A numerical simulation on the perforation of reinforced concrete targets

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Abstract

The perforation of steel-bar-reinforced concrete target is studied numerically in this paper using LS-DYNA code and the modified Taylor–Chen–Kuszmaul continuum damage model. The crater diameters on both the front and back surfaces of the concrete target and the residual velocity of the projectile predicted by the numerical simulation are in good agreement with the experimental results reported by Hanchak et al. [Int J Impact Eng 1992; 12: 1–7]. The influence of the steel-bar-reinforcement on the perforation of concrete target is also studied numerically in the present paper.

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1. Introduction

The reinforced concrete (RC) is widely used as the fundamental building construction material for both civilian and military purposes. When a projectile penetrates a RC target, a larger crater on the back surface and a smaller crater on the front surface are generally observed. There exist at least two kinds of failure mechanisms, i.e., the scabbing on the back surface of the target due to tensile stress induced by the reflection of the compressive waves and the rupture due to the...
breaking and extrusion during the penetration process. The penetration process and the appearance of the crater are related to the target thickness, the shape of the projectile warhead as well as the impact velocity, as shown by Luk and Forrestal [1,2] and Hanchak et al. [3]. Therefore, the tensile rupture of the concrete should be taken into account in order to obtain a satisfactory result in a numerical simulation of the RC perforation.

A valid constitutive equation of the concrete is necessary for a reliable numerical simulation. Several constitutive models have been successfully applied for concrete, which include Johnson–Cook model [4] and Ottosen model where effects of both strain rate and high pressure were considered by Holmquist et al. [5]. Chen [6] further introduced a continuum damage model to study the dynamic process of concrete perforation numerically.

In the present paper, a continuum damage model, TCK model [7], is modified and implanted into LS-DYNA’s user-defined material model. The RC perforations conducted by Hanchak et al. [3] are simulated. The numerical simulation results agree well with experimental results.

2. Continuum damage accumulation model

The TCK material model is capable of predicting the brittle failure of concrete. Under the compressive loading of material, the concrete material is idealized as an elastic, perfectly plastic material. In order to take into account the effect of tensile failure on the compressive damage, TCK model is modified in the compressive loading regime.

TCK model is originally a brittle rock damage model, which was proposed by Taylor et al. [7] based on the Kipp and Grady [8] model and an equivalent bulk module considering cracks in damaged material [9]. The basic assumption of the damage model is that the rock is permeated by an array of randomly distributed cracks that grow and interact with one another under the tensile loading. An internal state variable was introduced in TCK model to represent the damage accumulation in the material, which is reflected in the degradation of the material stiffness and results in the strain softening behavior.

The TCK model in tensile domain adopted the elastic module of a cracked solid derived by Budiansky and O’Connell for a random array of penny-shaped cracks in an isotropic elastic medium, i.e.

\[
\frac{K}{\bar{K}} = 1 - \frac{16}{9} \left( \frac{1 - \tilde{\nu}^2}{1 - 2\tilde{\nu}} \right) C_d, \tag{1}
\]

where \(K\) and \(\nu\) are the original material bulk modulus and the Poisson’s ratio, \(\bar{K}\) and \(\bar{\nu}\) represent the degraded properties of the damage material. \(C_d\) is the crack density parameter, which is related to the original and damaged Poisson’s ratios:

\[
C_d = \frac{45}{16} \frac{(\nu - \bar{\nu})(2 - \bar{\nu})}{(1 - \bar{\nu}^3)[10\nu - \bar{\nu}(1 + 3\nu)]}. \tag{2}
\]

Kipp and Grady used the Weibull distribution theory to determine the number of flaws per unit volume \((N)\), which become active at a critical pressure level \(P\), i.e.

\[
N = k(P/3K)^m, \tag{3}
\]
where \( k \) and \( m \) denote the material constants, which are dependent on the relation of tensile fracture stress to strain rate.

The average crack dimension \( a \) can be estimated from the nominal fragment diameter for dynamic fragmentation in a brittle material derived by Grady based on the kinetic energy considerations, namely

\[
    a = \left( \frac{\sqrt{20} K_{IC}}{\rho C \dot{e}_{\text{r} \text{max}}} \right)^{2/3},
\]

where \( K_{IC} \), \( \rho \) and \( C \) denote, respectively, the fracture toughness, the mass density and the uniaxial wave speed \( (E/\rho)^{1/2} \), \( \dot{e}_{\text{r} \text{max}} \) is the volumetric strain rate experienced by the material at fracture.

The relationship between the crack density parameter \( C_d \) and characteristic crack size \( a \) is given by

\[
    C_d = N \cdot (\beta a^3),
\]

where \( \beta \) is an unknown constant.

Combining Eqs. (3)–(5) and defining \( k = k \cdot \beta \), the crack density expression becomes

\[
    C_d = \frac{5}{2 (3K)^m} \left( \frac{K_{IC}}{\rho C} \right)^2 \left( \frac{\dot{e}_{\text{r} \text{max}} - \dot{e}_{\text{r}}}{\dot{e}_{\text{r} \text{max}}} \right). \tag{6}
\]

Thus, Eqs. (2) and (6) denote two independent expressions for the crack-density parameter \( C_d \). Eq. (6) defines the evaluation of the crack density in terms of the pressure and strain rate history. Based on Eq. (6), Eq. (2) can be solved for the current degraded Poisson’s ratio \( \bar{\nu} \). These values and the crack density can then be used in Eq. (1) to determine the degraded bulk modulus.

According to Eq. (1), the single damage parameter \( D \), defined as the volume fraction of the damage voids, varies from zero when damage is zero to a maximum value of one when material has lost its load-carrying capability, which can be expressed by

\[
    D = \frac{16}{9} \left( 1 - \bar{\nu}^2 \right) C_d. \tag{7}
\]

For the volume tension of the material, crack-density parameter \( C_d \) can be deduced from Eqs. (3)–(6) at each time step of integration when \( D \) is given by Eq. (7).

### 3. Model modification

Though TCK model has been successfully applied to the dynamic tensile failures of the rock and concrete under blast loads, it cannot be used to predict the compression damage. For many brittle solids, pressure-dependent inelastic response takes place under compressive loads. Therefore, it is necessary to apply Mohr–Columb yield surface with the consideration of effects of strain rate and tensile failure, i.e.

\[
    Y = [C_1 (1 + C_2 \ln \dot{\varepsilon}_p) + C_3 P](1 - D), \tag{8}
\]

where \( \dot{\varepsilon}_p \) is the equivalent strain rate, \( P \) is the mean pressure, \( c_1-c_3 \) are material constants determined by the experimental data.
4. RC perforation calculations

The continuum damage accumulation model described in Section 3 can be implemented into LS-DYNA through user-defined material model and the vectorized numerical algorithms, which is then used to simulate RC perforation experiments in Hanchak et al. [3]. The bench-mark experimental results on the perforation of concrete targets in Hanchak et al. [3] have been used by other publications to verify their models, e.g., Li and Tong [10].

Figs. 1 and 2 show, respectively, the geometric configuration of the steel (T-250) projectile and the concrete target used in Hanchak et al. A three-dimensional finite-element (FE) model was generated with the pre-processor LS-INGRID version 3.5B. Due to the limitation of computer resources, only a quarter of the concrete slab model, as shown in Figs 3–5, are simulated where the target is a cuboid of $400 \times 400 \times 178$ (mm). In this case, we can define two symmetrical planes on the side face of concrete target. The cuboids target is meshed into eight-node solid elements (SOLID164) in LS-DYNA. The reinforcing steels are considered in the FE analyses in order to investigate the effects of the steel reinforcement, where the reinforcement bars are modeled as the solid cylinders in contact with the concrete surfaces and the static and dynamic friction coefficients are defined in LS-DYNA. The elements in the concrete slab near the perforation area are 2 mm cubes. In addition, it is also necessary to define the eroding contact surface between the reinforced concrete and the projectiles. Photographs to record the projectiles after perforation in similar experiments conducted in our laboratory shows that the projectiles were not fractured by the RC targets and the nose erosion was minor. Therefore, the Plastic/Kinematic material model, i.e. Type 3 material model in LS-DYNA, was used for the steel (T-250) projectiles, with material parameters given in Table 1. Relevant material parameters can be found in Ref. [6].

In the above Table 2, the material failures under compression and tension are defined by the effective plastic strain $f_s$ and the magnitude of the tensile damage parameter $f_d$, respectively, as shown in Eq. (7). When the effective plastic strain $f_s$ and the damage parameter $f_d$ in any concrete element reach critical value, the concrete element will be immediately deleted. In Hanchak’s experiments, the impact velocities were given; thus, the critical fracture and failure parameters were determined by calibrating them against the experimental data for a selected impact velocity. Then, the same fracture and failure parameters were used to simulate other impact tests. The corresponding critical tensile damage parameter and effective plastic strain obtained in our study are 0.5 and 3.0, respectively.

![Fig. 1. Projectile geometry.](image-url)
Fig. 2. Reinforced concrete target geometry.

