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Review

Dynamic rock tests using split Hopkinson (Kolsky) bar system – A review

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A R T I C L E I N F O

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A B S T R A C T

Dynamic properties of rocks are important in a variety of rock mechanics and rock engineering problems. Due to the transient nature of the loading, dynamic tests of rock materials are very different from and much more challenging than their static counterparts. Dynamic tests are usually conducted using the split Hopkinson bar or Kolsky bar systems, which include both split Hopkinson pressure bar (SHPB) and split Hopkinson tension bar (SHTB) systems. Significant progress has been made on the quantification of various rock dynamic properties, owing to the advances in the experimental techniques of SHPB system. This review aims to fully describe and critically assess the detailed procedures and principles of techniques for dynamic rock tests using split Hopkinson bars. The history and principles of SHPB are outlined, followed by the key loading techniques that are useful for dynamic rock tests with SHPB (i.e. pulse shaping, momentum-trap and multi-axial loading techniques). Various measurement techniques for rock tests in SHPB (i.e. X-ray micro computed tomography (CT), laser gap gauge (LGG), digital image correlation (DIC), Moiré method, caustics method, photoelastic coating method, dynamic infrared thermography) are then discussed. As the main objective of the review, various dynamic measurement techniques for rocks using SHPB are described, including dynamic rock strength measurements (i.e. dynamic compression, tension, bending and shear tests), dynamic fracture measurements (i.e. dynamic imitation and propagation fracture toughness, dynamic fracture energy and fracture velocity), and dynamic techniques for studying the influences of temperature and pore water.

1. Introduction

The accurate determination of rock dynamic properties has always been a very important issue for a variety of rock engineering and geophysical applications, including rock quarrying, rock drilling, rockbursts, blasts, earthquakes, and projectile penetrations. In these applications, rock materials are subjected to dynamic loading over a wide range of loading rates. Therefore, accurate determination of dynamic strength and fracture properties of rocks over a wide range of loading rates is crucial. However, in sharp contrast to many static rock testing methods suggested by the International Society for Rock Mechanics (ISRM), only three dynamic testing methods have recently been suggested by the ISRM Commission on Rock Dynamics (Zhou et al., 2012), including dynamic compression, dynamic Brazil test, and dynamic notched semi-circular bend (NSCB) test using split Hopkinson pressure bar (SHPB), while other methods are good candidates for future ISRM suggested methods.

SHPB system is an ideal and reliable high strain rate loading technique to measure dynamic properties of rocks under high strain rates (10^2–10^3 s^{-1}). As a widely used device to quantify the dynamic compressive response of various metallic materials at high loading or strain rates, SHPB was invented by Kolsky in 1949 (Kolsky, 1949, 1953). Shortly after, researchers started to use SHPB to test brittle materials such as concretes (Ross et al., 1989, 1995), ceramics (Chen and Ravichandran, 1996, 2000), and rocks (Christensen et al., 1972; Dai et al., 2010a). However, some major limitations of using SHPB for brittle materials were not fully explored until two decades ago (Subhash et al., 2000).

Several comprehensive reviews have been conducted concerning dynamic behaviors of brittle materials, such as mortar, ceramic, concrete and rocks (Bischoff and Perry, 1991; Malvar and Ross, 1998; Zhao et al., 1999; Toutlemonde and Gary, 2009; Walley, 2010; Zhao, 2011) and dynamic experimental techniques (ASM, 2000; Field et al., 2004; Ramesh, 2008). There are also reviews on rock dynamics and applications (Barla and Zhao, 2010; Zhao et al., 2012) and dynamic experimental techniques and results (Xia, 2012; Zhao et al., 2012; Zhang and Zhao, 2014). The systematic discussion of dynamic experimental techniques for rocks using SHPB system is

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not yet available. Therefore the objective of this work is to provide detailed procedures and principles of techniques for dynamic rock tests using SHPB.

This review is organized as follows. After the Introduction, Section 2 briefly describes the history and principles of SHPB system. Section 3 presents new loading techniques for dynamic rock tests and Section 4 discusses the advanced measurement techniques deployed in SHPB for testing rock materials. In Section 5, the dynamic strength measurements for rocks using SHPB system are first critically assessed, including dynamic compression, tension, bending and shear tests. Dynamic fracture tests are then presented, followed by dynamic techniques concerning the influences of temperature and water saturation level. Section 6 summarizes the entire paper.

2. History and principles of SHPB system

2.1. History of SHPB system

The name of SHPB was derived from John Hopkinson (1849–1898) and his son Bertram Hopkinson (1874–1918). John Hopkinson investigated the propagation of stress waves in the iron wire in 1872, and his son, Bertram Hopkinson, invented a pressure bar to obtain the pressure-time curve with the dynamic load exerted by detonation (Hopkinson, 1914). However, the measurements were not accurate because of the limitation of the measurement technique. Davies (1948) improved the measurement technique by utilizing an electrical method. Later, Kolsky (1949) developed the split bar system, which included two bars (known as incident bar and transmitted bar) with a specimen in between. That is why SHPB is also called the Kolsky bar. Using his SHPB system, Kolsky obtained the dynamic relationship between stress and strain for several materials with condenser microphones. Shortly after that, Krafft et al. (1954) adopted strain gauge to measure the stress waves and applied a striker bar to produce a repeatable impact stress wave in the incident bar. In order to measure valid dynamic properties of different materials, Lindholm (1964) combined previous modifications and designed an updated version of Kolsky bar system, which became a template of current SHPB system. Thereafter, the SHPB system has been continually improved to obtain more accurate measurements for different materials under high strain rate loading.

