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# Numerical study of the influences of pressure confinement on high-speed impact tests of dynamic material properties of concrete

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## HIGHLIGHTS

- Pressured fluid influences the testing results of modified SHPB test system.
- Strain rate sensitivity of concrete decreases with the increment of confinement.
- An empirical relation is proposed to describe DIF of confined concrete.

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## ABSTRACT

Although tests of Modified Split-Hopkinson Pressure Bar (MSHPB) system with a pressure vessel filled with pressurized fluid or air give concrete material properties under multi-axial stress states, as will be demonstrated in this study, they do not lead to accurate results because the confining pressure under impact tests changes when specimen deforms. Unfortunately there is no reliable apparatus yet to perform impact tests on specimens with a controllable confining pressure. In this study, a mesoscale concrete model with consideration of randomly distributed aggregates is developed to study the strain rate effect on concrete under confining pressures. The results show that the strain rate sensitivity of concrete decreases with the increment of the confining pressure, indicating the strain rate effect of concrete under multi-axial stress states is less prominent as compared to that under uniaxial stress state. Using the uniaxial impact testing data overestimates the strain rate effect of concrete material under multi-axial stress states. An empirical relation is proposed in this study to model the concrete Dynamic Increase Factor (DIF) for the case with pressure confinement, which can be used to more accurately represent the DIF of concrete material under multi-axial stress states.

## 1. Introduction

Concrete structures might expose to multi-hazard loadings such as blast and impact loads during their service life. Under such dynamic loadings, the stress states of concrete material are very complex owing to the complex stress wave propagations and inertial confinement from concrete structure mass to resist fast dynamic deformations. The strength increment of concrete material under dynamic multi-axial stress states is not well understood yet due to the lack of proper testing facilities for conducting multi-axial impact tests, as well as the lack of effective analysis methods to predict the dynamic performance of concrete under such conditions [1]. Most existing concrete material models adopt the uniaxial dynamic testing results for modelling the strain rate effect of concrete material properties under multi-axial stress states [2]. Obviously strain rate effect obtained from uniaxial impact tests is not able to reliably represent the true strain rate effect of concrete material under multi-axial stress states. Modified Split-Hopkinson Pressure Bar (MSHPB) system with a pressure vessel filled with pressurized fluid or air is normally used to test concrete material properties under dynamic multi-axial stress states. Although the impact tests on confined concrete specimen give a better understanding of the dynamic behavior of concrete under multi-axial stress states compared with the unconfined uniaxial SHPB tests, it is proved in this study that the current testing technique of the MSHPB system does not give reliable results because the confinement pressure changes when specimen deforms under impact loads. On the other hand, the reliability of numerical simulations of structural responses subjected to blast and impact loads, which

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have been becoming more and more common in practice, depends on the accuracy of material models. Therefore accurate modelling of the dynamic material properties of concrete under multi-axial stress states is deemed necessary.

