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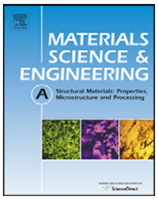

Experimental and numerical investigation of pulse-shaped split Hopkinson pressure bar test

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ABSTRACT

Employing a proper pulse shaper in the conventional split Hopkinson pressure bar (SHPB) test helps to achieve dynamic equilibrium condition and to fulfill a constant strain rate condition in the test specimen. To this end, the parameters affecting the incident pulse shape, i.e., pulse shaper thickness, pulse shaper diameter, striker bar length and striker bar velocity are experimentally studied. Moreover, simulation results, validated by experimental data together with wave propagation analysis, are exploited to provide general guidelines to properly design a pulse shaper. It is recommended to use a relatively large diameter pulse shaper for testing work-hardening materials. Also, for different test conditions, e.g., striker bar velocity, it is recommended to scale the pulse shaper thickness and cross-sectional area proportional to the striker bar velocity. Employing these guidelines considerably reduce the try and error process for selecting proper pulse shaper. Finally, to show the effectiveness of the proposed guidelines in practice, SHPB experiments on copper and cast iron specimens are performed. The results show that the variation of strain rate in the specimens is reduced significantly when a proper pulse shaper is employed.

1. Introduction

Split Hopkinson pressure bar (SHPB) is an important apparatus used for characterizing the mechanical behavior of materials at high strain rates in the range of 10^2–10^4 s^{-1} [1]. In order to determine material behavior at a specific strain rate, it is necessary to achieve the constant strain rate condition during the test [2,3]. The incident pulse generated by the direct impact of the striker and incident bars has a rectangular shape. While this shape is proper for testing perfectly plastic materials, it is improper for testing materials with considerable work hardening or brittle materials with linear stress–strain behavior [4].

To adjust the incident pulse shape, several methods have so far been addressed in the literature, e.g., shaping the striker bar, employing a preloading bar and using a pulse shaper. Christensen et al. [5] have used striker bars with truncated cone on the impact end to achieve ramp pulses desirable for rock materials. Li et al. [6,7] have designed a striker bar with truncated cone on both ends to produce a half sine incident pulse for testing rock materials which eliminates oscillations and helps to achieve constant strain rate in the specimen. Utilizing a preloading bar with a strength lower than that of the Hopkinson bars, Parry et al. [8] have introduced a modification to the conventional SHPB test to eliminate the oscillations of the incident pulse.

In addition to the aforementioned works on shaping the striker bar and using a preloading bar, pulse shapers have widely been used to shape the incident pulse in the SHPB test of various materials. Franz et al. [2] and Follansbee [3] have discussed the necessities and advantages of shaping the incident pulse, stating that it minimizes the dispersion effects and allows to achieve dynamic stress equilibrium in the sample. They have placed a pulse shaper between the striker and incident bars with a diameter slightly larger than that of the bars and a thickness of 0.1–2.0 mm. Moreover, Ellwood et al. [4] have proposed a modified SHPB which uses a pulse shaper (called dummy specimen) and a preloading bar. The dimensions and material of the dummy specimen and the preloading bar were the same as the real specimen and incident bar, respectively. Utilizing front and rear pulse shapers, Song and Chen [9] have developed a pulse shaping technique for both loading and unloading paths of SHPB experiments of nickel–titanium shape memory alloys. To achieve dynamic stress equilibrium and nearly constant strain rate in the specimen in both elastic and plastic regions, Chen et al. [10] have designed a copper/mild-steel pulse shaper consisting of two disks. Vecchio and Jiang [11] have selected a high-strength, high work-hardening rate material to fabricate pulse shaper and tested several specimens within a wide range of strength and work-hardening

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behavior. They determined the proper dimensions of the pulse shaper for different test conditions via experimental trials. Li and Xu [12] discussed about pulse shaper diameter in SHPB test of a special concrete and stated that a certain diameter can only offer one optimum nearly constant strain rate. Moreover, in several studies, e.g., [13–17], pulse shapers with different materials and dimensions have been employed in SHPB experiment for determining dynamic behavior of various materials.

Besides experimental methods to shape the incident pulse, there has been much interest to study the plastic deformation and wave propagation in the pulse shaper. Modeling the plastic deformation of the pulse shaper has been considered by Nemat-Nasser et al. [18]. They used a power-law relation in a one-dimensional wave propagation analysis to predict the incident pulse for OFHC copper pulse shapers. Frew et al. [19,20] have extended the model proposed by Nemat-Nasser et al. [18] for a two-material pulse shaper and also to accommodate large strains in C11000 copper pulse shapers. They have also shown that a broad range of incident pulses can be obtained when the pulse shaper geometry and striking velocity are changed. Moreover, using simulations in LS-DYNA, Ramirez and Rubio-Gonzalez [21] have studied the effects of pulse shaper material and dimensions on the incident pulse. Although several studies on modeling the pulse shaper deformation and predicting the incident pulse have been performed, the proper pulse shaper dimensions for testing different materials are usually selected via try and error [1,11].

