International Journal of Impact Engineering 88 (2016) 54–60

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

A split Hopkinson pressure bar device to carry out confined friction tests under high pressures

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ARTICLE INFO

Article history:
Received 23 April 2015
Received in revised form 16 July 2015
Accepted 7 September 2015
Available online 11 September 2015

Keywords:
Friction parameter
Identification
Confinement
Split Hopkinson pressure bars

ABSTRACT

Numerical simulations of mechanical loadings on pyrotechnic structures require the determination of the friction coefficient between steel and explosives. Our study focuses on contact pressures of around 100 MPa and sliding velocities of around 10 m/s. Explosives are brittle materials which fracture when submitted to such pressures in uniaxial compression. They have therefore to be confined to avoid any fracture during the tests. A new Hopkinson bar device which simultaneously enables to confine a sample and rub it on steel has therefore been designed. This device is composed of two coaxial transmission bars. It consists in a cylindrical sample confined in a steel tube, the cylindrical sample being inserted between the incident bar and the internal transmission bar, and the confinement tube being leant against the external transmission bar. The high impedance of the external transmission bar keeps the confinement tube quasi-motionless whereas the impedance of the internal transmission bar is calculated to reach the desired pressure and the desired velocity at the tube–sample interface. Tests have been carried out with an inert material mechanically representative of explosives. The friction coefficient and the stresses at the tube–sample interface are deduced from strain measurements on the Hopkinson bars and on the external face of the confinement tube, and from an analytical model.

1. Introduction

Numerical simulations are performed to predict the ignition of confined explosives submitted to accidental impacts [1–3]. Such impacts are characterised by velocities of several tens of metres per second and are usually called “low-velocity impacts”. These simulations are based on:

- an elasto-plastic model simulating the macroscopic behaviour, whose parameters are identified from triaxial tests;
- a thermo-chemical model enabling the calculation of the local heat due to the irreversible macroscopic strain and due to chemical reactions.

The parameters of the thermo-chemical model are identified from normalised experimental tests supposed to reproduce accidental situations: the drop-weight test [4], the Steven-test [3,5,6], the Susan-test [3] and the Taylor test [7] among others. Unfortunately, numerical simulations of these normalised tests show that the ignition time of the explosive strongly depends on the friction coefficient at the interface between the explosive and the contact materials (generally steel). A test enabling the friction coefficient measurement between steel and explosives under the “low-velocity impacts” conditions has therefore to be designed.

Numerical simulations display that the “low-velocity impacts” lead to contact pressures reaching 100 MPa and sliding velocities reaching 10 m/s at the interfaces. Few tribometers satisfy these requirements: tribometer with explosively-driven friction [8], target–projectile assembly with oblique impact [9], Hopkinson torsion bars [10], dynamometrical ring with parallelepipedic specimen launched by a gas gun or an hydraulic machine [11] and the friction of a pin on a revolving disc [12,13]. With these classical tribometers, mainly used on metals and ceramics, the friction samples are tested in simple compression and this configuration is unfortunately not adapted to our situation, as explained above.

For safety reasons, our friction tests are carried out with an inert material mechanically representative of an explosive. This material is named the I1. The I1 Young’s modulus is 2 GPa, its Poisson’s ratio ν is estimated to 0.4 and its density is 1850 kg/m^3 [14]. Its inelastic behaviour has been studied by carrying out triaxial compression tests [14]. The material flow when its plasticity

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http://dx.doi.org/10.1016/j.ijimpeng.2015.09.002
0734-743X/

threshold has been attained (for the sake of simplicity the maximal stresses obtained using triaxial tests are used to define a plasticity threshold). The plasticity flow threshold is defined by a Drucker–Prager criterion [14]:

$$\sigma_{mis} - \alpha P < C \tag{1}$$

where P is the hydrostatic pressure and σ_{mis} the Von Mises equivalent stress.

Conventionally, the stress in the I1 is positive in compression and negative in traction. A plastic incompressibility and a perfectly plastic behaviour (i.e. C constant) are assumed. The parameters have been determined: $C = 25$ MPa and $\alpha = 0.64$ [14].

According to relation (1), in the case of a simple compression loading, the maximum axial stress is only 31 MPa. The I1 behaviour is quasi-brittle, so when this limit stress is reached, it breaks. The desired 100 MPa pressure cannot therefore be reached with classical tribometers because of the I1 fracture. The material has therefore to be confined during our tests for two following reasons:

- The behaviour of the confined material remains elastic even under high stresses.
- A confinement situation avoids any fracture to occur when the elasticity limit is reached.

A cylindrical I1 sample is thus enclosed in a steel tube. This technique is usually employed to perform compression tests with quasi-uniaxial strain states [14,15]. Our test bench has to be designed to enable friction to occur between the I1 sample and the steel tube. Our experimental configuration is similar to the compaction tests one [16–18].

The Hopkinson bar set-up, its potential performances and the friction identification from a test and from an analytical model are described in Section 2. Then, the consistency of this identification is verified in Section 3 by performing numerical finite element simulations.

2. The Hopkinson bar set-up

2.1. Design and modeling

The Hopkinson bar device used for our friction tests has two coaxial output bars (Fig. 1). It consists in an I1 cylindrical sample confined in a steel tube, the sample being inserted between the incident bar (via a plug, see Fig. 2) and the internal output bar, and the confinement tube being leant against the external output bar. The high impedance of the external output bar keeps the confinement tube quasi-motionless whereas the impedance of the internal output bar is calculated to reach the desired pressure and the desired velocity at the tube-sample interface. Thus, the steel tube acts both as a confinement, which avoids any fracture in the I1 sample, and as a friction surface. The radial pressure at the confinement tube–sample interface is generated by the axial compression of the sample.

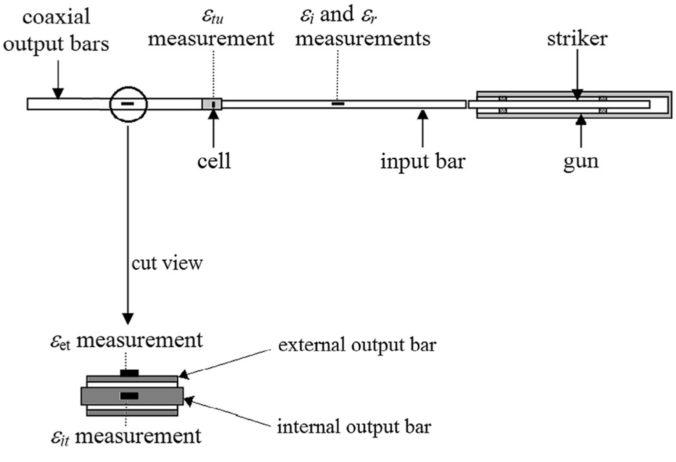

Fig. 1. The Split Hopkinson Pressure Bar device. ε_i: incident strain wave, ε_r: reflected strain wave, ε_{tu}: strain measured on the confinement tube, ε_{et}: external transmitted strain wave, ε_{it}: internal transmitted strain wave.

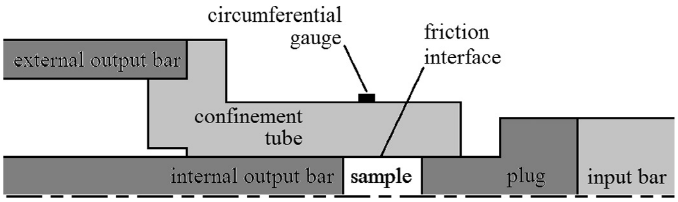

Fig. 2. Zoom on the mounting with the cell composed of the plug, the sample and the confinement tube (axisymmetric cut view).

The impact of the striker induces an incident compressive strain wave ε_i in the input bar (Fig. 1). Reverberation occurs in the cell (cell details are given on Fig. 2), which leads to a reflected strain wave ε_r in the input bar, to a transmitted compressive strain wave ε_{it} in the internal output bar and to a transmitted compressive strain wave ε_{et} in the external output bar. ε_i and ε_r are both measured by a longitudinal strain gauge glued on the input bar, at 1.22 m from the plug interface, where the two waves are separated in time. ε_{it} is measured by a longitudinal strain gauge glued at 330 mm from the sample interface and ε_{et} is measured by a longitudinal strain gauge glued on the external face of the external output bar and at 295 mm from the confinement tube interface.

The sample has a diameter $2R$ and a length L equal to 10 mm, the confinement tube has an external diameter $2R_t$ equal to 24 mm and the length scale is respected on Fig. 2. The confinement tube and the plug, made of steel, have Young's modulus E_t and Poisson's ratio ν_t respectively equal to 200 GPa and to 0.29. The friction face of the confinement tube has been reamed and the sample was turned on a sliding lathe. Both have a weak surface roughness representative of the pyrotechnic structures roughness (arithmetic average of absolute values R_a roughly equal to 0.8). The radial clearance between the plug and the tube and between the internal output bar and the tube is of the order of 0.01 mm. Teflon sheets have been inserted between the plug and the sample and between the internal output bar and the sample in order to reduce the friction at these interfaces and thus increase the pressure at the tube–sample interface. The circumferential gauge glued on the confinement tube is 2 mm wide. The initial axial distance between the sample middle and the gauge middle is chosen equal to 2.5 mm because the sample displacement relatively to the tube during the test is supposed to be around 5 mm. Thus, the gauge is glued at the mean axial position of the sample middle.

The force F_i applied by the input bar on the plug and the velocity V_i at the input bar–plug interface can be determined from the Hopkinson formulae (2) and from strain waves ε_i and ε_r measured by the gauge and virtually transported at the input bar–plug interface (see Table 1 for symbols definitions):

$$\begin{cases} F_i = -\pi R_i^2 E_i (\varepsilon_i + \varepsilon_r) \\ V_i = C_i (\varepsilon_r - \varepsilon_i) \end{cases} \tag{2}$$

The force F_{io} applied by the internal output bar on the sample and the velocity V_{io} at the internal output bar–sample interface can be determined from the Hopkinson formulae (3) and from strain wave ε_{it} measured by the gauge and virtually transported at the internal output bar–sample interface: