



Sensitivity and uncertainty analysis of interfacial effect in SHPB tests for concrete-like materials

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HIGHLIGHTS

- SHPB experiments are performed for cement mortar specimens at different strain rates.
- A numerical model is established in ABAQUS and validated by experimental results.
- A sensitivity ranking is given by sensitivity analysis of interfacial effect.
- Uncertainty analysis of interfacial effect is performed by interval analysis method.

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ABSTRACT

The Split Hopkinson Pressure Bar (SHPB) equipment has been widely used to measure the dynamic properties of concrete-like materials at high strain rate between 10 s^{-1} and 10^3 s^{-1} . As we know, a crucial factor that influences the accuracy of SHPB tests is the interfacial effect between specimen and bars. In our work, interfacial effect was investigated and summarized into three types of parameters, i.e., interfacial friction coefficient, specimen diameter and specimen non-parallelism. A series of concrete-like (cement mortar) specimens with two different strengths were tested at three different strain rates on SHPB equipment, and the uncertainty of the interfacial effect was transformed into intervals of these three types of parameters. A numerical model was established in ABAQUS and verified to study the interfacial effect, then the sensitivity analysis of three types of parameters was undertaken to figure out a sensitivity ranking using the full factorial design method. The sensitivity analysis provides an effective measure to promote the experimental accuracy and it is meaningful for understanding the interfacial effect in SHPB tests. Moreover, uncertainty analysis was conducted to give an interval of dynamic response of SHPB tests based on a non-probabilistic interval analysis method. The uncertainty analysis can provide an effective estimation of SHPB experimental results considering the uncertainty of interfacial effect.

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1. Introduction

Concrete materials are extensively used in various engineering structures, such as high-rise buildings, subway projects and other civil infrastructures. Engineering structures may accidentally suffer impact or explosion load, such as earthquake, gas explosion and even man-made explosion in the terrorist attacks. Therefore, investigating the dynamic properties of concrete materials is a significant issue for the application in engineering structures. Usually,

the dynamic properties of concrete materials are obtained from the Split Hopkinson Pressure Bar (SHPB) tests [1–3], the drop-weight tests [4,5] or other testing techniques [6].

The SHPB technique developed by Kolsky [7] is commonly used by researchers to investigate the dynamic properties of concrete-like materials at high strain rates ($10 \text{ s}^{-1} - 10^3 \text{ s}^{-1}$). Lu [8] tested flexible particles concrete and rigid particles concrete with six different volume content. His research pointed out that the flexible particles concrete with volume content of 20% has the most excellent energy dissipation. Hassan [9] investigated ultra-high performance concrete by SHPB tests. His research focused on constant strain rate and stress equilibrium under different pulse shaper conditions. Yao [10] investigated the influence of thermally induced damage on the dynamic uniaxial compressive strength (UCS) of

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mortars. His research presented an empirical model for dynamic UCS considering thermal effect. Su [11] performed static and SHPB test for steel fiber reinforced concrete materials. His research pointed out that steel fiber additions have prominent influence on the dynamic compressive strength. Bagher [12] experimentally and numerically studied the selection of proper shapers for concrete specimens in SHPB tests. His research recommended a relatively small diameter and thick pulse shaper as a proper pulse shaper for testing the concrete specimens. Qiao [13] experimentally investigated the dynamic behavior of concrete under several low temperatures. His research established the relationship between dynamic compressive strength and temperature for concrete materials. Yang [14] experimentally investigated the behavior of aramid fiber reinforced polymer confined concrete subjected to high strain rate compression. His research focused on lateral confinement effect. Xie [15] experimentally investigated the dynamical properties of cement and asphalt mortar (CA mortar) on SHPB equipment. In his research, a constitutive model of CA mortar was established and verified by experimental results. Hao [16] experimentally investigated spiral steel fiber reinforced concrete (SFRC) on SHPB equipment. His research focused on the relationship between different volume fractions of fibers and several material dynamic properties, i.e. strength, Young's modulus, stress-strain relation and energy absorption. In addition, his research proposed an empirical DIF (dynamic increase factor) relation for spiral SFRC. Chen [17] performed SHPB experiments to investigate dynamic material properties for paste, mortar and concrete. His research presented a compressive constitutive model with strain rate and damage effects. Wu [18] performed SHPB experiments to investigate dynamic material properties for copper slag reinforced concrete. His research also used Scanning Electron Microscope for effect of microstructure, it concluded that increasing content of copper slag could result in deterioration of concrete quality. Zhu [19] focused on the stress uniformity for concrete-like specimens (cement mortar) during SHPB experiments. His research recommended an optimum rise-time ratio for reaching stress uniformity in specimen. Lu, Xu and Bischoff [20–22] analyzed the effects of interfacial friction, elastic wave dispersion, Poisson ratio and length/diameter ratio on the peak stress, axial strain at peak stress, volumetric strain, energy absorption capacity and elastic modulus through the SHPB tests of concrete materials. DonzE [23] numerically studied the compressive behaviors of concrete materials at high strain rates by a 3D discrete-element method, his research concluded that the material strength can be enhanced by the lateral inertial effect. Li [24] numerically studied the concrete-like materials in the SHPB tests by using the finite element method and the Drucker–Prager model, his research claimed that the lateral confinement makes a large contribution to the enhancement of dynamic strength for the concrete-like materials. Zhang and Li [1,25] experimentally and numerically studied the enhancement of dynamic strength by the comparison of solid specimens and tubular specimens for the concrete-like materials, their investigations claimed that the lateral confinement in the SHPB tests is responsible for the increase of dynamic compressive strength. Many other researches [20,21,26–32] indicated that the lateral confinement is mostly induced by the interfacial friction. However, the interfacial effect is not only determined by interfacial friction, it is also determined by the interfacial geometry and the non-parallelism of specimens. Thus, the interfacial effect should be investigated as three types of parameters, i.e., interfacial friction coefficient, specimen diameter and non-parallelism of specimens.

On the other hand, it should be significant that the uncertainty of interfacial parameters can be analyzed considering the errors of machining precision and manual operation in the SHPB tests. The parameter uncertainty in the SHPB tests was analyzed by few investigators. Prabhu [33] provided a method to analyze the

systematic and random uncertainty in the SHPB tests for the soft material of porcine brain. In the literatures [34–39], the size effect of specimen diameter was discussed, but the effect of errors of specimen diameter on the SHPB test results is still ambiguous for the concrete materials. Moreover, the non-parallelism of specimens in the SHPB tests was also barely analyzed. Tao [40] discussed the relationship between the non-parallelism in the SHPB equipment and the waveforms recorded by strain gages, it figured out that the non-parallelism less than 0.33% makes test error less than 5% for metal material. Combining with finite element analysis and interval mathematics, Qiu [41] presented a non-probabilistic interval analysis method to predict the structural dynamic response from uncertainty parameters, the non-probabilistic interval analysis method was validated by comparing with the probabilistic approach in numerical examples. In the SHPB tests, it is reasonable to regard the uncertainty coefficients of interfacial effect as the interval parameters.

Therefore, the efforts of this paper are focused on investigation of the interfacial effect in the SHPB tests with considering the influence of interfacial friction coefficient, specimen diameter and non-parallelism. For this purpose, the interfacial effect is analyzed firstly in Section 2. In Section 3, the specimens of cement mortars with different strengths are tested with SHPB equipment at different strain rates, the uncertainty interfacial parameters are regarded as the interval parameters based on experimental measurements in this paper. In Section 4, a numerical model is established in ABAQUS software. The parameter sensitivity analysis is achieved in Section 5. In Section 6, the uncertainty propagation analysis of interfacial parameter is conducted and the numerical results are compared with experimental results. Finally, some conclusions are drawn. This paper provides a further insight into the interfacial effect of SHPB tests.

2. Interfacial effect in SHPB tests

In the SHPB tests, as shown in Fig. 1, the specimen is sandwiched between the incident bar and the transmitted bar. Since the striker bar impacts the incident bar with velocity V_0 , an incident stress pulse $\sigma_i(t)$ is generated and propagates into the incident bar. When the incident stress pulse travels to the bar/specimen interface, due to the mechanical impedance mismatch between the bars and the specimen, a reflected pulse $\sigma_r(t)$ appears in the incident bar and a transmitted pulse $\sigma_t(t)$ appears in the transmitted bar. Strain gauges on the incident bar and the transmitted bar will record these three stress pulses.

The propagation speed of elastic stress pulse C_b , the incident stress pulse $\sigma_i(t)$ and the duration Δt of the created incident stress pulse can be defined as follows:

$$C_b = \sqrt{\frac{E_b}{\rho}} \quad (1)$$

$$\sigma_i(t) = \frac{1}{2} \rho C_b V_0 \quad (2)$$

$$\Delta t = \frac{2l}{C_b} \quad (3)$$

where E_b and ρ are the Young's modulus and the mass density of bars, respectively. V_0 and l are the velocity and the length of striker bar, respectively. According to the stress or strain uniformity assumption [42], the strain signal of incident wave $\varepsilon_i(t)$, reflected wave $\varepsilon_r(t)$ and transmitted wave $\varepsilon_t(t)$ satisfy the following equation:

$$\varepsilon_i(t) + \varepsilon_r(t) = \varepsilon_t(t) \quad (4)$$

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