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Influence of interfacial friction and specimen configuration in Split Hopkinson Pressure Bar system

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ABSTRACT

Influences of interface friction and specimen configuration on the material dynamic response using split Hopkinson pressure bar (SHPB) experiment are evaluated using nonlinear finite element (FE) analysis. The effect of various friction conditions between specimen and the transmitted/incident bars in SHPB system is investigated for different specimen geometries. Cylindrical and cuboid specimens with one- and four-layered configurations are adopted and the stress states along the specimen are analyzed. Results indicate that the transmitted signal decreases and the reflected signal increases with friction coefficient increasing. Interface friction brings great variation in stress triaxiality and Lode parameters in the SHPB specimen. Experimental tests are also conducted in this study to verify the conclusions made through FE simulations.

1. Introduction

Split Hopkinson Pressure Bar (SHPB), also known as Kolsky bar, is a widely-applied test to investigate uniaxial dynamic compression behaviour of material at a range of high strain rates between $10^2\ s^{-1}$ and $10^4\ s^{-1}$ [1–6]. In this experiment, a cylindrical specimen is sandwiched between two bars and the uniaxial elastic wave is generated throughout the specimen by a striker to establish the compressive stress–strain curve of the material [7]. With advanced measurement technology and machine process upgrading, Hopkinson bar facility was modified recently to test non-metal, soft material and cellular structure to evaluate their dynamic properties [8–15]. The validity of such modified SHPB system, however, is difficult to be evaluated using traditional stress wave propagation theory. Numerical simulation is, therefore, utilized as a comparatively effective approach to achieve quantitative evaluation of unconventional SHPB system in advance. Several influential factors, such as pulse shaping, uniaxial stress assumption, stress distribution uniformity, wave dispersion effect and interface friction, which affect the overall SHPB results, have been studied numerically [16–20].

Interfacial friction is a significant factor in determining the stress state of the specimen in a SHPB testing process. It brings a negative effect on the most important assumption of uniaxial stress state, and therefore, lubricant is usually used at the interfaces to avoid multi-axial stress states [21–23]. Several studies have been conducted recently to investigate the effect of interfacial friction between specimens and bars in the SHPB technique. Experimental and theoretical results showed that, interfacial friction effects are influenced by material Poisson's ratio, friction coefficient, specimen's length-to-diameter ratio and the axial strains [24–44]. For example, Davies and Hunter [24] experimentally investigated the mechanical behavior of some metals and polymers, and discussed the relationship of friction effect and specimen dimension in compression experiments. In order to minimize the effect of the opposite responses of the longitudinal and radial inertias, an optimized aspect ratio between the length and diameter of a cylindrical specimen was also suggested. This aspected ratio was found to be related to Poisson's ratio of the material, and thus, a specimen's aspect ratio of 0.5 was a preferable choice for a metal specimen. Meng and Li [25] studied numerically the friction and specimen size effects to measure the stress uniformity in axial and radial directions of the specimen in a SHPB test. It was shown that the accuracy of a SHPB test can be correlated to these two stress uniformity coefficients. Iwamoto and Yokoyama [26] conducted computational simulations to check the validity of the modifications for ductile pure aluminum specimens. Both rate-independent and rate-dependent models were adopted for the tested material. Simulations were performed by varying two different control parameters: a friction coefficient between the specimen and the pressure bars and a slenderness ratio of the specimen. Brisco and Nosker [27] described the influence of interface friction on the yield behaviour of a high

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density polyethylene when it is compressively deformed up to 25% strain at high strain rates ($\sim 10^3\ \mathrm{s}^{-1}$) in SHPB experiment. Hall et al. [28] tested the mechanical property of an aluminum alloy at a constant strain rate with no-lubricant, solid, and liquid lubricants. It was found that liquid lubricants were more effective in reducing the friction effect resulting in lower flow stress values, increasing the final strain values and consequently increasing the accuracy of the test results. Trautmann et al. [29] investigated the dynamic friction behaviour of polycarbonate at ambient 26 °C and low temperatures -60 °C using a Split Hopkinson Pressure Bar for specimens of varying thicknesses. The different influence between two types of lubricants, polytetrafluoroethylene and molybdenum disulfide was also discussed.

In relation to friction influence on the dynamic behaviour of concrete-like heterogeneous material, Hao et al. [30] developed a mesoscale concrete model with consideration of different components in a concrete specimen to study the influence of the confinement due to end friction between specimen and Hopkinson bars during impact tests. The results confirmed that the end friction confinement does affect the testing results, and its influence depends on the specimen length-to-diameter ratio. Huang et al. [31] pointed out that more fragmentation debris is produced during dynamic breakage of single grains, which promotes particle rearrangement and the corresponding frictional dissipation significantly. Frictional dissipation under dynamic loading was found to be higher than that under quasi-static loading corresponding to the same breakage extent.

