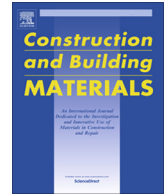




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Numerical study on the hard projectile perforation on RC panels with LDPM

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HIGHLIGHTS

- The rebar-concrete sliding interaction is applied to the RC perforation modeling.
- The projectile residual velocity is reduced when hitting the reinforced rebars.
- The reinforcement can limit the damage area and prevent the concrete shelter from structural failure.
- A simple but effective RC perforation analytical model is developed and validated.

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ABSTRACT

This paper numerically investigates the medium-caliber hard projectile perforation of steel rebar reinforced concrete panels by using the recently developed Lattice Discrete Particles Model (LDPM). With mesoscale constitutive laws governing cohesive fracture, strain hardening in compression and compaction due to pore collapse, LDPM naturally captures the failure mechanisms at the length scale of coarse aggregate of concrete. A constant area and shape partition method for circular cross-section is employed to determine the Gauss integration points distribution for beam elements. The sliding friction model for rebar-concrete interaction, in conjunction with LDPM for concrete are utilized for RC panel perforation modeling. Simulations of normal and high strength concrete panel perforation tests are carried out to validate the numerical model whereby agreement with the experimental data is achieved in terms of projectile residual velocity as well as damage contour. Extensive simulations are further performed to investigate the effect of projectile impact location and reinforcement on high strength concrete (HSC) panel perforation responses. Comparative numerical studies indicate that the projectile residual velocity is significantly reduced when the projectile hits the reinforced rebars. Furthermore, the reinforcement can considerably limit the damage area, crack openings and prevent the concrete shelter from structural failure. Finally, the LDPM simulations of HSC panel perforation are combined with cavity expansion analysis to achieve the RC perforation analytical model whereas the target resistance parameter R (Forrestal et al., 2003) is determined as 672 MPa while the shear plugging thickness value is estimated as 33 mm for the cases of interest.

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1. Introduction

As a common building material, concrete has been extensively applied to construct civilian infrastructures, such as dams, nuclear reactor containment, highway bridges, offshore platforms and civil defense etc. These concrete protective structures are designed to withstand the impact loadings of projectiles or explosive fragments. The structural performance, as well as the capability to resist the projectile impact loadings, make reinforced concrete

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(RC) a common engineering solution in the design of protective barriers [1]. Therefore, it is important to investigate the dynamic response of RC structures under impact loadings where large strain, high strain rate, fracture and crushing complex phenomena frequently exist. In the past decades, extensive perforation and penetration tests have been performed to explore the mechanism of the impact response on the RC targets [2–5]. Based on the experimental data, various empirical, semi-empirical and analytical formulae have been developed to analyze the perforation problems [3,6–8]. As computation becomes increasingly powerful, robust numerical simulation tools such as finite element method [9,10], discrete element method [11], material point method (MPM) [12,13] etc. are applied to model and analyze RC structure impact responses.

According to the RC penetration tests conducted by Hanchak [2] and Dancygier et al. [1], it was suggested that the light or moderate reinforcement has little effect on the ballistic performance or the penetration resistance. While Abdel et al. [5] concluded from the concrete impact tests that the reinforcement may affect the slab failure modes thus enhancing the barrier's performance. On the other hand, the comparative experimental studies performed by Rajput et al. [14] indicated that reinforced concrete targets, especially prestressed reinforced concrete targets, tend to have greater ballistic limit than plain concrete targets with same thickness.

Based on experimental data and some theoretical deductions, analytical approach could be an efficient and economical way to study the RC perforation problems. Li et al. [15] theoretically estimated the rear plugging thickness on the basis of the assumption that plug is separated from the concrete panel structure as soon as the shear failure criterion is satisfied along the conical plug surface. This approach is too complex and the estimated plugging thickness cannot be verified by vast experimental data. Based on successive concrete perforation experimental results, Li et al. [7] proposed the modified NDRC formula for rigid projectiles which has been widely used [16,17]. Considering energy balance, Grisaro et al. further developed a novel perforation analytical model whereas the energy dissipated in the fracturing of the ejected concrete blocks as well as the additional cracking of the concrete panel are taken into account [16]. Proposing the mean resistive pressure, Wen et al. presented an extension of the UMIST formulae to fit a wide range of hard projectile perforation of reinforced concrete targets [18].

