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Experimental and numerical study on choosing proper pulse shapers for testing concrete specimens by split Hopkinson pressure bar apparatus

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HIGHLIGHTS

- Using a proper pulse shaper is prerequisite for valid SHPB tests of concrete specimens.
- Numerical results validated by SHPB tests are used to provide guidelines to choose pulse shapers.
- Cross sectional area and thickness of pulse shaper is proportional to the striker bar velocity.
- Relatively small diameter and thick pulse shaper is recommended as proper one for concrete specimens.

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ABSTRACT

Dynamic behavior of concrete specimens is investigated experimentally and numerically by split Hopkinson pressure bar (SHPB) tests. In order to accurately determine dynamic properties of brittle materials such as concrete, specimens should be subjected to particular pulse loading that can be generated by using pulse shapers. Choosing proper pulse shaper dimensions helps to obtain dynamic stress equilibrium, achieve constant strain rate and minimize pulse oscillation in the concrete specimens. To this end, SHPB tests are performed for concrete specimens and effective parameters on shaping pulses such as striker bar velocity, diameter and thickness of the pulse shaper are studied experimentally and numerically. In this regard, dynamic compressive strength, modulus of elasticity, toughness and damage behavior of the concrete specimens are calculated incorrectly if improper pulse shaper is used. Numerical results validated by the experimental data are used to provide general guidelines to properly choose dimensions of the pulse shapers for the concrete specimens in the SHPB test. Results show that use of a relatively small diameter and thick pulse shaper is suggested as a proper one for testing concrete specimens. Based on the findings of this research, if a proper pulse shaper is available for testing the concrete specimen in a specified strain rate, for other strain rates the cross sectional area as well as thickness of the pulse shaper should be changed proportional to the striker bar velocity that is related to the strain rate in the specimen.

1. Introduction

Split Hopkinson pressure bar (SHPB) or Kolsky apparatus is an important experimental device for characterizing dynamic behavior of materials at high strain rates [1]. However, experimental research works [2,3] have shown that dynamic stress equilibrium and constant strain rate condition during SHPB tests are prerequisites for valid results.

In conventional SHPB test, the incident pulse has a rectangular shape with high frequency oscillations [4,5]. The high-frequency oscillations cause severe fluctuations in the dynamic stress-strain (σ-ε) curve [6,7]. In brittle specimens such as concrete, duration of effective deformation is very short under impact loading, so it is a major problem for maintaining constant strain rate and dynamic stress equilibrium. Also, the sharp rising edge of the incident pulse in the conventional SHPB test initiates undesired damage in the concrete specimens. Thus, the rising time and stress intensity of the incident pulse could be adjusted to maintain constant strain rate and dynamic stress equilibrium in a SHPB test [8]. Concrete has usually failure strain less than 1% when the

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loading is applied too fast like in SHPB test. It is hard to obtain dynamic stress equilibrium in the concrete specimen because the specimen may fail immediately in a non-uniform manner (i.e. the front of the specimen may be shattered while the back remains intact). In order to accurately determine dynamic behavior of materials by SHPB test, several pulse shaping techniques have been utilized. Using a soft disc known as pulse shaper between the striker and incident bars is a common pulse shaping technique in SHPB apparatus. The striker bar impacts on the pulse shaper before the incident bar. It generates a non-dispersive ramp pulse that controls the shape of the loading pulse in the incident bar [9–11]. Pulse shaper absorbs high-frequency oscillations of the incident pulse and changes the rectangular-shaped incident pulse to a trapezoidal or half sinusoidal shape with a longer rise time. Slowly rising incident pulse is a preferred loading pulse to minimize effects of dispersion and inertia, which facilitates dynamic stress equilibrium in the specimen [12–14]. Other pulse shaping methods have been investigated in previous studies. Christensen et al. [15] have used conical striker bars at impact end instead of the striker to achieve ramp pulse for rock specimens. Li et al. [16,17] used a tapered or truncated cone shape striker bar on both ends to generate a half sinusoidal incident pulse shape for testing rock specimens. Ellwood et al. [18], Parry et al. [19] and Forrestal et al. [20] introduced modified SHPB apparatus which used dummy specimen and preloading bar between the striker and input bars. In order to calculate the impact properties of aramid fiber reinforced polymer confined concrete, Yang et al. [21] used H62 brass pulse shaper with thickness of 1 mm to reshape the waveform of the incident pulse. They suggested that for valid SHPB tests, pulse shapers should be used to improve the stress equilibrium in the tests. Deng et al. [22] applied a copper disk with diameter of 12 mm and thickness of 1 mm as the pulse shaper to prolong the rise time of the incident stress pulse for studying compressive behavior of cellular concretes subjected to high strain rate loadings. Performing SHPB tests, Naghdabadi et al. [23] recommended proper pulse shapers for work hardening materials such as C10200 copper and GGG60 cast iron. They suggested that thickness and cross sectional area of the pulse shaper should be changed proportional to the striker bar velocity. It has been shown that a broad range of incident pulses can be obtained by changing dimensions of pulse shaper and striking velocity. The proper material for pulse shaping depends on the mechanical characteristics of the specimen as well as velocity of the striker bar. Considering the literature on SHPB test of cement based materials such as concrete, the pulse shaper may be made of copper [3,11,22,24,25], rubber [25], stainless steel [11] and brass [21,26–29].