In this study, we use a thin copper disc as a pulse shaper and study parameters affecting the incident pulse shape through both performing experiments and simulations in LS-DYNA software. Moreover, we draw general guidelines to determine the proper pulse shaper dimensions for testing different materials. To this end, the paper is organized as follows. In Section 2, we briefly review both conventional and pulse-shaped SHPB tests. In Section 3, we explain experimental and numerical methodologies to be used in this study. In Section 4, we study different parameters, including pulse shaper thickness, pulse shaper diameter, striker bar velocity and its length, and propose general guidelines. In Section 5, we use the proposed guidelines and show the effects of employing a pulse shaper on constant strain rate condition, dynamic equilibrium, and oscillation elimination. In the SHPB tests, we use specimens made of two different materials, i.e., C10200 copper and GGG-60 cast iron. We finally draw conclusions in Section 6.

2. Split Hopkinson pressure bar test

2.1. Conventional SHPB test

A conventional SHPB test apparatus consists of a gas gun, a striker bar, an incident bar, a transmission bar and a measurement system. The gas gun launches the striker bar to impact the incident bar which sandwiches the specimen between the incident and transmitted bars. Due to the impedance mismatch between the specimen and pressure bars, a tensile pulse is reflected into the incident bar and a compressive pulse is transmitted into the transmission bar. The strain gages measure the incident (ε_I), reflected (ε_R) and transmitted (ε_T) strain pulses shown in Fig. 1. These strains are then used to compute the strain rate ($\dot{\varepsilon}_s$), strain (ε_s) and stress (σ_s) in the specimen as follows [22]:

$$\dot{\varepsilon}_s(t) = \frac{c_b}{h_s}(\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)) \tag{1}$$

$$\varepsilon_s(t) = \frac{-2c_b}{h_s}\int_o^t \varepsilon_R(t)dt \tag{2}$$

$$\sigma_s(t) = \frac{A_b E_b}{A_s}\varepsilon_T(t) \tag{3}$$

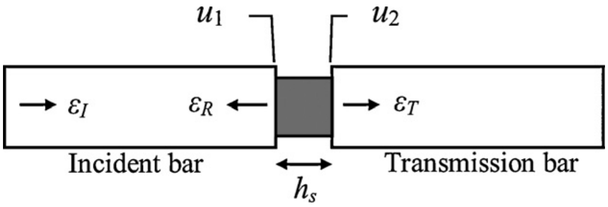

Fig. 1. Schematic of the wave propagation in Hopkinson pressure bars.

where c_b is the wave speed in the bars (assumed to have the same material), h_s and A_s are the length and cross-sectional area of the specimen, while A_b and E_b are the cross-sectional area and Young's modulus of the pressure bars.

Assuming dynamic stress equilibrium in the specimen ($\varepsilon_I + \varepsilon_R = \varepsilon_T$) and substituting (3) into (1), we obtain [11]:

$$E_b A_b \varepsilon_I(t) - A_s \sigma_s(t) = \frac{h_s E_b A_b}{2c_b}\dot{\varepsilon}_s(t) \tag{4}$$

Eq. (4) shows that in order to achieve a constant strain rate in the specimen, the incident pulse should be proportional to the stress in the specimen. In other words, the incident pulse must mimic the work-hardening behavior of the specimen. However, in the conventional SHPB test, the incident pulse is nearly rectangular, i.e., it is proper for testing perfectly plastic specimens.

2.2. Pulse-shaped SHPB test

Instead of direct impact of striker and incident bars in the conventional SHPB test, a pulse shaper is usually placed between the striker and incident bars. In the pulse-shaped SHPB test, it is possible to shape the incident pulse to mimic the specimen work-hardening behavior. The dimensions and material of the pulse shaper can be properly determined to achieve the following conditions:

1. minimum dispersion effects
2. dynamic stress equilibrium
3. constant strain rate

The pulse shaper is usually a thin disk made of soft materials such as copper, aluminum and mild steel [1]. Fig. 2 shows a schematic of the pulse-shaped SHPB test. In general, use of a pulse shaper changes the incident pulse from a rectangular to a trapezoidal shape. In other words, the rise time and the duration of the incident pulse increase when a pulse shaper is employed.

3. Methodology of the experimental and numerical studies

3.1. Experiment methodology

To study the effects of geometric parameters on the incident pulse shape, it is required to prepare pulse shapers with different thicknesses and diameters from a soft material. According to the previous studies, the dimensions and material of the pulse shaper strongly depend on the strain rate and stress–strain curve of the material to be tested [3,11]. Since metallic specimens are investigated in this study, we choose copper pulse shapers which have widely been used in the literature [18–21]. Similar to Follansbee [3], Frew et al. [19,20] and Vecchio and Jiang [11], we also use pulse shapers with 0.5–2.0 mm thicknesses and diameters smaller than the pressure bar diameter (12.8 mm). Consequently, pulse shapers are made from C10200 copper with diameters of 5, 8, 10 and 12 mm and thicknesses of 0.5, 1.0, 1.3, and 2.0 mm.

Table 1 shows the specifications of the striker, incident and transmission bars of the apparatus utilized in the present work.