In addition to the compression version of Kolsky bar system—SHPB, the tensile version of Kolsky bar system—split Hopkinson tension bar (SHTB) was also developed to obtain the characteristics of materials under dynamic tensile loading. The initial design of dynamic tension apparatus was a hollow tube inside which a single elastic bar and a specimen were attached (Harding et al., 1960). This design was later replaced by placing the entire bar system inside a tube (Hauser, 1966; Harding and Welsh, 1983). Meanwhile, the methods using the compression bar system to achieve tensile experiments were also proposed, such as the top-hat specimen (Lindholm and Yeakley, 1968), and a specimen with a rigid collar (Nicholas, 1981). Moreover, other direct tension loading methods for SHTB were also developed: store elastic energy to stretch a section of incident bar in tension (Staab and Gilat, 1991; Cadoni et al., 2009), an explosive loading device (Albertini and Montagnani, 1974), a ballistic apparatus (Goldsmith et al., 1976), a rotating disk (Kawata et al., 1979; Li et al., 1993), a tubular striker (Ogawa, 1984) to impact the flange attached to the incident bar. The design of a tubular striker in SHTB was followed by many researchers (Ross, 1989; Li et al., 1993; Chen et al., 2002; Nie et al., 2009; Huang et al., 2010a) and became the standard design of modern SHTB system. The detailed SHTB configuration and procedure are discussed in Section 5.2.1.

The details of the Kolsky bar history, recent modification and application have been discussed in ASM handbook (Gray, 2000), in the recent book (Chen and Song, 2010), and in recent reviews (Nemat-Nasser, 2000; Field et al., 2004; Gama et al., 2004; Jiang and Vecchio, 2009; Ramesh, 2008; Zhang and Zhao, 2014). We will discuss the techniques and methods using SHPB for testing rocks in this work.

2.2. Principles of SHPB system

SHPB consists of three bars: a striker bar, an incident bar, and a transmitted bar (Gray and Blumenthal, 2000). The impact of the striker bar on the free end of the incident bar induces a longitudinal compressive wave propagating in both directions. The left-propagating wave is fully released at the free end of the striker bar and forms the trailing edge of the incident compressive pulse ε_i (Fig. 1). Thus, the duration of ε_i depends on the length and longitudinal wave velocity in the striker. Upon reaching the bar–specimen interface, part of the incident wave is reflected as the reflected wave ε_r and the remainder passes through the specimen to the transmitted bar as the transmitted wave ε_t. Strain gauges are used to record the stress wave pulse on both incident bar and transmitted bar. The principles of the SHTB are similar to those of the SHPB, except that the way to generate the loading pulse and the way to grip the specimen are different as will be discussed later.

In most of the tests, the distance between the strain gauges and the sample should be known, which is needed to determine the starting point of incident, reflected and transmitted pluses. Besides, the velocity of the striker bar can be measured by simple optical methods and the strain signals are usually collected using the Wheatstone bridge circuit with amplification.

The diameter of bar is governed by the diameter of rock specimen, which should be at least 10 times the average grain size of the rock (Dai et al., 2010b; Zhou et al., 2012). Based on the one-dimensional (1D) stress wave theory, the dynamic forces (see Fig. 1) on the incident end (P_1) and the transmitted end (P_2) of the specimen are (Kolsky, 1949, 1953):

$$P_1 = AE(\varepsilon_i + \varepsilon_r), \quad P_2 = AE\varepsilon_t \tag{1}$$

where E is the Young's modulus; A is the cross-sectional area; ε_i and ε_r are the incident strain signal and reflected strain signal, respectively.

The velocities at the incident bar end (v_1) and the transmitted bar end (v_2) are:

$$v_1 = c(\varepsilon_i - \varepsilon_r), \quad v_2 = c\varepsilon_t \tag{2}$$

where c is the 1D longitudinal stress wave velocity of the bar.

The displacement of the incident bar end (u_1) and the transmitted bar end (u_2) are thus:

$$u_1 = c\int_0^t (\varepsilon_i - \varepsilon_r)\mathrm{d}t, \quad u_2 = c\int_0^t \varepsilon_t \mathrm{d}t \tag{3}$$

where t is the time.

One of the objectives of an SHPB test is to determine the material dynamic stress–strain curve, from which the mechanical properties can be derived, e.g. dynamic failure strength, dynamic failure strain and dynamic Young's modulus. Thus, several methods have been proposed to determine the dynamic stress–strain curve, i.e. one-wave analysis (Gray, 2000; Mohr et al., 2010), two-wave analysis (Gray, 2000; Gray and Blumenthal, 2000), three-wave analysis (Gray, 2000; Mohr et al., 2010), direct estimate (Mohr