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Kinetic Energy Required for Perforating Double Reinforced Concrete Targets: A Parametric Numerical Study Considering Impact Velocity and Penetrator Presented Area

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Abstract

The U.S. Army's interest in breaching double-reinforced concrete (DRC) walls has revealed a need to better understand the energy required to perforate DRC. In an effort to determine the minimum kinetic energy required for perforating a DRC target, a parametric numerical study was conducted at the U. S. Army Research Laboratory. As an initial step in the exploration of minimum kinetic energy required for perforating DRC targets, large scale, high-fidelity, three-dimensional numerical simulations were conducted using an Eulerian shock physics code and an empirical concrete constitutive model. The parametric study investigated right cylindrical steel rods with masses of 500-2000 g and length-to-diameter ratios (L/D) of 1-10 impacting with velocities ranging from 500-2000 m/s, and perforating rebar reinforced concrete targets at three different impact locations with impact orientations to target of either end-on or side-on. This paper describes the modeling methodology used to generate the data, and then uses this data to consider the kinetic energy of perforation of DRC for the described range of conditions. Finally, an empirical fit to the data is reported, which may be used to estimate the conditions necessary for perforation of a DRC target of given parameters.

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Keywords: numerical simulation; modeling; reinforced concrete; kinetic energy; perforation

Nomenclature

\[ v_0 \quad \text{initial velocity of projectile (m/s)} \]
\[ v_r \quad \text{residual velocity of projectile (m/s)} \]
\[ \rho_p \quad \text{projectile density (kg/m}^3) \]
\[ \rho_T \quad \text{target density (kg/m}^3) \]
\[ C_T \quad \text{speed of sound in target (km/s)} \]
\[ A \quad \text{empirical parameter (m/s)} \]
\[ B \quad \text{empirical parameter} \]
\[ d \quad \text{projectile diameter (m)} \]
\[ l \quad \text{projectile length (m)} \]
\[ m \quad \text{projectile mass (kg)} \]

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1. Introduction

The U. S. Army’s interest in breaching double-reinforced concrete (DRC) walls has revealed a need to better understand the energy required to perforate DRC. Considerable prior research in concrete penetration and perforation has been conducted. Experimental investigations of concrete penetration typically take the form of either penetration into concrete, in which depth of penetration is reported, e.g., Luk et al. [1] and Gomez and Shukla [2], or perforation of concrete, in which residual velocity is reported, e.g., Hanchak et al. [3], Cargile et al. [4], and more recently, Jinzhu et al. [5]. Empirical and semi-analytical models for predicting depth of penetration into concrete by ogive and truncated ogive-nosed projectiles have been proposed, e.g., Forrestal et al. [6], Lixin et al. [7], and Teland and Sjøl [8], and semi-empirical models for predicting residual velocity for ogive and truncated ogive-nosed projectiles after perforation of concrete have been proposed, e.g., Wu et al. [9]. Numerical studies investigating rigid penetration, e.g., Liu et al. [10], and perforation, e.g., Huang et al. [11] of concrete have been conducted with penetration at normal and oblique angles and using Lagrangian and Arbitrary Lagrangian-Eulerian frames as well as numerical studies investigating eroding penetration of concrete, e.g., Nia et al. [12]. Analytical studies of normal and oblique concrete perforation by rigid projectiles have also been conducted, e.g., Chen et al. [13, 14].

However despite decades of research on the penetration and perforation of concrete, breaching double reinforced concrete, removing both concrete and reinforcement remains a difficult problem. Understanding the energy required to perforate concrete and reinforcement will enlighten development of tools for breaching DRC. Recently Latif et al. examined the minimum kinetic energy for penetration of concrete by a rigid penetrator [15, 16, 17]. The work by Latif et al. followed directly from that by Li et al. [18] who developed an empirical formula that ostensibly predicts the minimum kinetic energy required for a projectile of a given diameter to perforate concrete of a given thickness and unconfined compressive strength. Li et al. [18] validate their formulae with data by Bainbridge [19]. Comparing the Li et al. [18] formula for the “critical impact energy for the occurrence of perforation” of thick targets (defined in Li et al. as a target whose thickness is 3.8 to 18 times the diameter of the projectile) with perforation data by Hanchak et al. [3] and Cargile et al. [4], the Li et al. [18] equation appears to predict the experimental results near the ballistic limit quite well for ogive-nosed projectiles. However, the Li et al. [18] semi-empirical formula for determining the minimum kinetic energy required for perforation of a thick concrete target apparently is applicable for ogive-nosed projectiles, assumes the concrete targets are non-reinforced, and is not predictive of residual velocity, only limit velocity. The Li et al. [18] formulae also do not consider what effect projectile impact orientation or presented area has on perforation. Latif et al. [16, 17] attempt to expand the Li et al. [18] formulae for penetration into concrete to account for different nose shapes, but Latif et al. [16, 17] focus on depth of penetration rather than concrete perforation.

The present work considers a flat-nosed projectile perforating a thick reinforced concrete target. To better understand the kinetic energy required for a blunt-nosed projectile to perforate a reinforced concrete target a parametric numerical study was conducted. Parameters considered in the study include the projectile initial velocity, mass, length-to-diameter ratio, and impact orientation. The area each projectile presented to the target scaled the initial kinetic energy of each projectile configuration and these data were compared with the projectile residual velocity. The data was then fit to determine an empirical expression that may be used to estimate whether a given projectile design will perforate reinforced concrete at a given impact velocity.