Several studies have recently been conducted focusing on the assessment and correction of the unconventional SHPB tests [45–53]. For example, Lu and Zhang [45] pointed out that the difference between the constant and kinetic interface friction models may cause different results, and suggested that the assessment and correction procedure for SHPB test should be performed based on a kinetic friction model. Experimental assessment of friction effects on the Split Hopkinson Pressure Bar was also implemented by Hartley et al. [46] using mild steel, copper and aluminum ring specimens with molybdenum disulfide grease lubricants. Alves et al. [47] showed that a ring specimen with a large inner diameter and a small radial thickness offers some advantages, compared with the traditional disk sample, in limiting the friction influence. In particular, it can improve the reliability of the test results for ductile materials in the presence of friction.

The importance of involved measured errors increases dramatically. Therefore, friction effects should be quantified, particularly for materials having strain rate sensitivities and different configurations. The present work aims at investigating the influences of interfacial friction between specimen (with different configurations) and Hopkinson bars on the overall material behavior. For this reason, finite element (FE) simulations of SHPB tests are conducted to study the variation in the material dynamic response for a range of friction coefficients between 0 and 0.50. Four different specimen geometries including cylinder, cylinder sheet (laminated), cuboid and cuboid sheet (laminated) are considered to analyze configuration sensitivity in Hopkinson bar compression process. Finally, experimental tests on cylinder and cylinder sheet specimens are conducted to verify the numerical conclusions.

2. Specimen deformation characteristic in SHPB with various interface contact conditions

2.1. Principle of Split Hopkinson Pressure Bar

Conventional SHPB setup is made up of a striker, an incident bar and a transmitted bar as shown in Fig. 1. The bars are usually cylindrical, having the same diameter and material. During the test, the specimen is sandwiched between the incident and transmitted bars. When the striker hits the end of the incident bar along the axial direction with an initial velocity V_0, a trapezoidal incident stress pulse σ_i is generated and propagates in the incident bar. Once the incident pulse reaches the interface between the specimen and the bars, a reflected pulse σ_r appears in the incident bar and a transmitted one σ_t in the transmitted bar. Strain gauges are mounted on the incident and transmitted bars to record these three basic stress pulses.

The length of the striker is usually short compared to the total length of the incident bar and transmitted bar. For bars with uniform cross-section under impact, the elastic stress wave propagation speed C, incident pulse amplitude σ_i and the duration of the created incident stress pulse Δt can be defined as follows:

$$C=\sqrt{\frac{E}{\rho}} \tag{1}$$

$$\sigma_i=\frac{1}{2}\rho C V_0 \tag{2}$$

$$\Delta t=\frac{2L}{C} \tag{3}$$

where E is Young's modulus of the bar, ρ is the mass density of the bar, V_0 is the velocity of the striker and L is the length of the striker. Based on the assumptions of uniaxial wave propagation and uniform stress distribution in the specimen, stress σ_s, strain ε_s, and strain rate $\dot{\varepsilon}_s$ along the specimen can be calculated as follows:

$$\left.\begin{array}{l}\sigma_s=\frac{AE}{2A_s}(\varepsilon_i+\varepsilon_r+\varepsilon_t)\\ \varepsilon_s=\frac{C}{l}\int(\varepsilon_i-\varepsilon_r-\varepsilon_t)dt\\ \dot{\varepsilon}_s=\frac{C}{l}(\varepsilon_i-\varepsilon_r-\varepsilon_t)\end{array}\right\}\rightarrow\varepsilon_t=\varepsilon_i+\varepsilon_r\rightarrow\left\{\begin{array}{l}\sigma_s=\frac{A}{A_s}E\varepsilon_t\\ \varepsilon_s=-\frac{2C}{l}\int\varepsilon_r dt\\ \dot{\varepsilon}_s=-\frac{2C\varepsilon_r}{l}\end{array}\right. \tag{4}$$

where A and A_s denote the cross-sectional areas of Hopkinson bars and the specimen, respectively, l is the initial length of the specimen, ε_i, ε_r and ε_t are the strain values of incident, reflected and transmitted signals in the bars, respectively. The approach given by the set of definitions in the left hand side of Eq. (4) is generally referred to as the three-wave method in SHPB data processing. With the hypothesis of uniaxial waves and uniform stresses, the sum of incident and reflected pulses equals to the transmitted pulse (i.e., $\varepsilon_i+\varepsilon_r=\varepsilon_t$) and thus, the

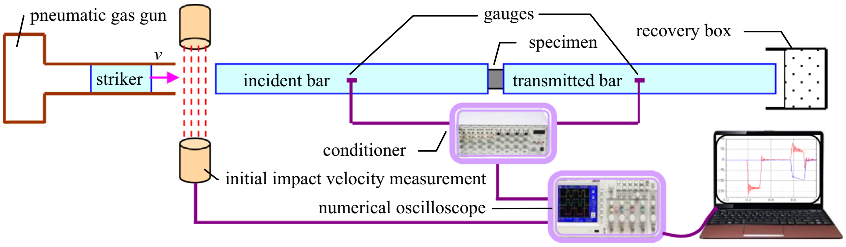

Fig. 1. Split Hopkinson Pressure Bar set-up description.