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Dynamic mechanical responses of concrete under the influence of extreme loads

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ABSTRACT

Understanding dynamic mechanical behaviors of concrete subjected to extreme loads is necessary to analyze and design infrastructures. The dynamic increase factor (*DIF*) is defined as the ratio of the dynamic stress to the static stress and can be normally expressed as a function of strain rate. In general, a servo-hydraulic testing machine has been used for a static or quasi-static strain, whereas drop weight impact and split Hopkinson pressure bar tests have been conducted for the material response at high strain rates. This paper 1) summarizes the features of these experimental methods and 2) systematically reviews the design curves and prediction models for concrete.

1. INTRODUCTION

There have been rising requirements for improved protective civilian buildings and military infrastructures due to a dramatic increase in the use of highly explosive composite materials in chemical plants, industrial structures, and nuclear power facilities as well as a sharp increase of terrorist attacks. When designing buildings and infrastructures, structural and geotechnical engineers have been required to consider predicting and designing against extreme dynamic load conditions from man-made actions, e.g., blast or impact, and natural actions. In the late 1960's, the first UFC (Unified Facilities Criteria) manual "Structures to Resist the Effects of Accidental Explosions" was proposed on the basis of comprehensive experimental data for the following reasons: 1) to make parameters of the blast load for protective structures; 2) to propose ways for determining the dynamic mechanical response of the concrete and steel; 3) to suggest construction details and procedures for blast-resistant structures; and 4) to provide guidelines for the location of explosive facilities. For past several decades, the efficiency and precision of blast analysis and blast-resistant design guideline have been considerably updated through advanced experimental and

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computational techniques.

Experimental techniques such as the servo-hydraulic, drop weight hammer, SHPB, and plate impact tests have been primarily used in the laboratory to observe dynamic mechanical behavior. Servo-hydraulic machine systems are one of the best methods for static or quasi-static loading tests on various engineering materials and composites in the strain rate range of 10^{-7} to 10^{1} s^{-1}, while one of the principal experiments to obtain the range of the intermediate strain rates between 10^{0} and 10^{2} s^{-1} is the drop-weight hammer (or drop hammer) test. Kolsky (1949) is considered as the pioneer who introduced the Kolsky bar or split Hopkinson pressure bar (SHPB) method for measuring the mechanical properties of engineering materials such as alloys, concrete, metals, and steels at high strain rates in the range of 4.4 to 8000 s^{-1} (Hughes et al. 1993). The SHPB consists of two long bars, i.e., incident and transmitter pressure bars (called the input and output bars), with a small cylindrical specimen between them (see Fig. 1; Lok and Zhao 2004). Because the bars must have very high yield strength and toughness, the potential bar materials should be maraging steel, 7075-T6 aluminum, magnesium alloys, poly methyl methacrylate, or tungsten carbide. Impacting the incident pressure bar by a striker bar generates an incident compressive pulse which propagates the input bar to the specimen. A transmitted wave through the specimen is sent to the transmitter pressure bar and a reflected pulse from the specimen is sent back to the incident pressure bar.

A pressure-shear plate impact experiment was developed to investigate the dynamic plastic response of materials at very high shear strain rates of 10^{4} to 10^{6} s^{-1}. A flat specimen which consists of a very thin and flat plate with thicknesses between 2 μm and 300 μm are placed between two flat and parallel impact plates that are inclined relative to their direction of approach. This thin and flat specimen is installed with an epoxy to a hard plate (called the flyer) which is launched down the barrel of a gas gun towards an anvil plate. Nominal stresses and strains in the specimens are determined by a normal velocity interferometer and a transverse displacement interferometer positioned to take measurements at the rear surface of the anvil plate (Fig. 2; Sharpe 2008). The fundamental concept of the plate impact technique (or normal plate impact experiment) is the same as the pressure-shear plate impact experiment.

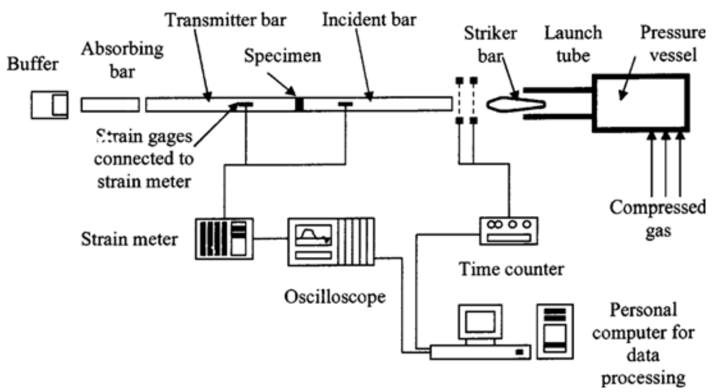

Fig. 1 Schematic configuration of split Hopkins pressure bar system (Lok and Zhao, 2004)

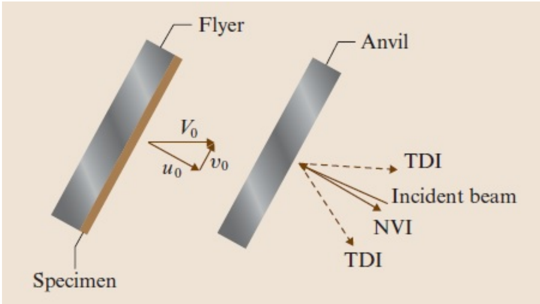

Fig. 2 Schematic of pressure-shear plate impact techniques (Sharpe, 2008)

2. DYNAMIC INCREASE FACTOR FOR CONCRETE

In 2002, the United States of Department of Defense released and distributed the Unified Facilities Criteria (UFC) for structures to resist the effects of accidental explosions. The UFC proposed the bilinear relationship between the dynamics increase factor and a function of strain rate with a change in slope of 1 msec^{-1} and 30 msec^{-1} for compression and tension, respectively. It was found that the experimental results are different from the proposed model in the UFC.

Figures 3 and 4 show the dynamic increase factor for tensile and compressive strengths of concrete, respectively. The main character of the dynamic increase factor for tensile strength is the transition strain zone at 10^{1} msec^{-1}, while the dynamic increase factor for compressive strength of concrete considerably increases with the strain rate without transition strain zone. In this paper, the equations for tensile and compressive cases are proposed for numerical analysis, as shown in Eqs. (1) and (2).

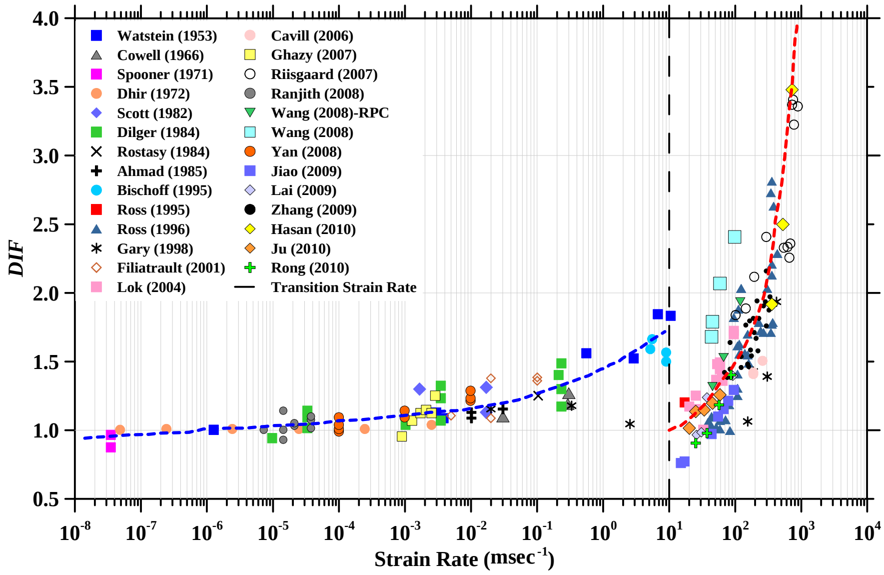

Fig. 3 Strain rate effect on compressive strength of concrete (updated from Pajak, 2011)

