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Analyses of rigid projectile penetration into UHPCC target based on an improved dynamic cavity expansion model

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HIGHLIGHTS

- An improved dynamic cavity expansion model for projectile penetrating into UHPCC was proposed.
- A series of practical parameters for hyperbolic yield criterion and EOS of HJC model were given.
- Rigid projectile penetration model into UHPCC target was established and verified.
- Frequently used empirical formula was inapplicable for the penetration analyses of UHPCC target.

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ABSTRACT

Ultra-high performance cement based composite (UHPCC) has prominent projectile impact resistance. Aiming to theoretically predict the depth of penetration for rigid projectile penetrating UHPCC target, an improved dynamic cavity expansion model was proposed to describe the plastic behavior of UHPCC material under projectile penetration with a hyperbolic yield criterion and nonlinear equation of state (EOS). Then, combined with the Newton's second law, rigid projectile penetration model into UHPCC target was established, which was verified by comparing with the previous penetration test data, classic empirical formula and prediction of previous cavity expansion model based on linear yield criterion and EOS. Besides, a series of practical parameters of the hyperbolic yield criterion and nonlinear EOS for the improved dynamic cavity expansion model were given and validated.

1. Introduction

Ultra-high performance cement based composite (UHPCC) is a relatively new cement based composite with both prominent static and dynamic mechanical properties [1–4], which is considered as the most prospective construction material for military and civil protective structures to resist the intentional or accidental intensive dynamic loadings. Rebentrost and Wight [5], Wu et al. [6], Mao et al. [7], Ellis et al. [8] and Aoude et al. [9] conducted experimental and numerical investigations on the blast resistance of UHPCC members such as panels and columns. In the present paper, the projectile impact resistance of UHPCC target is mainly concerned.

In order to study the impact resistance of UHPCC slab against the light weight high-speed fragments, Sovják et al. [10] and Máca et al. [11] conducted the deformable (Pb core) and non-deformable (steel core) small caliber bullets (7.92 mm in diameter, 8.04 g in weight) impacting tests on UHPCC (148–164 MPa) slabs. The influences of steel fiber volumetric fractions (1%–3%) on the depth of penetration (DOP) and impact crater size were studied, respectively. Peng et al. [12] performed the 7.62 mm armor-piercing incendiary bullets impact tests on bare and rear fabric strengthened UHPCC panels, in which a practical approach to predict the terminal ballistic parameters of bullets perforating on UHPCC slabs was suggested. As for the medium caliber projectiles, Wu et al. [13–14] further carried out the 25.3 mm in diameter ogive nosed projectile penetration tests on UHPCC targets with basalt and corundum aggregates, respectively. The influences of target compressive strength, coarse aggregate type, steel fiber mixing ratio, striking velocity on DOP and impact crater dimensions were discussed. Recently, the flat nosed projectiles penetration tests on UHPCC targets were further carried out by Peng et al. [15], and both rigid and erosive projectile penetrations were discussed respectively.

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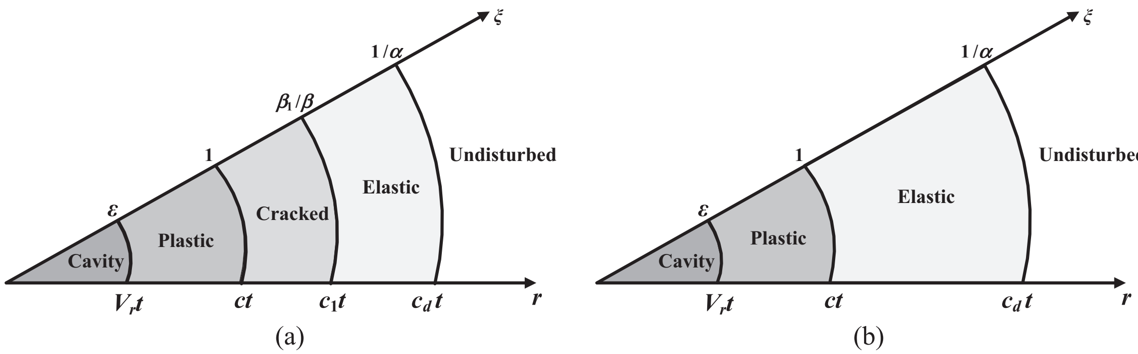

Fig. 1. Response regions of UHPCC target (a) elastic-cracked-plastic response (b) elastic-plastic response.

Generally speaking, the projectile impact resistance analyses of UHPCC target were mostly based on the reduce-scaled tests empirically, relatively limited theoretical works were conducted, e.g., prediction of DOP. Dynamic cavity expansion model is an efficient tool for projectile penetration analysis, which has been successfully applied to determine the resistance to projectile penetrating into concrete target [16–19]. When a proper yield criterion and equation of state (EOS) are introduced to describe the plastic behavior of target, the solution of dynamic cavity expansion model can be obtained analytically (incompressible target assumption) or numerically (compressible target assumption) with the similarity transformation method.

In the existing works, aiming to simplify the solution procedure, the linear yield criteria were adopted in the dynamic cavity expansion models, such as Tresca [16], Mohr-Coulomb [17,18] and modified Drucker-Prager [19] criteria. Besides, the EOS associated with the existing dynamic cavity expansion models was usually described by the bulk modulus of elasticity [17] or a locked one (material becomes incompressible beyond a critical value of volumetric strain) [16]. For high-speed projectile penetration into UHPCC target, the pressure around the projectile-target interface can reach a magnitude of several GPa, where the relationship of pressure-volumetric strain exhibits nonlinear characteristic. Consequently, the linear or locked EOS should be replaced with a more appropriate nonlinear one. Feng et al. [19] used a three-stage EOS to consider the nonlinear pressure-volumetric strain relationship of concrete material under projectile penetration. However, the yield criterion used in Ref. [19] cannot describe the nonlinear shear strength-pressure relationship.

Aiming to predict the DOP for rigid projectile penetrating UHPCC target theoretically, an improved dynamic cavity expansion model was firstly proposed, where a hyperbolic yield criterion and a nonlinear EOS were introduced to describe the plastic behavior of UHPCC material under projectile penetration. Then, based on previous triaxial compression test data [20] and existing pressure-volumetric strain data, parameters of the hyperbolic yield criterion and nonlinear EOS were proposed for UHPCC material, respectively. Furthermore, by combining with the Newton's second law, the rigid projectile penetration model was established and compared with our previous projectile penetration test data on UHPCC targets [13], predicted results of classic empirical formula [21] and previous cavity expansion model [17].

2. Improved dynamic cavity expansion model

Under the projectile penetration, a spherically symmetric cavity is expanded radially from the projectile surface, and the cavity radius increases from zero at a constant velocity V_r. Shown in Fig. 1, depending on V_r, cavity expansion produces elastic-cracked-plastic or elastic-plastic response, where r, t, c, c_1 and c_d are the radial Eulerian coordinate, time, cracked-plastic boundary velocity, elastic-cracked boundary velocity and dilatational velocity, respectively. For relatively low cavity-expansion velocity, there are three response regions shown in Fig. 1(a). When the cavity-expansion velocity is larger than a critical value ($c > c_1$ satisfied beyond this value), the cracked region will vanish, consequently the response is elastic-plastic shown in Fig. 1(b).

Previously, as introduced in Section 1, the linear yield criteria [16–19] and EOS [17] were used. In this section, a hyperbolic yield criterion and nonlinear EOS of Holmquist-Johnson-Cook (HJC) model [22] are introduced to describe the UHPCC target in plastic response region, the classic dynamic cavity expansion model is improved.

The hyperbolic yield criterion in Eulerian coordinates with spherical symmetry is described by

$$\sigma_r - \sigma_\theta = a_0 + \frac{P}{a_1 + a_2 P} \tag{1a}$$

$$P = (\sigma_r + \sigma_\theta + \sigma_\varphi)/3, \sigma_\theta = \sigma_\varphi \tag{1b}$$

where σ_r and σ_θ are the radial and hoop components of the stresses, and P is the hydrostatic pressure, which are measured positive in compression. a_0, a_1 and a_2 are the constants, which need to be determined from a suitable set of triaxial compression data. Specially, Eq. (1) reduces to Mohr-Coulomb yield criterion when $a_2 = 0$.

The EOS of HJC model [22] shown in Fig. 2 is suitable to describe the compressive behavior of concrete-like materials and expressed as

$$P = \begin{cases} K\mu \\ \frac{(\mu-\mu_{crush})(P_{lock}-P_{crush})}{(\mu_{plock}-\mu_{crush})} + P_{crush} \\ K_1\bar{\mu} + K_2\bar{\mu}^2 + K_3\bar{\mu}^3, \bar{\mu} = (\mu - \mu_{lock})/(1+\mu_{lock}) \end{cases} \tag{2}$$

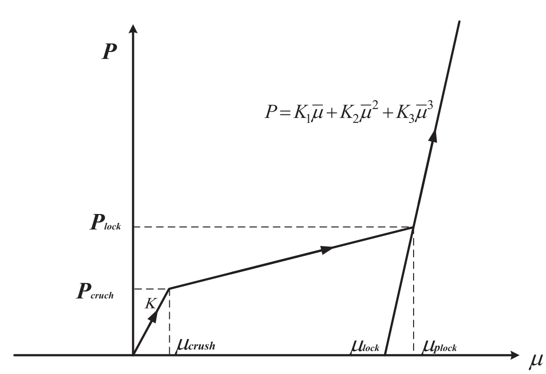

Fig. 2. EOS of HJC model [22].