Fig. 3. The concrete FE model of RC target.
The present simulations of the perforation process were conducted on the 1.8 GHz single CPU computer and it took about 48 h CPU time. The post-processing was conducted by LSTC/LSPOST ver.2.0. Figs. 6–9 demonstrate simulation results for perforation test with 743 m/s.

![Fig. 4. The steel rebar FE model of RC target.](image)

![Fig. 5. The FE-model for RC penetration calculations.](image)

<table>
<thead>
<tr>
<th>Items</th>
<th>Density (kg/m³)</th>
<th>Elastic module (GPa)</th>
<th>Possion’s ratio</th>
<th>Plastic failure strain</th>
<th>Yield stress (MPa)</th>
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<td>2.1</td>
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</tbody>
</table>

Table 1

Projectile and reinforcing steel bar material parameters

The present simulations of the perforation process were conducted on the 1.8 GHz single CPU computer and it took about 48 h CPU time. The post-processing was conducted by LSTC/LSPOST ver.2.0. Figs. 6–9 demonstrate simulation results for perforation test with 743 m/s.
striking velocity. Fig. 6 \((t = 180 \mu s)\) indicates the crash and crater on the impact surface caused by the reflecting tensile stress while Fig. 7 \((t = 280 \mu s)\) demonstrates the cracks beginning to appear on the exit surface. With the damage expansion, the spalling grows and expands continually until the projectile perforates the RC slab.
The craters range which is larger on the front side than on the backside and the central cylindrical region are characterized in the numerical simulation results (Fig. 9). Figs. 10 and 11 are the front and back sides in one of the experiments conducted by Hanchak et al. Comparing the simulation results with the experimental data, we can find that both the fracture diameters are 10–14 cm around the penetrator, which shows good agreement between simulation and experimental result. The residual velocity from simulation is 580 m/s, which is also in conformity with the experimental data, 544 m/s.
Fig. 10. Post-test photographs of impact surface for 140 Mpa

Fig. 11. Post-test photographs of exit surface for 140 MPa
If the spalling caused by the reflected tensile stress is not considered, only the plugging failure phenomena can be found during the RC perforation simulation. The simulation made to the brittle materials similar to concrete-like metals may soften the material for the impact, which was simulated (see Fig. 12) by Holmquist et al. with no account for the tensile fracture commendably. Zhang and Li [11] investigated the concrete spall fracture and found that Johnson–Cook model is not suitable to simulate concrete perforation (see Fig. 13). Cao [12] and Wu [13] investigated RC concrete penetration using LS-DYNA and the Concrete Damage Model (Type 72 in LS-DYNA).
with the ALE arithmetic and developed a method for studying projectile penetration into concrete (Fig. 14).

In the present numerical study, the projectiles strike the RC target according to the experimental arrangements in Hanchak et al. during which the projectiles are made not to strike the steel reinforcement and to impact on the target block at the center of a reinforcing steel grid.

Fig. 14. Numerical simulate results with ALE arithmetic & damage model.

Fig. 15. The model of projectile hitting one steel bar of three layers.
In order to examine the effects of the steel reinforcement on the perforation resistance of RC target, different impact arrangements were simulated, as shown in Figs. 15–18 and 20 below.

Finally, the concrete perforation is simulated without considering steel reinforcements, as shown in Figs. 19 and 20.

It shows that the steel bar and steel grid of the three steel layers are hit by projectile and the reinforcing steels experience the rupture. The surrounding steel bars may be distorted by the motion of projectile and the concrete. The resistant force on projectile may become asymmetric, which may change the ballistic trajectory of the projectile. However, the reinforced concrete and

![Fig. 16. The simulation results of projectile hitting one steel bar of three layers.](image1)

![Fig. 17. The model of projectile hitting steel bar infall of three layers.](image2)
Steel-free concrete have almost the same penetration/perforation resistance for the parameters (diameter of the projectile, warhead shape and impact velocity etc.) used in the present study. The main function of the reinforcement comes from the contact of the projectile and the reinforcing.
steel, which helps to increase the resistance of the reinforced concrete. It is the destruction degree of the reinforced concrete that helps to weaken and reduce the residual velocity of the projectile (see as Fig. 20) because of the felted function between the reinforcing steel bar and the concrete.

5. Conclusions

The present study demonstrates that the modified TCK model is capable of simulating the dynamic fracture for brittle solids, such as rock and concrete.

The damage model is successfully implemented in LS-DYNA to simulate the crater formation, spall of concrete and the fracture during the perforation process of a RC target.

The model is also used successfully to simulate the dynamic behavior of RC target as well as the effect of the reinforcing steel on the perforation of RC target.

The reinforced steel is proved to give the reinforce function, especially when the projectile strikes the steel bar, which can improve the safety engineering resistibility.

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References


