International Journal of Impact Engineering 38 (2011) 171–180

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

About the dynamic uniaxial tensile strength of concrete-like materials

Y.B. Lu [1], Q.M. Li *

School of Mechanical, Aerospace and Civil Engineering, Pariser Building, The University of Manchester, Sackville Street, Manchester M13 9PL, UK

ARTICLE INFO

Article history:
Received 6 September 2009
Received in revised form
20 October 2010
Accepted 23 October 2010
Available online 11 November 2010

Keywords:
Concrete-like material
Tensile strength
Dynamic increase factor
Strain-rate effect

ABSTRACT

Experimental methods for determining the tensile strength of concrete-like materials over a wide range of strain-rates from 10^{-4} to $10^{2}\,s^{-1}$ are examined in this paper. Experimental data based on these techniques show that the tensile strength increases apparently with strain-rate when the strain-rate is above a critical value of around 10^{0}–$10^{1}\,s^{-1}$. However, it is still not clear that whether the tensile strength enhancement of concrete-like materials with strain-rate is genuine (i.e. it can be attributed to only the strain-rate effect) or it involves "structural" effects such as inertia and stress triaxility effects. To clarify this argumentation, numerical analyses of direct dynamic tensile tests, dynamic splitting tests and spalling tests are performed by employing a hydrostatic-stress-dependent macroscopic model (K&C concrete model) without considering strain-rate effect. It is found that the predicted results from these three types of dynamic tensile tests do not show any strain-rate dependency, which indicates that the strain-rate enhancement of the tensile strength observed in dynamic tensile tests is a genuine material effect. A micro-mechanism model is developed to demonstrate that microcrack inertia is one of the mechanisms responsible for the increase of dynamic tensile strength with strain-rate observed in the dynamic tensile tests on concrete-like materials.

1. Introduction

Concrete-like materials (e.g. mortar, concrete and geo-materials) have been widely used in civil and military engineering structures, which may be threatened by intensive dynamic loads (e.g. explosion and impact). Dynamic strengths of concrete-like materials are frequently required in the design and modelling of these structures. Two important parameters in a dynamic strength model are dynamic uniaxial tensile and compressive strengths. The former controls the tensile failure (e.g. spalling, scabbing and fragmentation) while the latter is responsible for the compressive resistance (e.g. penetration and perforation) when the structure made of concrete-like materials responds to impact or blast loading.

It has been observed that both the tensile and compressive strengths of concrete-like materials increase with strain-rate, especially when the strain-rate is greater than a transition strain-rate, which is around 10^{0}–$10^{1}\,s^{-1}$ for uniaxial tension and $10^{2}\,s^{-1}$ for uniaxial compression, respectively. However, it has been found that the strain-rate enhancement of the compressive strength of concrete-like materials is largely caused by the introduction of radial confinement in split Hopkinson pressure bar (SHPB) tests [1–6], which cannot be simply interpreted as material behaviour. A similar argument was made by Cotsovos and Pavlović [7] for the dynamic tensile strength of concrete, i.e. the tensile strength enhancement of concrete based on direct dynamic tensile tests was caused by axial inertial effects, and thus, represents a "structural" effect. Cotsovos and Pavlović's [7] conclusion, however, is in contradiction with the findings in Hentz et al. [2] that the dynamic tensile strength based on spalling tests represented the material-intrinsic behaviour of concrete. In spite of these different opinions on the dynamic tensile strength of concrete-like materials, experimental results consistently demonstrate the strong strain-rate dependence of the tensile strength when the strain-rate is above a transition strain-rate, which will be shown with further details in Section 2. Therefore, it is necessary to answer following two questions, i.e. (i) can the observed dynamic tensile strength enhancement of concrete-like materials be attributed to strain-rate effect, and (ii) is it necessary to consider the dynamic tensile strength enhancement in the dynamic strength model of concrete-like materials.

Available experimental methods for the measurement of tensile strength of concrete-like materials are examined in Section 2. Stress states in three types of dynamic tensile tests (i.e. direct dynamic tensile test, dynamic splitting test and spalling test) are calculated in Section 3 based on a macroscopic hydrostatic-stress-dependent material model where the material behaviour is assumed to be strain-rate-independent. It is shown that the effect

* Corresponding author. Tel.: +44 1613065740; fax: +44 1613063849.
E-mail address: qingming.li@manchester.ac.uk (Q.M. Li).
[1] Present address: School of Manufacturing Science and Engineering, Southwest University of Science and Technology, Mianyang 621010, Sichuan, PR China.

0734-743X/$ – see front matter
doi:10.1016/j.ijimpeng.2010.10.028

of non-uniaxial stress state on tensile strength enhancement is negligibly small, which supports findings in Hentz et al. [2]. Thus, the increase of dynamic tensile strength of concrete-like materials at the macroscopic level is primarily attributed to the influence of strain-rate. Based on a micro-mechanism model, it is found in Section 4 that the microcrack inertia is one of the mechanisms responsible for the dynamic tensile strength enhancement of concrete-like materials observed in dynamic tensile tests. Conclusions are presented in Section 5.

2. Tensile tests of concrete-like materials

2.1. Quasi-static tensile tests

In order to establish a reference for the study of the dynamic tensile strength of concrete-like materials, quasi-static tensile tests are required. Three testing methods are generally accepted to measure the quasi-static tensile strength of concrete-like materials, i.e. the direct tensile test, the modulus of rupture test and the splitting (or Brazilian) test [8]. In a direct tensile test, a specimen is gripped at its two ends and pulled apart in tension where the tensile strength is calculated by dividing the load at failure over the cross-sectional area of the specimen, which can be performed up to strain-rate of $10^{-1}\,s^{-1}$ on a universal loading machine. For the modulus of rupture test, a rectangular beam is loaded at the mid-point up to the bending failure, from which the maximum tensile flexural stress calculated at failure is called the modulus of rupture and is considered to represent the tensile strength. In a splitting test, a cylindrical specimen is positioned such that its longitudinal axis lies horizontally between the loading platens in different ways [Fig. 1(a–c)]. The load applied through bearing stripes is increased until the specimen is split along its vertical axis by tension due to the much smaller tensile strength of concrete-like materials than their corresponding compressive strength.

Researchers have indicated that, among the three testing methods, the splitting test gives the most accurate measurement of the true tensile strength of concrete-like materials in a wide range of strain-rates from $10^{-7}\,s^{-1}$ to about $10^{0}\,s^{-1}$ (e.g. [9]). Difficulties are encountered in the direct tensile tests when it requires a pure tensile force free of eccentricity. Often, when grips are used to anchor the specimen, compression from the grips is combined with tension from the testing machine. This particular combination of forces has been shown to result in failure at stress levels below the maximum tensile strength [10]. Although the modulus of rupture test is easier to conduct than the direct tensile test, it tends to overestimate the tensile strength [11] as a result of the assumption that there is always a linear distribution of stress on the cross-section of the beam whereas the actual stress distribution becomes parabolic when the failure load is approached [8].

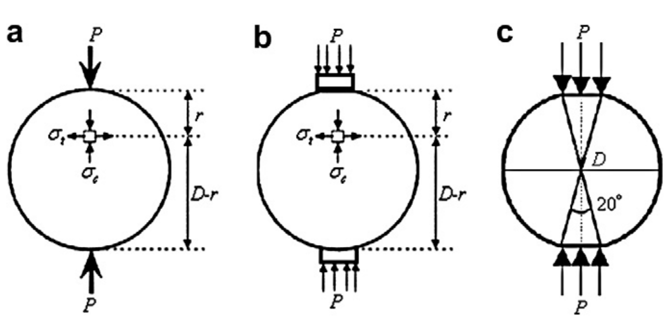

Fig. 1. Schemes of the splitting test, (a) when concentrated line load is applied, (b) with bearing strips, and (c) diametric compression on the flattened Brazilian cylinder.

The stress state of the splitting test has an analytical solution if a plane-strain state is assumed and a concentrated line load is applied [12]. The stresses associated with such loading configuration are illustrated in Fig. 1(a). When the compressive load, P, is applied to the specimen, points located near the centre of the cylinder along its vertical diameter are subjected to a vertical compressive stress of [9]

$$\sigma_c = \frac{2P}{\pi BD}\left[\frac{D^2}{r(D-r)} - 1\right] \tag{1}$$

where B is the length of the cylinder, D is its diameter, and r is the distance from the point on the vertical diameter to the top of the cylinder. This point is subjected to a horizontal tensile stress as well, whose magnitude is equal to [9]

$$\sigma_{ts} = \frac{2P}{\pi BD} \tag{2}$$

In an actual splitting test, the load is applied through a relatively small zone, as shown in Fig. 1(b). For concrete-like materials, this zone is usually controlled using bearing strips that spread the load to the actual loading–bearing width. The tensile strength determined from tests conducted without the bearing strips is typically about 8% lower than that recorded by tests conducted with the bearing strips [9]. ASTM [11] recommended that the width of the strips (b) should be approximately 1/12 of the diameter of the cylinder (D). A modified expression to measure the tensile strength is proposed [12],

$$\sigma_{ts} = \frac{2P}{\pi BD}\left(1-\beta^2\right)^{3/2} \tag{3}$$

where $\beta = b/D$ is the relative width of the load-bearing strips.

Wang et al. [13] employed flattened cylindrical specimens to perform Brazilian tests [Fig. 1(c)]. The tensile strength with flat angle of 20° can be estimated by the following expression

$$\sigma_{ts} = 0.95\frac{2P}{\pi BD}. \tag{4}$$

It is worth noting that Eqs. (2–4) can only be used to calculate the maximum tensile stress. Strain at failure and the stress–strain relationship before failure cannot be obtained from splitting tests.

2.2. Dynamic tensile tests

The splitting test technique has been used to test brittle materials when loading conditions belong to quasi-static or low strain-rates. The loading process has been modelled by different researchers and the testing results have been justified (e.g. [12]). It has been recently brought into use for measuring the dynamic tensile strength of concrete-like materials at intermediate strain-rates. The SHPB is used for dynamic splitting tests, as illustrated in Fig. 2. The dynamic tensile strength, σ_{td}, of the splitting cylinder is proportional to the average of input and output force histories (P_t) through a modification of Eq. (4), which is expressed as [13]

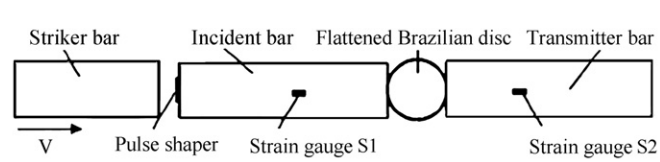

Fig. 2. The side view of a dynamic splitting test arrangement in the SHPB [13].