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Semi-empirical equations for the dynamic strength enhancement of concrete-like materials

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ABSTRACT

SHPB tests are often employed to characterize the dynamic compressive strengths of concrete-like materials which are very important for the construction of reliable constitutive equations used in numerical simulations. The SHPB test data, however, need to be interpreted correctly as recent studies have revealed that the apparent compressive strength enhancement found in the SHPB tests might be due to a combination of effects such as material inherent behavior (rate sensitivity) and inertial confinement. To this end, semi-empirical equations are suggested for the dynamic strength enhancement of concrete-like materials. The equations are formulated on the basis of the recent numerical analysis that dynamic tensile tests on concrete-like materials have no inertial confinement effects and the assumption that the increments of the tensile and compressive strengths due to strain rate effects only are equal at the same strain rate. It is shown that the present semi-empirical equations are in reasonable agreement with available test data for concrete materials.

1. Introduction

Strain rate effects on the compressive and tensile strengths of concrete-like materials play an important part in the construction of material constitutive models which, in turn, exert a great deal of influences on the numerical simulations of concrete structure subjected to intense dynamic loadings.

A great body of test data has now been acquired for concrete materials under a wide range of strain rates. The SHPB technique is often used to investigate the rate sensitive behavior of concrete-like materials at relatively high strain rates ($\sim 10^3$ s^{-1}) and dynamic increase factor (DIF) is often employed to characterize the rate sensitive behavior of concrete-like materials. The SHPB test results show that the dynamic compressive strength increases sharply when strain rate is greater than a critical value. Based on the experimental results, several empirical equations of the dynamic increase factor (DIF) have been given for concrete.

Inherent material behavior and internal confinement effects are the two main factors which are often considered to be responsible for the dynamic strength enhancement of concrete-like materials. The transition from a uniaxial stress state to a uniaxial strain state was firstly noted by Brace and Jones [1] when they tested the dynamic compressive strength of rocks. Bischoff and Perry [2] summarized the scattered evidence about the lateral inertia confinement influence on the compressive strengths of concrete-like materials in dynamic tests and suggested that the sharp increase in the compressive dynamic enhancement may not real. This viewpoint was supported by several other studies, e.g., Janach [3], Glenn and Janach [4], Young and Powell [5], Donze et al. [6]. Similar argument wad made by Cotsovos and Pavlovic [7] who suggested that tensile strength enhancement of concrete based on direct tensile tests was caused by axial inertial effect. However, from the traditional point of view, dynamic strength enhancement based on spalling and SHPB tests represented the material intrinsic behavior of concrete-like materials. Therefore, it is necessary to answer the questions that whether the lateral inertial effect should be considered on both compressive and tensile dynamic strength enhancement, and that how to quantitatively describe the lateral inertial effect and the real strain rate effect on dynamic strength enhancement.

In recent years, several numerical SHPB tests and spalling tests performed by Li et al. [8–11], Hentz et al. [12], Zhang et al. [13], Kim et al. [14] and Hao et al. [15] indicated that the dynamic compressive strength enhancement is caused by a combination of material inherent behavior (rate sensitivity) and lateral inertial confinement effects and that inertial effects have no contribution to the dynamic tensile strength enhancement. It implies that the dynamic tensile test data may reflect the true rate sensitive behavior

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of concrete-like materials whereas the SHPB test results may overestimate the strain rate effects. In other words, the SHPB test data need to be critically reviewed and interpreted correctly.

The objective of the present paper is to formulate semi-empirical equations for the dynamic strength enhancement of concrete-like materials. The equations are developed on the basis of the aforementioned recent findings and the assumption that the increments of dynamic compressive and tensile strengths due to strain rate effects only are equal at the same strain rate. The equations are compared with available test data for concrete materials and discussed.

2. An overview of the previous work

The dynamic material test data are often characterized by dynamic increase factor (DIF) which is defined as

$$\mathrm{DIF_c} = f_{\mathrm{cd}}/f'_{\mathrm{c}} \tag{1}$$

or

$$\mathrm{DIF_t} = f_{\mathrm{td}}/f_{\mathrm{t}} \tag{2}$$

where f_{cd} is the dynamic uniaxial compressive strength, f'_{c} is the static uniaxial compressive strength, f_{td} is the dynamic uniaxial tensile strength, f_{t} is the static uniaxial tensile strength.

2.1. Strain rate effects on the tensile strength

Many different methods have been proposed to estimate the dynamic strength enhancement in a wide range of strain rates. The direct tensile tests are suitable to study the tensile strength of concrete for strain rates ranging from 10^{-1} to 10 $\mathrm{s^{-1}}$, the spalling experiments are needed to achieve higher strain rates up to 100 $\mathrm{s^{-1}}$. Fig. 1 shows a collection of the dynamic tensile test data from literature in terms of dynamic increase factor versus strain rate. It can be seen from Fig. 1 that a sharp increase of dynamic tensile strength is observed above the strain rate 10 $\mathrm{s^{-1}}$, approximately.

European CEB [16] recommended the following empirical formulae for dynamic strength enhancement of concrete in tension with strain rates up to 300 $\mathrm{s^{-1}}$, viz.

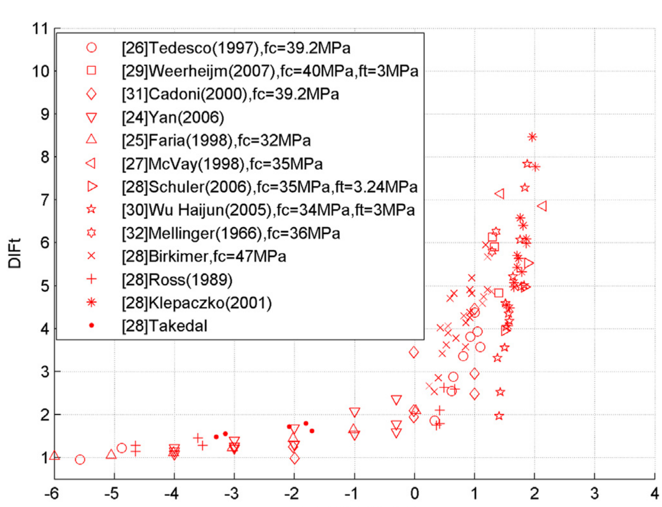

Fig. 1. Variation of the experimentally obtained tensile dynamic increase factor with strain rate [24,25,27–32].

$$\mathrm{DIF_t} = \frac{f_{\mathrm{td}}}{f_{\mathrm{t}}} = \begin{cases} \left[\dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_{\mathrm{s}}}\right]^{1.0168\delta} & \dot{\varepsilon} \le 30\ \mathrm{s^{-1}} \\ \beta\left[\dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_{\mathrm{s}}}\right]^{1/3} & \dot{\varepsilon} > 30\ \mathrm{s^{-1}} \end{cases} \tag{3}$$

where $\delta = 1/(10+0.6f'_{\mathrm{c}})$, $\beta = 10^{7.11\delta-2.33}$, $\dot{\varepsilon}_{\mathrm{s}} = 3\times10^{-6}\ \mathrm{s^{-1}}$.

Zhou and Hao [17] suggested the following empirical equations for the dynamic tensile strength enhancement of concrete, i.e.

$$\mathrm{DIF_t} = \frac{f_{\mathrm{td}}}{f_{\mathrm{t}}} = \begin{cases} 1 & \dot{\varepsilon} \le 10^{-4}\ \mathrm{s^{-1}} \\ 1+0.26[\log(\dot{\varepsilon})+4.0769] & 10^{-4}\ \mathrm{s^{-1}} \le \dot{\varepsilon} \le 1\ \mathrm{s^{-1}} \\ 1+2[\log(\dot{\varepsilon})+0.53] & \dot{\varepsilon} > 1\ \mathrm{s^{-1}} \end{cases} \tag{4}$$

Based on a series of dynamic splitting tests, Tedesco and Ross [18] proposed the following equations for $\mathrm{DIF_t}$

$$\mathrm{DIF_t} = \frac{f_{\mathrm{td}}}{f_{\mathrm{t}}} = \begin{cases} 1+0.1425[\log(\dot{\varepsilon})+5.8456] \ge 1 & \dot{\varepsilon} < 2.32\ \mathrm{s^{-1}} \\ 1+2.929[\log(\dot{\varepsilon})-0.0635] \le 6 & \dot{\varepsilon} > 2.32\ \mathrm{s^{-1}} \end{cases} \tag{5}$$

On the other hand, Yamaguchi et al. [19,20] suggested a formula for the $\mathrm{DIF_t}$ of concrete in a parabolic form, i.e.

$$\mathrm{DIF_t} = \frac{f_{\mathrm{td}}}{f_{\mathrm{t}}} = 0.04379[\log(\dot{\varepsilon})]^2 - 0.02987\log(\dot{\varepsilon}) + 0.8267 \tag{6}$$

More recently, numerical simulations of direct dynamic tensile tests, dynamic splitting tests and spalling tests based on a rate-independent constitutive model of concrete were performed by Lu and Li [9]. The numerical results indicated that the dynamic tensile enhancement is associated with inherent material behavior rather than structural effects. Hence, the experimentally obtained tensile dynamic increase factor as shown in Fig. 1 can be seen authentic which represent the true strain rate effects on the tensile strength of concrete-like materials.

Since the inertia effect does not contribute to the dynamic tensile enhancement, what is responsible for it? It is found that micro-cracking contributes to the observed dynamic tensile enhancement from dynamic tensile tests according to the theoretical analysis performed by Lu and Li [9]. Lu and Li [9] concluded that "It shows that the observed increase of tensile strength with strain rate from dynamic tensile tests can be largely attributed to the inertia effects of micro-cracks." This conclusion is in fact consistent with that of Cotsovos and Pavlovic [7]. In other words, the observation made by Lu and Li [9] is not in conflict with that made by Cotsovos and Pavlovic [7].

2.2. Strain rate effects on the compressive strength

To study dynamic compressive strength enhancement of concrete-like materials, test methods which can cover a wide range of strain rates are very important. The quasi-static low strain rate (10^{-4}–10^{0} $\mathrm{s^{-1}}$) compression tests are conducted on a universal material testing system (MTS). The medium to high strain rate (10^{0}–10^{3} $\mathrm{s^{-1}}$) compression tests are performed on the SHPB apparatus, which is based on the principle of one dimensional wave propagation. Fig. 2 shows a collection of the dynamic compressive test data from literature in terms of dynamic increase factor versus