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Simulation of compaction and crushing of concrete in ballistic impact with a new damage model

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ABSTRACT

Although many aspects of the fracturing process of concrete are now well understood and successfully simulated with various models, it is still very difficult to properly simulate the different failure mechanisms observed in a concrete structure induced by ballistic impact. In this paper, an enhanced version of the *effective-rate-dependent* nonlocal damage model [Eng. Fracture Mechanics, 176 (2017)] is proposed to simulate the response of concrete in such events. Hydrostatic damage has been added to the formulation in order to take the damage of the material matrix observed while porosity reduces during compaction into account. Besides controlling the evolution of the nonlinear volumetric response of the material, this new damage variable contributes to the deterioration of the material stiffness upon confinement.

It is demonstrated that the description of the nonlinear volumetric response of concrete by an equation of state (EOS) as a plasticity phenomenon, as it is commonly done in hydrodynamic constitutive modeling, is unrealistic for concrete. Such formulations fail to represent the effect of the loss of cohesion observed during compaction on the deviatoric response of the material. By taking this phenomenon into consideration, the proposed model systematically predicts the relevant failure modes (cratering, tunneling, radial cracking and spalling) observed during ballistic impact on a concrete plate as a function of the projectile velocity and plate thickness.

1. Introduction

Extraordinary actions such as blast loadings and high velocity impact are rare, but usually have devastating effects. Thus, making critical infrastructures, such as military and governmental facilities, powerplants, dams, bridges, hospitals, etc., more resilient against these hazards is one of the best ways to protect ourselves and our societies. Since concrete is a very common construction material, the development of realistic numerical tools to efficiently simulate its failure behavior under extreme dynamic loading conditions is of paramount importance, but still a major challenge [1].

The capacity of a concrete structure to withstand these impulsive loads is mainly dictated by how it dissipates the incoming energy. For example, in the particular case of ballistic impact, a pressure wave is induced which expands radially through the structural element, leading to a complex process of interfering stress waves. Consequently, the material is exposed to rapidly changing multiaxial stress states and strain rate conditions. The material may fail locally *long before* the dominant structural response takes place. Experimental evidences with different quasi-brittle materials (see for example [2,3]) suggest that the local evolution of failure in concrete during ballistic impact can be divided into five main stages (see Fig. 1): (1) the formation of the Mescall zone due to crushing and compaction of the material in front of the impactor (strike face), associated with pore collapse and comminution (pulverization) of the material under pressure; (2) tunneling resulting from the flow of the comminuted (pulverized) material around the penetrator; (3) radial cracking in front and around the impactor, caused by hoop stresses raised in the wake of the initial pressure wave [4]; (4) spalling (tensile fracture) at the rear face, upon reflection of the pressure wave; and (5) formation/expansion of the crater due to spalling at the strike face [5]. Conical punching failure (Hertzian cone) may occur in some conditions, as an extension of preformed radial cracks, at the end of the projectile deceleration phase. In a later stage, structural oscillations at moderate strain rates become the leading loading condition and the main cause for further mechanical degradation [6], such as the formation of visible radial cracks at the front and back surfaces of the target. In a normal impact on a slender concrete plate, the extension or even the manifestation of the different failure

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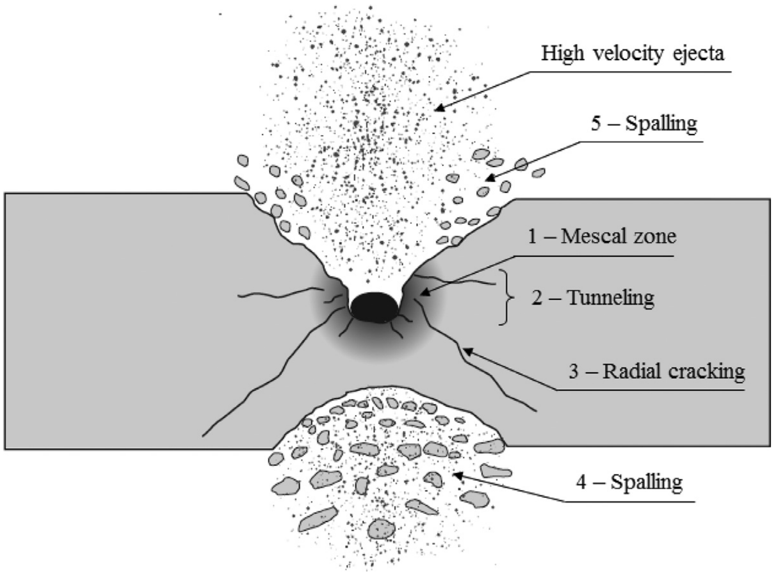

Fig. 1. Failure mechanics in impact scenarios.

modes depends on both the thickness of the concrete plate and the impact velocity. The dynamic failure observation of the target can vary from a small crater, for a relatively low impact velocity, to complete perforation, for a high velocity impact. The example depicted in Fig. 1 represents an intermediate impact velocity where both cratering and spalling occurs.

Many aspects of the fracturing process of quasi-brittle and brittle materials, such as the propagation and branching of individual cracks and spalling, are now well understood and successfully simulated with various models (e.g. plasticity [7–13], damage [14–24], plastic-damage [25–36] and fracture based approaches [37–39]). However, despite the vast literature on the topic, very few models used in dynamic FEM analysis are able to capture all relevant failure modes of concrete [38]. It is believed that the development of better models is being hampered by a poor description of material failure in front of the impactor, in the early stages of loading [32,40]. Since the first failure mechanism governs how and how much energy is transmitted to the structure, a proper description of the initial phenomena responsible for the fragmentation (and pulverization) of the material immediately after impact is critical for an adequate representation of the subsequent failure processes.

It is well known that concrete behavior is highly affected by both pressure and strain rate. But, considering the complexity and short duration of these events, it is technically impossible to separate the contributions of each to the fracturing processes and strength increase [41]. In reality, under dynamic loading conditions both pressure and rate increase simultaneously. It has been acknowledged that the raise of compressive strength observed at high strain rate loading tests is largely due to inertia-induced confinement, especially above a critical strain rate value, $\dot{\varepsilon} > 10\ \mathrm{s}^{-1}$. Many experimental, theoretical and numerical studies (e.g. [42–49]) support these observations and make it clear that the experimentally observed dynamic compressive strength increase with rate is not a constitutive property. For example, based on split Hopkinson pressure bar (SHPB) tests of concrete specimens cast in steel rings, Forquin et al. [50] recently proved that the strain rate effect on the material compressive strength is relatively small when structural inertia effects are minimized. Thus, experimentally derived dynamic increase functions (DIFs), like the one proposed in the CEB/*fib* model code [51], does not describe the dynamic increase of strength for modeling at constitutive level.

Experimental evidences suggest that, above a critical strain rate ($10\ \mathrm{s}^{-1}$), the dynamic compressive strength growth is followed by an increase in fragmentation. The experimental results of SHPB tests of concrete reveal that fragmentation evolves from a few large pieces at $\dot{\varepsilon} \approx 30\ \mathrm{s}^{-1}$, with fracture taking place almost exclusively through the mortar, to diffuse cracking at $\dot{\varepsilon} \approx 300\ \mathrm{s}^{-1}$, characterized by small fragments with fracture crossing both mortar and aggregates (see for example Al-Salloum et al. [48] and Zhang and Zhao [41]). This increase of fragmentation is usually interpreted as a consequence of additional crack initiation with rate, which leads to an increase of effective fracture surface (damage) and the ability to absorb energy [39,52,53]. The increase of material strength observed in these experiments is mostly due to a raise of the inertia induced confinement. Only recently, in a series of triaxial and hydrostatic tests conducted at the university of Grenoble (France) [54–56], it was possible to evaluate the behavior of concrete at pressure levels similar to the ones observed in ballistic impact or after a blast, in controlled quasi-static conditions. It was shown that pressure alone is responsible for strength increase and the fragmentation process which leads to additional energy dissipation.

Fig. 2 schematically represents the different failure modes of concrete based on experimental observations of Gabet et al. [54] and Poinard et al. [56] of triaxial and hydrostatic quasi-static tests with confining pressures up to 650 MPa. These experimental results reveal that the failure mode/mechanism of concrete changes considerably with increasing pressure. This progressive alteration of the failure mode/mechanism is driven by the damage of the structure of the material while porosity decreases during compaction. At low confinement ($p < p_{el}$), the cement matrix is barely damaged and failure is characterized by a few localized cracks (zone *b* in Fig. 2). But, with increasing pressures, the cement matrix is progressively crushed (damaged), leading to a triaxial diffuse damage mode characterized by numerous small cracks (zone *c* in Fig. 2).

The hydrostatic tests in the same studies also help to explain the mechanisms behind the nonlinear volumetric behavior of concrete, and divide it in two stages. First, the strong volumetric deformation observed immediately after the elastic phase (zone c_i in Fig. 2(b)) is the result of the collapse of the pores associated with significant damage (crushed) of the cement matrix, which leads to a reduction of the compressive/tangent stiffness of the material. Then, due to compaction and an increase of density, the compressive stiffness, of the material, which now behaves like a granular material, raises again until consolidation is reached, to K_{solid} (zone c_{ii} in Fig. 2(b)). When confinement decreases and the stress state drifts away from the purely hydrostatic state, damage developed during compaction progressively manifests itself by a significant degradation of the elastic properties of the material and loss of tensile stiffness.

These results highlight the fact that it is not realistic to separate the