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Quantification of dynamic tensile behavior of cement-based materials

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HIGHLIGHTS

- Dynamic tensile tests were conducted using a modified Kolsky bar.
- Pulse shaper helps to achieve dynamic equilibrium in the test specimen.
- A numerical analysis was conducted to verify the experimental data.
- Results of the strain rate sensitivity of cement-based materials are presented.
- A tensile constitutive model with strain rate effects was modified.

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ABSTRACT

The modified split Hopkinson pressure bar testing method was used to quantify the dynamic tensile behavior of cement mortar using flattened Brazilian disc specimens. Experimental procedure for testing dynamic behavior of cement-based materials under high loading rate is presented. Employing a proper pulse shaper in the conventional split Hopkinson pressure bar (SHPB) test helps to achieve dynamic equilibrium in the test specimen. Strain histories from strain gauges offer comprehensive information to evaluate the stress equilibrium of specimen under dynamic loading. A numerical analysis was conducted to verify the experimental data. In addition, the results of the strain rate sensitivity of cement mortar are analyzed. Based on the experimental results and an existing quasi-static model, a tensile constitutive model with strain rate effects was formulated. This model provides a good description of dynamic experimental results for cement mortar.

1. Introduction

The responses of concrete to transient dynamic loading have been studied extensively for both civil and military applications [1–4]. Understanding the response of concrete to impact or explosive loading is essential to protect fortifications. For instance, the protective shells of nuclear power plants must survive the impact loading of an aircraft crash [5–9]. The protection structures of military facilities are subjected to dynamic loading arising from factors such as missile impact or non-contact air explosion [10]. When subjected to dynamic loading, concrete is subjected to different failure modes. Near the impacted area, severe hydrostatic compression is observed, and the state of stress irreversibly compact the material. Further from the impacted location, the confinement stresses are reduced and the materials experience compression with a moderated state of stress. Moreover, the compressive wave reflection from the rear faces of the target generates a tensile wave which interacts with compressive waves and leads to spalling [11].

The dynamic mechanical properties of concrete can be very different from those exhibited in quasi-static conditions [12,13]. Specific investigations in such dynamic ranges appear necessary to correctly understand their behavior under high strain rate condition. Experimental studies focusing on the dynamic compressive behavior of concrete have been conducted by numerous researchers [14–23]. As reported by many researchers [24–26], concrete is considerably weaker in tension than in compression. In contrast to the abundant test results for concrete subjected to dynamic compression, studies focusing on the dynamic tensile behavior of concrete are limited. This is mainly because it is much harder to test and measure the dynamic response of concrete in tension than in compression. From a conceptual point of view, the most appropriate method to characterize the behavior and determining the tensile strength of concrete is by means of the direct tensile test [27,28]. However, this test is not used very often due to difficulties associated with the application a pure tensile load on the plain concrete specimen, which is reflected in the fact that the regulations or recommendations for its execution are scare [27]. Alternatively, other methods used for determining the tensile strength of concrete are the bending test with center-point loading [29] or third-point loading [30] as well as indirect tensile tests such as

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the diametral compression test (also known as the Brazilian test) [31]. However, the tensile strength values obtained from those tests are not equivalent. In the case of the bending tests, the maximum strength reached is governed by the tensile strength of the surface of the beam and is very sensitive to its humidity conditions, whereas in the case of the Brazilian test, most of the concrete mass in the loading plane is subjected to a constant tensile stress; therefore, the latter is closer to a direct tensile test [32,33].

The conventional Brazilian test indirectly establishes the tensile strength of materials assuming biaxial linear elasticity in two-dimensions. Theoretically, the sample is considered to fail within the central portion of the disc, where the tangential stress will overcome the uniaxial tensile strength under the application of a radially compressive stress. Fairhurst [34] proposed that the tensile strength calculated from Brazilian test results is highly dependent upon the loading method used. The ASTM adopts the use of flat platens, where loading is applied to the disc at diametrically opposing points (Fig. 1(a)), with recommended thickness (t)/diameter (D) ratios ranging between 0.2 and 0.75 [35]. The ASTM method has been criticized as sample crushing resulting from stress concentration has been found to initiate failure at the loading points rather than at the centre of the disc, which is critical in ensuring the validity of the test [36]. Several authors, including Andreev [37] and Yu et al. [38], have attempted to mitigate the crushing behavior through the positioning of 'cushions' and spacers of materials of various stiffness relative to the sample under investigation to decrease the localized stress. This has been shown to reduce the crushing effect of point loading; however, it adds a layer of complexity. In contrast, the ISRM recommends the application of load through a curved platen of radius 1.5 times that of the sample between t/D ratio should be 0.5 (Fig. 1(b)) [39]. This method requires the manufacture of loading platens of different curvature depending upon the diameter of the sample disc being tested in order to retain a consistent loaded section of the circumference. In order to address these issues, Wang et al. [40] proposed a modified flattened Brazilian disc that allows a good contact between the sample and flat loading platens (Fig. 1(c)) while minimizing the crushing associated with point loading. The amount of flatness is defined by an interior angle, α, where a high α value indicates a wider flat face. Through the testing of different rock samples, it was shown that the flattened Brazilian test significantly reduced crushing in the vicinity of loaded areas while still providing reasonable strength.

