a brittle material consisting of multiphase ingredients and its tensile strength is much smaller than its compressive strength. Therefore, it is of important practical significance to investigate the dynamic behaviors of concrete material under the high-rate loading conditions [1,2].

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Most experimental results [3–8] show that concrete is quite sensitive to the strain rate. Under a wide range of strain rates, different test devices have been employed to investigate the mechanical behaviors of concrete. Among these laboratory techniques, split Hopkinson pressure bar has been widely used to investigate the dynamic compression performance of various solid materials, i.e. metal, metalloid, homogeneous or heterogeneous materials, etc. It should be pointed out that concrete is a kind of heterogeneous material, of which internal components are very complex and its uniformity is fairly poor. In order to balance the influence derived from all aspects of factors, i.e. material uniformity, lateral inertia confinement effect etc., it is fairly important to set the concrete specimen size reasonably in SHPB test. Lv et al. [8] had analyzed and discussed the size setting of the concrete specimen in the large size SHPB test. To better satisfy the uniformity condition and also not result in oversize confining pressure effect, the size of the concrete specimen had been set as $\Phi 120 \times 100$ mm.

In most previous studies [9–11], concrete is usually assumed as homogeneous medium that only contains mortar owing to some practical considerations in performing high-speed impact tests and difficulties in developing detailed numerical models. Indeed, concrete is a kind of heterogeneous composite material consisting of coarse aggregates, mortar matrix and interface transition zone (ITZ) between them [12,13]. Because different ingredients have different material properties, the homogeneous assumption of concrete material must result in not accurate enough predictions in either experimental studies or numerical simulations.

Generally, ITZ is assumed as a kind of porous heterogeneous material of which strength is smaller than that of mortar matrix [12]. The results by Hao and Ai [12,13] indicate that, as the weakest link in the concrete, ITZ has important influence on the failure modes and macroscopic mechanical properties of the concrete. Based on the experimental results achieved by Xiao et al. [14], the thickness of ITZ is about in the range of 0.01–0.05 mm, much smaller than the specimen size. Obviously, meshing the ITZ in a continuous meso-scale model will lead to enormous number of elements and other solution troubles. However, Kim et al. [15] set the ITZ thickness as 0.1–0.8 mm to study the influence of the ITZ thickness on the concrete mechanic properties, and the results indicate that the ITZ thickness has slight influence only on the post-peak behaviors of concrete. For diminishing the difficulties caused by the ITZ thickness in developing the meso-scale FE model, Zhou and Hao et al. [16,17] set the ITZ thickness as 0.2–0.8 mm, and 0.5 mm is adopted in the researches by Song and Pedersen et al. [18,19].

The meso-scale model of concrete specimen contains two aspects: meso-scale geometric model and meso-scale FE model. There are two main ways to create the meso-scale model. The first one is, the meso-scale geometric model is firstly created and then the FE model is generated through directly meshing the geometric model [14,15,20–22]. In this FE model of concrete, the aggregate shape will be better. However, due to the complexity of the internal structure of concrete, the mesh quality cannot be well controlled, and thus the solution precision will also cannot be guaranteed. Furthermore, this modeling method will also inevitably lead to non-uniform FE mesh grid, such as very small size element. And it may result in very large time consumption.

The second one is, similarly, the meso-scale geometric model is created firstly, and then uniform FE mesh grid will be generated in the space occupied by the generation model. Then the meso-scale FE model will be established by the grid mapping method [12,22–26]. By this modeling method, uniform hexahedral element will be generated from aggregates to mortar matrix in the model. Thus the time consumption will be significantly saved and the solution precision also will be improved due to the use of hexahedral element in the dynamic computation. By the way, in the studies of Prof. Qin Fang et al. [22,26–30], with consideration of the randomness of particles in size, shape and distribution, very excellent particle generation methods are developed. Especially, the compaction algorithm is developed in [22], which can largely improve the generation amounts of the particles. However, in their modeling methods, the bonding mode between particles and material matrix is not considered but share bonding.

The selection of the constitutive model and the determination of the material parameters are quite important in the numerical investigation of concrete material. Concrete is a multiphase composite material with complex mechanic properties. Large amounts of initial damage and defects exist in concrete material and the evolution and development of these damage and defects are also quite complex. So far, no dynamic constitutive model is widely accepted. However, according to different research needs, the scholars have developed large amounts of constitutive models to investigate the dynamic properties of concrete.

For the brittle tension failure of concrete-like materials, based on the GK model [31], the TCK model is developed by Chen, Kuszmaul and Thorne [32–34]. The TCK model assumed that the development and accumulation of tension damage of concrete-like materials are related to the mean tensile stress, crack density and volumetric strain rate. It can well simulate the tensile fracture of brittle materials.

Regarding the compression failure, HJC model is proposed by Holmquist, Johnson and Cook [35] in 1993. Because the influence of the strain rate, pressure and compression damage on the yield failure of concrete material is synthetically considered in this model, it can better describe the dynamic behaviors of concrete under the conditions of high pressures, high strain rates and large strains.

Due to the convenient parameters obtaining and better modeling effect, the plastic concrete material model (K&C model) proposed by Malvar et al. [36] in 1997 is widely used to simulate the impact and blast of concrete. With the K&C model, the spalling test of concrete is simulated by Chen et al. [22] and the simulation results show good agreements with relevant experimental data. Furthermore, being a strength model, the Drucker-Prager model [37] is always extended to model the behaviors of concrete-like materials, because it can interpret a typical feature of pressure-dependent flow caused by the internal friction. This model is used by Li et al. [38] to study the effect of hydrostatic pressure on the SHPB test results of concrete-like material.

Based on the above research, obviously, the HJC model is an appropriate choice in the numerical study of SHPB test of concrete material as the specimen failure is dominated by the dynamic compression. However, HJC model is relatively complicated. It needs a large amount of material parameters of which determination process are very tedious. With respect to the concrete with the strength of 48 MPa, Holmquist et al. [3] provided the HJC parameters and the relevant determination methods. The research results in Refs. [35,39] show that, with these material parameters, it well agrees with the experimental data in performing the numerical simulation of concrete under the conditions of high pressures, high strain rates and large strains, e.g. penetration and blast.

In general, whether the material parameters are reasonably determined will directly affect the reliability of the numerical results. Therefore, when the research conditions are changed, e.g. strain rate or material strength, etc., the parameters in the HJC model should be re-determined based on the relevant experiments and the methods determining the original parameters for meeting the new research needs. Furthermore, given that aggregates, mortar and ITZ are belong to the concrete-like materials, when the meso-scale model is used to model the concrete [12,14,15,24,40,41], these three materials are usually modeled by the same kind of material model. In general, the ITZ material