Motivated by the high cost of impact tests and the ease of parameters effects evaluation, numerical modeling becomes increasingly popular in impact engineering research field. To model the interaction between the reinforced steel rebars and concrete, the rebars were modeled either as solid cylinders with contact surfaces [19] or a fictitious interface layer featured by a bond interaction between them [20,21]. These methods are not appealing for practical rebar concrete structure numerical analysis due to extremely large computational cost. Instead, three typical alternative techniques are usually adopted to describe the rebar-concrete interaction based on perfect bonding assumption [12], which are classified as discrete, embedded and smeared technique. By using discrete technique, rebars are modeled by truss or beam elements connected to the concrete mesh nodes [22–24]. By using embedded technique, concrete and rebars are discretized together without inter-facial elements in between [25,26]. While the smeared technique treated the RC material as a homogeneous material by considering the contribution from rebars to strength model [27] which sometimes is too rough to further study the reinforcement effects. Coupling Lagrangian meshes with Belytschko-Schwer beam elements, [22] took advantage of AUTODYN-3D hydrocode to examine the influence of constitutive model on the penetration and perforation of steel bar reinforced concrete targets. Lian et al. [12] proposed a hybrid finite element-material

point method to model the reinforced concrete slab response subjected to projectile impact with various striking velocities. Based on the TCK and HJC models, Liu et al. [9] developed a new damage model for concrete by incorporating the tensile and compressive damage. With joint nodes, the steel bar reinforced concrete was modeled to analyze the bar deformation due to the projectile impact.

Discrete element methods, in contrast to traditional mesh-based methods, do not rely on a structured mesh topology to compute the discrete numerical solution. Consequently, large deformation as well as crack initiation and propagation can be naturally captured without element deletion treatments. A comprehensive discrete model entitled Lattice Discrete Particle Model (LDPM) was recently developed by Cusatis et al. [28] to simulate the meso-structure of concrete like materials. Along with the confinement-shear lattice (CSL) model [29], it adopts constitutive laws analogous to those of the microplane model [30]. Later, LDPM was extensively calibrated and validated against large variety of simulations in both quasi-static and dynamic loading conditions [31–33]. Smith et al. [34,35] successfully applied LDPM to dynamic modeling of Hopkinson bar test, penetration analysis of high performance fiber reinforced concrete (HPFRC). Recently, Feng et al. [36–38] conducted LDPM impact simulations for plain concrete targets as well as HPFRC slab backed by armour steel plate where the numerically predicted penetration depth and projectile residual velocities match well with test data. Moreover, LDPM simulation of concrete panel perforation in Ref. [37] exhibits realistic target damage contour, i.e., crack distributions and crater dimensions where cratering on the impact surface and rear surface shear plugging phenomena are also reproduced. As a further study of LDPM application in dynamic regime, this work develops the RC model to numerically investigate the perforation responses of RC panels subjected to hard projectile impact.

In this present article, we briefly introduce the LDPM formulations and constitutive laws which are then utilized in the concrete perforation modeling. A constant area and shape scheme for circular cross-section partition is adopted herein and the corresponding Gauss integration points distribution is implemented and validated with cantilever beam bending. To model the reinforced concrete material, the rebar-concrete sliding interaction is calibrated with rebar pullout test data. By successfully predicting projectile residual velocities and post-test damage contours, the developed numerical model is validated against 10 shots RC panel perforations with striking velocity ranging from 400 m/s to 1000 m/s. Extensive simulations are then carried out to analyze the effects of projectile impact location, reinforcement on the perforation responses. Combining the cavity expansion analysis with the constant projectile velocity penetration simulation, we derive the analytical model for the NSC panel perforation.

2. Lattice Discrete Particle Model (LDPM)

Based on the CSL model and discrete method, Cusatis et al. [28] developed the theoretical framework of Lattice Discrete Particle Model, a mesoscale discrete model that simulates the mechanical interaction of coarse aggregate pieces embedded in a binding matrix. The geometrical representation of concrete meso-structure is constructed by randomly introducing and distributing spherical shaped coarse aggregate particles inside the volume of interest and zero-radius aggregate particles on its surface. With Delaunay tetrahedralization of the generated particle centers, a three-dimensional domain tessellation creates a system of polyhedral cells interacting through triangular facets and corresponding lattice system [28].

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