Dynamic loads are characterized by high amplitude and short duration stress pulse or a high strain rate. Strain rates reported to be of relevance in cement-based materials range from 10^{-8} to 10^{5} s^{-1} [2,18] and indicate the large variations in strains to which concrete can be subjected depending on mode of fracturing. The strain rate spectrum for engineering application is illustrated in Fig. 2 along with the common testing method to obtain the dynamic properties. The strain rate achievable depends on the type of loading devices used. Ordinary hydraulic testing machines can load specimens at strain rates up to 10^{-3} s^{-1}. The strain rate obtainable by split Hopkinson pressure bar is on the order of 10^{0}–10^{4} s^{-1}. Besides the laboratory testing method, in situ blasting tests are usually conducted to examine the dynamic wave propagation and concrete damage due to blasting [41–44]. The response of the concrete is measured with accelerometers and relationships between peak particle velocity and blasting charge and distance established for either qualitative or quantitative damage assessment. The Brazilian test technique has now expanded to high strain rate testing (using a split Hopkinson pressure bar) for measuring the dynamic tensile strength [45,46] and dynamic fracture toughness [47] of materials. Compared to the classical Hopkinson "direct" tensile test, the dynamic Brazilian test has several advantages, including: the loading configurations including Brazilian sample and loading bars are relatively simple compared to the tensile experiments; the pulse magnitude, duration, and shape can be controlled by pulse shaping, and therefore stress-state equilibrium can be achieved prior to the sample failure.

In this paper, an experimental technique using flattened Brazilian disk specimen in a SHPB system is proposed to investigate the dynamic tensile behavior of cement mortar. Strain gauges were glued to the flattened Brazilian specimens to record materials strain and derive testing strain rate. A numerical simulation using finite element method was performed to show the evolution of dynamic stress distribution in mortar specimens. A constitutive modeling of cement mortar under dynamic loading is also presented based on crack propagation model proposed by Huang and Li [48]. Computed results are compared with experimental data to highlight the capabilities of the proposed techniques.

2. Experimental details

2.1. Materials and sample preparation

Ordinary Portland cement (OPC) was used in the production of cement mortar specimens. This cement is the most widely used cement in general concrete construction work in China. The fine aggregate was river sand consisting mostly of quartz, with 10% feldspar. The gradation test showed that the particle size of the sand was continuously distributed within the range of 0.4–2.5 mm with 80% of sand. The water-cement ratio, w/c, 0.4 and the sand-cement ratio, s/c, 2 were used for cement mortar. The standard specimens were cast in steel molds with dimensions of 150 × 150 × 550 mm. Following casting, the specimens were covered with a plastic membrane to prevent moisture from evaporating. The specimens were demolded after 24 h, and then moist-cured in a water tank at 20 °C. After curing for 90 days, specimens were cored and cut to length using a water spray. The geometry of a flattered Brazilian disc (FBD) specimen was used in this investigation, with radius $R = 37$ mm, thickness $B = 30$ mm, and loading angle $2\alpha = 20°$. A total of 36

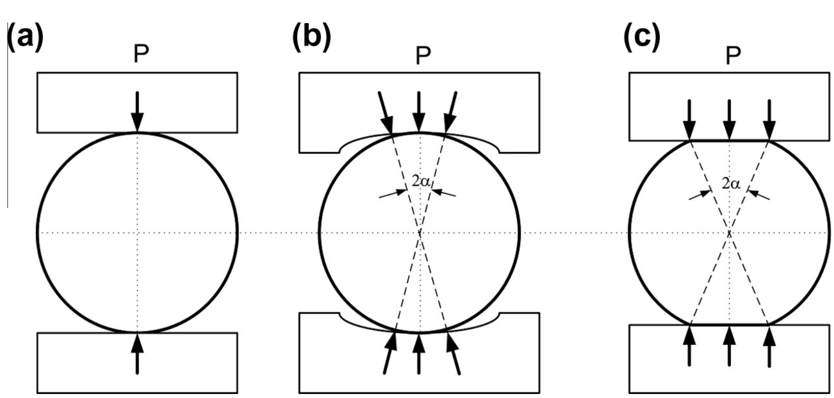

Fig. 1. Loading methods: (a) flat-point, (b) arch–arch, and (c) flat–flat.