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A nonlinear dynamic uniaxial strength criterion that considers the ultimate dynamic strength of concrete

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ABSTRACT

The existing test results and semi-empirical equations of the rate-dependent concrete strength have overestimated the actual dynamic strength because they do not distinguish between the actual dynamic strength related to the strain rate effects and the additional resistance caused by inertial effects. However, an ultimate strength of concrete exists at a strain rate exceeding a certain value. This paper proposes a nonlinear dynamic uniaxial strength criterion for concrete based on an analysis of the physical mechanisms governing the strain-rate-dependent behavior of concrete strength. The proposed criterion is able to describe the actual dynamic strength and to reflect the ultimate strength at a high strain rate of concrete. The results from two groups of dynamic uniaxial compressive tests and two groups of dynamic uniaxial tensile tests are used to verify the criterion. Moreover, the recommended physical parameters in the criterion are obtained by analyzing the statistical test results of dynamic uniaxial compression and tension. The recommended parameters can be used in the criterion to study the dynamic strength of concrete when dynamic tests are not feasible, and to predict the dynamic strength at high strain rates when tests are performed at lower strain rates.

1. Introduction

Many investigations, including experimental investigations, numerical simulations, and theoretical investigations, have been performed to understand the effects of the strain rate on the strength of concrete materials, especially the dynamic strength criteria. For example, the following relevant experimental studies have been performed: a drop-weight machine was used to conduct a dynamic strength test over a strain rate range from 10^{-1} to 10^{1}/s [1–3]; the strain rate of a split Hopkinson pressure bar (SHPB) was reported to be up to 10^{4}/s [4–14]; a one-stage light gas gun was used to obtain experimental results at a higher strain rate ranging from 10^{4}/s to 10^{5}/s [15]; and a servo-hydraulic machine was developed to perform dynamic multiaxial tests at extremely low strain rates ranging from 10^{-5} to 10^{-2}/s [16–21]. A summary of the different loading techniques and mechanical states over a wide range of strain rates is provided in Fig. 1, which illustrates that no single loading techniques can perform dynamic strength tests over the entire strain rate region. Therefore, semi-empirical equations for rate-dependent strength, i.e., the dynamic strength criteria [13,22,23], and numerical simulations [24,25] were developed to describe the strength properties of concrete over the full range of strain rates. This paper focuses on the dynamic uniaxial strength criterion for concrete.

The dynamic uniaxial strength criteria are typically reported as a dynamic increase factor (DIF) versus strain rate on a semi-log scale [26–28]; in addition, analytical solutions can be easily obtained for dynamic uniaxial problems in concrete by applying the dynamic uniaxial strength criteria. The most representative achievement in these researches was the bilinear dynamic uniaxial strength criterion suggested by the CEB-FIP standard [22]. Similar piecewise linear or nonlinear functions have also been proposed by Tedesco and Ross [29], Grote et al. [30], Li and Meng [6], Zhou and Hao [31], and Hao and Hao [32,33], among others. However, for the piecewise functions, the criteria include singular points, and the methods for determining these points have no theoretical support. Continuous and smooth dynamic uniaxial strength criteria for which the equation is a unified function were developed to overcome this problem. For example, Stolarski [23] proposed a nonlinear dynamic uniaxial strength criterion for concrete based on the Campbell criterion [34]. Similarly, a large number of nonlinear dynamic uniaxial strength criteria with continuous and smooth strength curves have been proposed by researchers [13,28,35–39]. The dynamic uniaxial strength criteria proposed by researchers are summarized in Table 1, and their strength curves are shown in Fig. 2. The strength curves of the dynamic uniaxial compressive and tensile criteria in Fig. 2 indicate that nearly all of the functions of these criteria are divergent.

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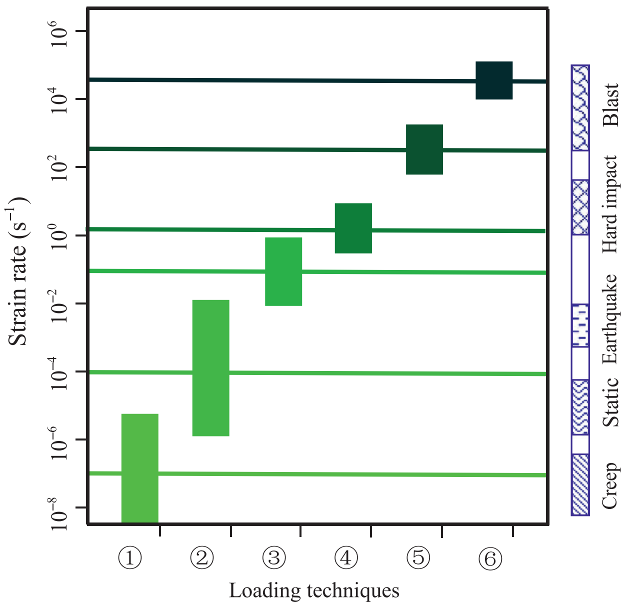

① is specialized-hydraulic machines, ② is a servo- hydraulic machines, ③ is a pneumatic- hydraulic machines, ④ is a drop weight machines, ⑤ is a split Hopkinson pressure bar, ⑥ is a one-stage light gas gun.

Fig. 1. Loading techniques and mechanical states over a wide range of strain rates.

More specifically, the dynamic strength infinitely increases with increasing strain rate. However, the test results obtained by Grady [40] and Yu et al. [41] showed that the dynamic strength does not increase indefinitely; instead, an ultimate dynamic strength exists at a high strain rate, as shown in Fig. 3. In addition, most of the above-mentioned dynamic strength criteria cannot describe this concrete property because they do not distinguish between the actual dynamic strength and the macroscopic resistance. The dynamic uniaxial tensile criterion proposed by Xu and Wen [28] can describe the ultimate resistance of concrete; however, it does not make the above distinction. This paper proposes a dynamic strength criterion that is able to both describe the actual dynamic strength and reflect the ultimate dynamic strength of concrete.

Understanding the physical mechanism of strain-rate-dependent behavior is the basis for establishing the dynamic strength criterion. In this paper, the macroscopic resistance of concrete is divided into the actual dynamic strength and the additional resistance caused by the inertial force, thus providing the physical mechanism governing the strain-rate-dependent behavior. Next, two physical parameters, the growth rate of the dynamic strength and the ultimate dynamic increase factor (UDIF), are obtained based on the understanding of these physical mechanisms. Furthermore, a nonlinear dynamic uniaxial strength criterion is derived using the obtained physical parameters. This criterion is capable of describing the actual dynamic strength and of reasonably reflecting the ultimate dynamic strength of concrete.

2. Physical mechanisms of the strain rate and inertial effects of concrete

Many studies have been performed to understand the mechanism governing the strain-rate-dependent behavior of concrete materials. Swan et al. [42] conducted dynamic triaxial tests and microscopic observations on shale and determined that the strain rate effect is an intrinsic property. Zhang and Zhao [43] reviewed studies by various researchers regarding the physical mechanisms of the strain rate effect and noted that the combined thermal activation effect, Stefan effect, micromechanics-based effect and dynamic fragmentation effect control the rate-dependent strength of materials. From a macroscopic perspective, the rate-dependent response of concrete is due to the following factors [25,44–46]: the rate dependency of the growing microcracks, the viscous behavior of the bulk material between the cracks and the inertial effect. Rossi and Toutlemonde [47] argued that the viscous mechanism is the main physical effect when the strain rate is less than approximately 10°/s, whereas the inertial effect becomes dominant at strain rates greater than or equal to approximately 10/s. Kipp et al. [48] noted that the inertial effect has the greatest influence on the dynamic response of concrete at higher strain rates, whereas the creep mechanism is dominant at lower strain rates. Qi et al. [49] concluded that both a heat activation mechanism and macroscopic viscosity mechanism exist in the strain-rate-dependent behavior. Cusatis [24] concluded that the rate dependence of concrete is caused by two different physical mechanisms: the fracture process during crack opening and the viscoelastic deformation of the intact cement paste. Hao et al. [50] investigated the influence of end friction confinement (inertial effect) on the compressive behavior of concrete under impact loading in SHPB tests; they then proposed an empirical formula that removed the influence of lateral inertia confinement on the increased dynamic strength of concrete. Al-Salloum et al. [51] studied the influence of radial confinement on the dynamic strength of concrete by the SHPB tests and the numerical simulations in LSDYNA. Then they concluded that both the shape and the aspect ratios affect the lateral confinement effect of concrete. Mu et al. [52] argued that the compressive strain rate effect of concrete is a pseudo-property that is mainly caused by the lateral confinement, which includes the lateral inertia of the material and the interface friction between the loading apparatus and the specimen. Some other researchers also stated that the concrete strength is rate independent [53, 54]. However, Zhang et al. [55] conducted numerical simulations that corresponded to SHPB laboratory tests to correct for the strain rate effects. These pioneering studies on the mechanical response of concrete under dynamic loading indicate that the inertial effect is typically considered at high strain rates and the lateral inertial effect was usually treated as the hydrostatic-stress-dependent properties; however, there is no unified understanding of the behavior at low strain rates. Moreover, the various mechanisms are often interrelated.

In this paper, the macroscopic resistance of concrete is divided into the actual dynamic strength and the additional resistance caused by the inertial force. The entire strain rate range is then categorized into three strain rate regions (i.e., the lower strain rate region, the intermediate strain rate region and the higher strain rate region), following the approach of other researchers. As shown in Fig. 4, the macroscopic resistance of concrete increases unlimitedly with the strain rate, and an ultimate value for the actual dynamic strength exists at high strain rates. Three physical mechanisms are used to describe the mechanical properties of concrete over the entire strain rate region: the physical mechanisms of the actual dynamic strength related to the strain rate are governed by the thermo-activated mechanism and macroscopic viscosity mechanism (i.e., the Stefan effect), while the inertial mechanism is mainly governed by the inertial resistance. Each mechanism is analyzed in the following sections.

2.1. Thermo-activated mechanism

The essence of the thermo-activated mechanism is the thermal vibration of atoms. This thermal vibration break atomic bonds and forms microcracks in the concrete. Increasing the strain rate causes excessive vibration of the atomic bonds, leading to the formation of additional cracks. From the perspective of energy dissipation, the destruction of concrete material is caused by the opening and growth of cracks. However, the energy required for opening cracks is considerably higher than that required for crack growth. When the strain rate is low, i.e., region I in Fig. 4, concrete failure is mainly due to the growth of a small number of cracks; thus, the cracks develop along