In previous studies [21,22,24,25], dimensions of pulse shaper for testing different concrete specimens have been determined via try and error by experimental trials solely. There is no established procedure for pulse shaper design used in testing concrete specimens. Also, in different strain rates or striker bar velocities, an identical dimension of the pulse shaper has usually been used for concrete specimens in the SHPB test. To obtain experimental results for different dimensions of pulse shaper, large number of SHPB tests should be performed. However, high costs of experiment, limitations of the measurement methods and parameter variation make it difficult to propose a procedure to choose proper pulse shapers for concrete specimen in the SHPB tests.

In this paper, employing a copper pulse shaper, effective pulse shaping parameters i.e., pulse shaper diameter (d_p) and thickness (t_p) are investigated through using the SHPB experiments and simulations by finite element software LS-DYNA. Also, dynamic behavior of concrete specimens is determined at different strain rates with and without pulse shaper. Guidelines to choose proper dimensions of pulse shaper for the concrete specimens are explained. In addition, effects of pulse shaper parameters on dynamic stress equilibrium, constant strain rate condition and pulse oscillation elimination are studied. Relations between the striker bar velocity and pulse shaper dimension are obtained. Finally, effects of different striker bar lengths on incident pulse are studied. To this end, the paper is organized as follows; in Section 2, we briefly review pulse shaped SHPB apparatus; concrete specimens preparation, also static and dynamic tests of the concrete specimens. In Section 3, simulations of SHPB test are explained. In Section 4, experimental and numerical methodologies for choosing proper pulse shapers to test concrete specimens are discussed. Finally in Section 5 conclusions are drawn.

2. Experimental details

2.1. Pulse shaped SHPB apparatus

To determine the dynamic compressive strength of concrete, a SHPB test is required. SHPB test apparatus consists of a gas gun as launching system, a striker bar, an incident bar, a transmission bar and a data acquisition system (Fig. 1) [23].

The gas gun is used to launch the striker bar impacting on the incident bar. Generating a half sinusoidal shaped pulse; the concrete specimen is sandwiched between the incident and transmission bars. According to wave impedance mismatch between the specimen and bars, part of the compression wave is reflected back in the incident bar while the rest transmits in the transmission bar. Identical strain gauges are attached on the mid-point of the incident and transmission bars to measure incident (ε_I), reflected (ε_R) and transmitted (ε_T) strain pulses (Fig. 2) [12,23]. Using one-dimensional (1-D) wave theory, strain rate ($\dot{\varepsilon}_s$), strain (ε_s) and stress (σ_s) in the specimen can be calculated [30]:

$$\sigma_s(t) = \frac{A_b E_b}{A_s} \varepsilon_T(t) \tag{1}$$

$$\dot{\varepsilon}_s(t) = \frac{C_b}{h_s} \{\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)\} \tag{2}$$

$$\varepsilon_s(t) = \frac{-2C_b}{h_s} \int_0^t \varepsilon_R(t)dt \tag{3}$$

where t and A_b are time and cross sectional area of the incident and transmission bars A_s and h_s are considered as cross sectional area and thickness of the specimen. Moreover, E_b and C_b denote Young modulus and wave velocity in the pressure bars, respectively. Table 1 shows specifications of the SHPB apparatus utilized for testing concrete specimens in the present work. The incident, transmission and striker bars have the same diameter of 63 mm and lengths of 2.5, 1.5 and 0.3 m, respectively.

Brittle specimens should be subjected to particular stress pulse loadings such that deform uniformly under a dynamic stress equilibrium state at a constant strain rate. In most cases, a trapezoidal incident pulse does not facilitate achievement of these experimental conditions. Therefore, in order to produce a ramp incident pulse, a pulse shaping technique should be used in SHPB [31]. For concrete specimens, pulse shaping improves the incident pulse profile. The pulse shaper is attached with grease between the striker and incident bars as shown in Fig. 3.

A half sinusoidal incident pulse is suitable for testing brittle materials with linear stress-strain behavior [18]. In this study, a C10200 copper disc with diameter of 12 or 24 mm and thickness of 1 or 2 mm is used to reshape the incident pulse. Chemical composition in weight percentage and quasi-static mechanical properties of the C10200 copper are summarized in Table 2.