The dynamic behaviors of concrete under uniaxial loadings have been extensively investigated through experimental tests and numerical simulations [3–6]. It is found that the uniaxial strength of concrete increases with the increment of strain rate. Fib model code for concrete structures 2010 [7] gives recommendations of concrete material DIF (Dynamic Increase Factor, defined as the ratio of dynamic-to-static strength) as a function of strain rate that can be used in the design and analysis. The behavior of concrete materials subjected to tri-axial static loadings have been studied by many researchers. It is found that concrete showed different performances under multi-axial stress states, and confinement greatly improves the maximum strength and the ductility of concrete [8–11]. Nevertheless, study of strain rate effect on concrete under multi-axial stress states is very limited because of the difficulties in conducting synchronized multi-axial impact tests. When strain rate is relatively low, servo hydraulic multi-axial testing system can be used to study concrete dynamic properties under certain confining pressures. Yan et al. [12] carried out a series of low strain rate tests (<0.1 1/s) and concluded that the strength of concrete tended to be independent of the strain rate when the confining pressure was higher than its uniaxial static strength. Fujikake et al. [13] also found that the strain rate effect on concrete maximum strength under tri-axial stress states decreased with the increment of the confining stress at a strain rate range from $3.0 \times 10^{-2}$ 1/s to 2.0 1/s. Owing to the difficulty in conducting the synchronized tri-axial impact tests, for high strain rate, MSHPB test system with a pressure vessel or using steel wrapped specimens to give confining pressures is normally used to generate pseudo tri-axial dynamic loadings. Chen et al. [14] used steel wrapped specimens to study the concrete dynamic properties under passive confining pressures. It was found that the dynamic damage evolution process was delayed significantly by the confining pressure and the strength of concrete increased obviously. However, it was noted that the confining pressure was certainly increasing and uncontrollable during the dynamic tests. Xue and Hu [15] used pressurized oil to fill the pressure vessel to give confining pressures in the mortar SHPB tests and found that the strain rate effect on mortar was obvious. Marvern et al. [16] used pressurized water to provide confinements on concrete specimens in impact tests. The results showed that concrete was sensitive to strain rate within the tested confinement pressure range of 3–10 MPa. Gary and Bailly [17] used a similar device and found that the strength of concrete increased about 30% as strain rate increased from 250 1/s to 600 1/s under 5.0 MPa confining pressure. They also found that the same level of oil pressure and air pressure led to different results, indicating that the pressurized media, i.e., fluid or air, influenced the test results under dynamic loadings. As will be demonstrated in this study, the confinement media affecting the testing results is because the pressurized fluid or air constrains the lateral deformation of the specimen under fast loading tests; and deformation of the specimen makes the confining pressure change, but the level of change in the confining pressures from fluid and air is different, hence influences the testing results. Since it is hard to keep the confining pressure constant with the current testing devices in impact tests, the dynamic properties and strain rate effects of concrete material under multi-axial stress states therefore cannot be accurate obtained with the current testing devices. For these reasons, most of the current concrete material models use the strain rate effect relation obtained from uniaxial stress state to represent those of tri-axial stress states [18].

On the other hand, with the development of computer technologies and computational mechanics methods, numerical simulations of uniaxial high-speed impact tests of concrete specimens have been reported and yielded good results [19–21]. In other words, numerical simulation of impact tests of concrete specimens is viable. Since it is difficult to obtain reliable results through physical tests of concrete specimens under dynamic complex stress states, in the present study, numerical simulations are utilized to simulate the modified SHPB test on concrete specimens with confinement pressures. It has been widely accepted that the true DIF of concrete material is mainly caused by the different failure modes of specimens under static and dynamic loadings [21–26]. Under static loading, the cracks develop and propagate along the weak zones of the concrete. While under dynamic loading, there is not enough time for the cracks to find the weak zones inside the concrete. Therefore widely spread cracks are forced to propagate through the higher resistance zone inside the concrete specimen. To capture these phenomena, in numerical modelling heterogeneity properties of concrete need to be modelled. Mesoscale concrete model can reflect the heterogeneity and anisotropy of the material [19,20,27].

In this study, a mesoscale concrete model with consideration of mortar matrix and randomly distributed aggregates is developed to explore the strain rate effect on concrete strength under confinement. The accuracy of the model is verified by comparing the numerical and available testing data of uniaxial impact tests. The evolutions of the cracks under low strain rate loading, high strain rate loading and axial loading with confining pressures are studied using the mesoscale concrete model. The results are compared and discussed. Discussions on the accuracy of the test results of current SHPB system with pressure confinement and possible improvement on concrete constitutive models are also made.

## 2. Influence of the confinement pressure on the modified SHPB test results

As mentioned above, the current understanding about the strain rate effect on concrete under confining pressure may not be accurate because of the difficulty in providing a constant confining pressure to the concrete specimen in dynamic tests. In this section, numerical models of the SHPB tests without or with pressure confinement vessels are developed. The accuracy of the model is verified by actual SHPB testing data without confinement. The variation of confinement pressure during the impact tests and its influences on testing data are demonstrated through numerical simulation results.

### 2.1. SHPB technique

Fig. 1 gives the schematic illustration of SHPB test system which consists of an incident bar and a transmitted bar with a specimen sandwiched between them. The one-dimension incident wave is produced by a strike bar impacting the incident bar and is recorded by strain gauge A. Part of the incident wave is reflected as a tensile stress wave (also recorded by strain gauge A) at the interface between the incident bar and the specimen, while another part travels through the specimen. The wave goes forth and back between the two end surfaces of specimen and makes the stress distribute uniformly in the specimen after a few reflections [28]. The compressive stress wave leaves the specimen, then propagates forward along the transmitted bar and is recorded by strain gauge B.

The compressive stress in the specimen can be deduced from the axial strain signal of strain gauge B on the transmitted bar. The compressive stress of the specimen is: