Photomechanical experimental methods to characterize the dynamic crack speed in brittle materials

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Abstract. The present paper highlights 3 experimental techniques developed to investigate the crack-propagation velocity in ceramic and concrete materials under dynamic tensile loading. These methods have in common to aim spreading a single crack at high-rates and to use a photomechanical method to analyse the crack propagation in the tested brittle material. The first one is based on direct impact of conical-noise projectile against a ceramic target in which a groove is performed on the backside, leading to the propagation of a crack along the groove on either side of impact point. The rear face is visualised by an ultra-high speed camera. In the second experimental technique, called nEOI (notched-Egde-On-Impact), a cylindrical projectile hits the edge of a rectangular ceramic tile. A crack develops from a notch tip located on the rear edge towards the front edge. The ultra-high speed camera is set to visualize the lateral surface. In the third testing technique, the so-called rocking spalling test, double-notched specimen is loaded in spalling tests. A compressive pulse transmitted to a parallelepiped specimen through a single Hopkinson bar provides a rocking effect of the rear part of the specimen thanks to a large notch, which leads to the propagation of a single unstable crack from the tip of a shorter notch. The three techniques can be easily applied to ceramics, concrete or rocks providing that the testing configuration (sample design, impact speed, amplitude of applied load) is well adapted to the tested material. Advantages and drawbacks of each technique are discussed.

Introduction

Dynamic crack propagation in brittle materials (concrete, rocks, ceramics) is involved in many civil and military applications involving high-strain-rate loadings such as: blasting or percussive drilling of rocks, ballistic impact against ceramic armour or transparent windshields, plastic explosives employed to damage or destroy concrete structures, soft or hard impacts against concrete structures, etc… [1]. However, the experimental characterisation of crack speed in non-transparent brittle materials remains a challenging task. Indeed, under high strain-rate conditions produced by impact or impulse loads brittle materials exhibit a multiple fragmentation process made of numerous oriented cracks [2]. The determination of crack speed of individual crack among many others is very complicated. It is the reason why, experimental techniques providing the propagation of a single crack at high rates need to be developed. In addition, due to low toughness of brittle materials (generally a few MPa.m$^{1/2}$), crack opening remains very small. Consequently, high resolution camera and subpixel data processing of pictures are required. Third, given the very high speed of unstable crack that is expected to develop in such materials (about 2 mm/µs in concrete and 4 mm/µs in ceramics) frame rate about a million of frames per second is necessary to apply successfully these photomechanical experimental methods.

In this work, two post-processing methods based on global DIC measurements were used to extract the crack velocity. The crack tip location was determined based on crack-opening-displacement measurement [3]. Second, the Eiko-crack software, which relies on both a discontinuous enrichment to the finite element approximation (extended approach) and the addition of mechanical constraints to prevent incoherent mechanical displacement regarding material constitutive or propagation law (integrated approach) was used [4].

Normal impact against grooved plate:

The principle of this technique is described on Fig. 1a. A conical noise projectile impacts the centre of a curved plate. An unstable cracks develops on both side along a groove performed on the back side. Projectile shape and impact speed are set to force the crack propagating along the groove. This technic was applied to a ceramic plate. A Kirana camera providing pictures (924 x 768 pixels) with recording frequencies set at 200kfps was used to visualize the rear surface covered by fine painted speckles. The Eiko-crack software [4] was used to process the data and to determine the crack speed.

The “n-EOI” notched Egde-On-Impact:

The “n-EOI” notched Egde-on-Impact may constitute a convenient technique to characterize the crack speed in brittle materials. Contrary to Egde-on-Impact which aims to produce a large number of cracks, this method aims to produce a single crack triggered on a notch implemented on the rear edge. To do so, a low impact speed needs to be considered. This technique was applied to alumina ceramics in [4]. The sample was again covered with fine speckle and the Kirana camera was set to a recording frequency of 5 Mfps. The pictures were processed with DIC (Digital Image Correlation) data processing.

The rocking spalling testing technique:

This experimental technique was used to investigate the cracking velocity under dynamic tensile loading in concrete [5] and more recently in ceramics [6]. The set-up based on spalling testing technique relies on the use of parallelepiped specimen in which two notched are performed. The biggest notch provides a fast rocking effect of the rear part of the sample leading to a local dynamic tensile loading in a zone that contains the small notch. The geometry of the specimen (size and location of notches) and the amplitude of the compressive pulse need to be carefully defined through a series of numerical simulations. The configuration allows triggering a single instable crack despite the high loading rate reached during the experiments.
Experiments were conducted on dry and water-saturated concrete samples in [5] and on alumina ceramic in [6]. In both testing campaigns the cracking inception and propagation was visualized with an ultra-high speed digital camera and using a DIC post-processing technique. The obtained results show that, in most case, a single crack is triggered on the small notch and propagates roughly perpendicularly to the loading axis. The cracking velocity was evaluated with both types of material and compared to the Rayleigh wave speed.

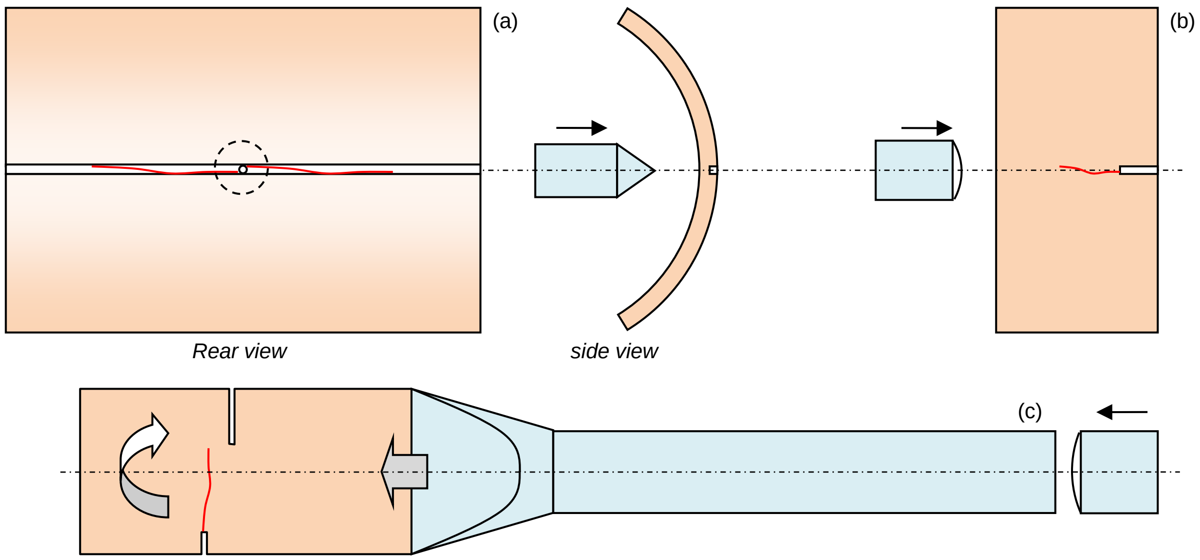

Fig. 1. Three photomechanical experimental methods developed to characterize the dynamic crack speed in brittle materials. (a) The normal impact against grooved plate, (b) The notched Egde-on-Impact, (c) The rocking spalling test.

Conclusion

The investigation of dynamic crack speed in brittle materials remains a challenging task due to their low toughness and ease to produce a multiple fragmentation at high loading rates. During the last decade three techniques were developed based on ultra-high imaging and photomechanical data processing. According to this experimental work, these methods are mature to characterize the crack speed in various kinds of brittle materials such as ceramics and concrete.

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