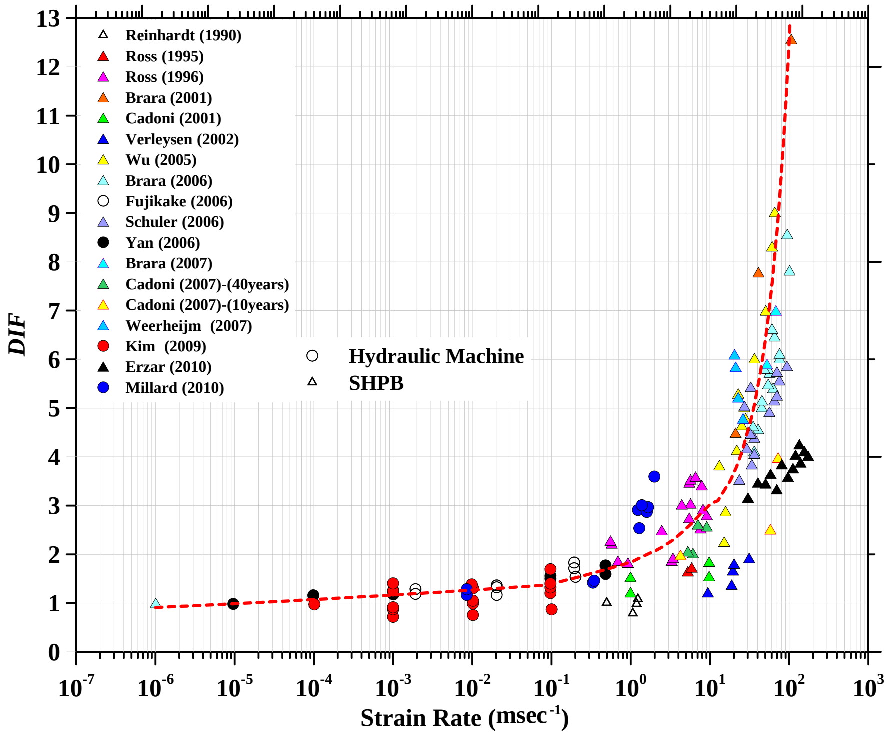

Fig. 4 Strain rate effect on tensile strength of concrete (updated from Pajak, 2011)

$$DIF_{com} = \begin{cases} 1.21\dot{\varepsilon}^{0.0135} & \text{for } \dot{\varepsilon} < 10^{-4} \text{ mm/mm / msec} \\ 1.26\dot{\varepsilon}^{0.019} & \text{for } 10^{-4} \le \dot{\varepsilon} < 10^{-2} \text{ mm/mm / msec} \\ 1.465\dot{\varepsilon}^{0.06} & \text{for } 10^{-2} \le \dot{\varepsilon} < 10 \text{ mm/mm / msec} \\ 0.63\dot{\varepsilon}^{0.185} & \textit{for } 10 \le \dot{\varepsilon} < 10^{2} \text{ mm/mm / msec} \\ 0.115\dot{\varepsilon}^{0.521} & \textit{for } \dot{\varepsilon} \ge 10^{2} \text{ mm/mm / msec} \end{cases} \tag{1}$$

$$DIF_{ten} = \begin{cases} 1.5\dot{\varepsilon}^{0.036} & \text{for } \dot{\varepsilon} < 10^{-1} \text{ mm/mm / msec} \\ 1.84\dot{\varepsilon}^{0.12} & \text{for } 10^{-1} \le \dot{\varepsilon} < 1 \text{ mm/mm / msec} \\ -0.0067\dot{\varepsilon}^{2} + 0.2\dot{\varepsilon} + 1.7 & \text{for } 1 \le \dot{\varepsilon} < 10 \text{ mm/mm / msec} \\ 0.0004\dot{\varepsilon}^{2} + 0.063\dot{\varepsilon} + 2.34 & \text{for } 10 \le \dot{\varepsilon} \text{ mm/mm / msec} \end{cases} \tag{2}$$

4. CONCLUSIONS

Experimental methods used to measure the wide range of strain rates between 10^{-6} and 10^{8} s^{-1} are introduced in this paper. The static or quasi-static strength is typically obtained by a servo-hydraulic testing machine in the range of strain rates from 10^{-7} to 10^{1} s^{-1}. The drop weight hammer technique is normally used to measure the range of intermediate strain rates. The SHPB and plate impact methods are appropriate for high, very high, and ultra-high strain rates. Finally, in this paper, the innovative equation of dynamic increase factor for concrete subject to blast and impact is derived on the basis of the comprehensive literature review, and the developed formulation is significantly useful for numerical analysis of concrete materials.

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