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Numerical analysis of concrete material properties at high strain rate under direct tension

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ABSTRACT

The tensile strength of concrete material increases with the strain rate. The dynamic tensile strength of concrete material is usually obtained by conducting laboratory tests such as direct tensile test, spall test or splitting test (Brazilian test). It is commonly agreed now that the DIF obtained from dynamic impact test is affected by lateral inertia confinement. Therefore, those derived directly from testing data do not necessarily reflect the true dynamic material properties. The influence of the lateral inertia confinement, however, is not straightforward to be quantified in laboratory tests. Moreover, concrete is a heterogeneous material with different components, but is conventionally assumed to be homogeneous, i.e. cement mortar only, in most previous experimental or numerical studies. The aggregates in concrete material are usually neglected owing to testing limitation and numerical simplification. In the present study, a mesoscale concrete material model consisting of cement mortar, aggregates and interfacial transition zone (ITZ) is developed to simulate direct tensile tests and to study the influences of the lateral inertia confinement and heterogeneity on tensile strength of concrete material with respect to strain rates between 1/s and 150/s. The commercial software AUTODYN with user provided subroutines is used to perform the numerical simulations of SHPB tests. The model is verified by testing data obtained by others. Numerical simulation results indicate that the lateral inertia confinement contributes to the dynamic increase factor (DIF) of concrete material tensile strength. The lateral inertia confinement effect is specimen size and strain rate dependent. Based on the numerical results, discussions on the relative contributions from the lateral inertia confinement and the material strain rate effect on DIF of concrete material tensile strength are made. Empirical relations are proposed to remove the influence of the lateral inertia confinement in dynamic impact tests on dynamic concrete material strength. The effect of aggregates inside the concrete specimen on its dynamic strength is also investigated. The results demonstrate that it is very important to include aggregates in experimental and numerical studies of concrete material dynamic strength, otherwise significant inaccuracy might be induced.

1. Introduction

Concrete is a common construction material used in both civil and defense engineering. For a better protection against high-rate loadings, e.g. impact or blast, and a more reliable design of concrete structures, it is important to understand the dynamic concrete material properties. The dynamic tensile strength of concrete is usually obtained by conducting laboratory tests such as direct tension test [1–3], spall test [4,5] or Brazilian splitting test [6]. Although it is widely agreed that the dynamic tensile strength increase factor (DIF), defined as the ratio of dynamic to static strength, of concrete material increases with strain rate, like concrete compressive strength DIF, apparent scatters of tensile strength DIF from different tests can be observed [7,8]. These scatters can be attributed to variations in testing conditions such as apparatus, specimen material and specimen size. Besides these variations, it is known that inevitable lateral inertia confinement, which is specimen size dependent, also influences the testing results. Thorough discussions on the possible influences of these parameters on impact testing of dynamic compressive material properties can be found in the literature [9,10]. Although most previous studies concentrate on discussions of parameters that influence the compressive test results, similar influences, such as the lateral inertia confinement, also applies to dynamic tensile tests. However, these influences are difficult to be removed nor quantified in laboratory tests. These raise the doubts on the

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reliability of the dynamic material properties obtained from impact tests. A number of analytical and numerical studies of the lateral inertia confinement effect on dynamic compressive material property have been reported in the literature [11–17]. However, there is no systematic study yet on the influences of lateral inertia confinement on dynamic concrete tensile material properties. Using the current empirical relations from the literature [3,5,7,18–20], which are derived mainly from testing data, might overestimate the concrete dynamic material strength because the inertia confinement effect, which increases the concrete dynamic tensile strength, inevitably exists in dynamic testing.

Moreover, real concrete consists of cement mortar, aggregates and interfacial transition zone (ITZ), but in most previous laboratory tests and numerical simulations, the aggregates inside the concrete are usually neglected owing to practical considerations in performing high-speed impact tests, and difficulties in developing detailed numerical models and carrying out numerical simulations. For example, concrete specimens were assumed as a homogeneous material with cement mortar only [2,8,21–24], or concrete-like material (micro-concrete) in which sand, or so-called fine aggregates up to 2 mm, is used to prepare the specimen in studies of dynamic concrete material properties [4,24–26]. Because different components in a concrete mix have different material properties, modelling concrete by cement mortar only may result in inaccurate predictions of concrete material properties in both experimental and numerical studies. Brara and Klepaczko conducted spall test and found almost all fine aggregates were cleaved at the fracture surface [26]. Similarly, Yan and Lin conducted direct tensile test and observed that the fracture surfaces of the specimens became more and more flattened with the increasing strain rate; and an increasing number of coarse aggregates were broken along the fracture surface. They concluded that a higher stress level is needed to break aggregates into pieces along the fracture surface [3]. These test results clearly demonstrated the influences of aggregates on concrete dynamic tensile strength. Therefore it is deemed necessary to include aggregates in both experimental and numerical studies in order to more reliably derive the concrete dynamic tensile strength.

The present study develops mesoscale models of concrete specimens with consideration of cement mortar, aggregates and ITZ to investigate the influence of lateral inertia confinement on dynamic tensile strength of concrete specimens under direct tensile tests. The commercial software AUTODYN with user provided subroutines is employed to perform the numerical simulations. The reliability of the numerical model in simulating the SHPB tests is verified by comparing the numerical results with the experimental data reported in [2]. With user provided subroutines linked to AUTODYN, the DIF relation proposed by Hao and Zhou [20] is used to define the strain rate effect of concrete material. The materials are assumed to be strain rate sensitive and insensitive, respectively in numerical simulations. The DIF derived from strain rate sensitive materials is caused by a combination of strain rate effect and lateral inertia confinement effect, while the DIF derived from strain rate insensitive materials is caused by only lateral inertia confinement. Because the lateral inertia confinement effect is specimen size dependent, to quantify the lateral inertia confinement effect on concrete specimens of different sizes, the radius of the specimen is varied from 6 mm to 20 mm in numerical simulations. The numerical simulations allow for a direct observation and quantitative assessment of the lateral inertia confinement effect on the concrete tensile DIF. Based on numerical results, empirical relations are proposed to remove lateral inertia confinement effect in dynamic impact tests. The influence of including aggregates in concrete specimen on its dynamic tensile strength is also discussed.

2. Material model

An accurate material model is essential for a reliable simulation of structural response and damage. The material model used in the present study includes equation of states (EOS), strength criterion, damage model and a model for strain rate effect, which is similar to those proposed by Hao and Zhou [20]. It should be noted that the property of ITZ is not well understood yet. Therefore, in this study it is assumed to be a weak mortar, with the same material model but a lower strength.

2.1. Equation of state (EOS)

In order to obtain a complete solution, in addition to appropriate initial and boundary conditions, it is necessary to define a further relation between the flow variables. This can be found from a material model which relates stress to deformation and internal energy (or temperature). In AUTODYN, the stress tensor is separated into a hydrostatic tensor and a stress deviatoric tensor associated with the resistance of the material to shear distortion [27]. The relation between the hydrostatic pressure, the local density (or specific volume) and local specific energy (or temperature) is known as an equation of state (EOS).

ITZ and cement mortar are considered as porous materials due to the porosity and complex non-linear compressive behaviour. They are modelled by P-α EOS [28] where the parameter α is defined by the equation

$$\alpha = \upsilon/\upsilon_s \tag{1}$$

where υ is the specific volume of the porous material and υ_s is the specific volume of the material in the solid state at the same pressure. $\upsilon_s = 1/\rho_s$ at zero pressure, and ρ_s is the solid density. The compaction path, $\alpha(p,e)$, represents the volumetric stiffness of the porous material between the initial compaction pressure p_e and the fully compacted pressure p_s as

$$\alpha = 1 + (\alpha_p - 1)\left(\frac{p_s - p}{p_s - p_e}\right)^n \tag{2}$$

where α_p is the value of α corresponding to the initial plastic yielding, p is the current pressure, n is the compaction exponent, which is assumed to be 3 in the present study.

Aggregate is assumed to experience brittle failure with a minimum deformation. Therefore, the simplest linear EOS is adopted for aggregates as

$$p = K\mu \tag{3}$$

where p is the pressure, $\mu=(\rho/\rho_0)-1$, in which ρ_0 is the initial density and ρ is the current density of the aggregate corresponding to pressure p, and K is the material bulk modulus.

2.2. Strength criterion

The deviatoric stress tensor is governed by a damage-based yield strength surface. The concrete material is assumed to be elastic before the stress state reaches the yield criterion. The incremental form of the Hooke's law is

$$\Delta s_{ii} = 2G\left(\Delta\varepsilon_{ii} - \frac{\Delta\upsilon}{3\upsilon}\right); \quad \Delta s_{ij} = 2G\Delta\varepsilon_{ij} \tag{4}$$

where G is the shear modulus, Δs_{ij} is the deviatoric stress increment, $\Delta\varepsilon_{ij}$ is the strain increment and $\Delta\upsilon/\upsilon$ is the relative change in the volume from EOS.