2. Modeling Approach

An approach described by the author in prior related works [20–22] was used in the present work to model and simulate reinforced concrete penetration and perforation. Large scale, three-dimensional numerical simulations were conducted on Department of Defense Supercomputing Resource Center High Performance Computing systems using CTH, an Eulerian shock physics code [23]. The CTH simulations included adaptive mesh refinement, which allows the Eulerian cubic mesh size to be refined in regions of interest and un-refined away from those regions, which improves computational efficiency for fine meshes. In the subject simulations, mesh cubes were refined to as small as 0.048 cm on a side (given by dividing ten cells across the computational domain by 2). Mesh sensitivity studies were not conducted in the present work, but prior experience suggests this level of adaptive mesh refinement (that is, 2) provides accurate results for the modeling approach as described for geological material penetration simulations (cf. [20–22]). All simulations were fully 3D, and the 8-inch

| $h$ | target thickness (m) |
| $L/D$ | length-to-diameter ratio of projectile |
A (20.32 cm) thick concrete target was assigned semi-infinite boundary conditions. Table 1 contains some elastic properties for the materials used in the subject simulations.

### Table 1. Sample elastic material parameters used in the numerical calculations. Concrete data provided by the U.S. Army Corps of Engineers, Engineer Research and Development Center, Geotechnical and Structures Laboratory [25, 26].

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile Yield Strength MPa (ksi)</th>
<th>Unconfined Compressive Strength MPa (ksi)</th>
<th>Poisson’s Ratio</th>
<th>Density (kg/m³)</th>
<th>Sound Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projectile Steel (4340)</td>
<td>1551 (225)</td>
<td></td>
<td>0.283</td>
<td>7,842</td>
<td>4,529</td>
</tr>
<tr>
<td>Rebar Steel (A615)</td>
<td>924 (134)</td>
<td></td>
<td>0.28</td>
<td>785</td>
<td>4,600</td>
</tr>
<tr>
<td>Concrete (SAM-35)</td>
<td>33.6 (4.873)</td>
<td></td>
<td>0.24</td>
<td>2,092</td>
<td>3,512</td>
</tr>
<tr>
<td>Concrete (RTC)</td>
<td>36.9 (5.352)</td>
<td></td>
<td>0.245</td>
<td>2,242</td>
<td>3,730</td>
</tr>
</tbody>
</table>

The dynamic compressive material behavior of concrete was simulated using the Holmquist-Johnson-Cook (HJC) concrete constitutive model [24]. The HJC constitutive model includes pressure- and strain-rate-dependent strength, and incorporates a progressive damage model to degrade strength. The HJC model also uses a linked equation of state to compute pressure from volumetric compression. See also prior related work by the author for additional discussion on the HJC model [20, 21]. Concrete material parameters were derived from mechanical characterization data for SAM-35 concrete [25] and for RTC concrete [26] provided by the U.S. Army Corps of Engineers, Engineer Research and Development Center, Geotechnical and Structures Laboratory. These materials were selected for the subject study as they are typical of concretes used in U.S. Army Research Laboratory testing.

Rebar reinforcement was placed in accordance with specification [27]. Rebar material was A615 steel and pressure response was modeled using the Mie-Grüneisen equation of state [28, 29] with CTH library parameters for alpha iron. The rebar steel strength behavior was modeled with the Johnson-Cook constitutive and damage model for metals [30] with user-defined material parameters found by fitting stress-strain data [31]. Likewise, the penetrator material, 4340 steel [32, 33], was modeled with user-defined material parameters for the Mie-Grüneisen equation of state and the Johnson-Cook constitutive and damage model.

### 3. Numerical Simulations

The subject parametric study investigated right circular cylindrical steel rods impacting rebar reinforced concrete at three different locations: between rebar (no interaction with rebar), through a single rebar, and through two crossed (tied) rebar, shown in the left, center, and right images respectively provided in Figure 1. It was quickly found that there was only a slight difference in residual velocity between the single rebar impacts and the crossed (two) rebar impacts, so the permutations of impact site were reduced to the center impact in which there was no interaction with rebar and the crossed rebar impact. Cylindrical rods impacted DRC walls with orientations to target of either end-on (that is, in typical long-rod fashion) or side-on (that is, rotated 90° from typical long-rod fashion). Rods with masses of 500–2000 g and length-to-diameter ratios (L/D) of 1–10 were simulated impacting DRC targets with velocities ranging 500–1500 m/s. The presented area of the penetrators varied 3–120 cm² according to the penetrator L/D and impact orientation. The permutations of these parameters examined in the subject work are provided in Table 2. From the data given in Table 2, the initial energy of a given projectile may be computed from the well-known equation for kinetic energy, \( \frac{1}{2}mv^2 \). The presented area of the projectiles provided in Table 2 is calculated from the projectile’s length, diameter, and impact orientation given in Table 2.
Comparing the initial energy divided by the presented area of a projectile with the residual velocity of the projectile provides a means of evaluating a projectile’s effectiveness at perforating a reinforced concrete target.

As mentioned earlier, the modeling approach has been validated in prior work [20, 21]. Most similar numerical work uses the Hanchak et al. [3] residual velocity data for validation (cf. [10−13]). This approach is approximately acceptable for initial validation, but is not necessarily predictive as there is wide variation in the unconfined compressive strength of

![3D CTH models with 3 impact conditions, no rebar interaction (left image), single rebar interaction (centre image), and crossed interaction (right image). The target is modelled with semi-infinite boundary conditions on all four sides and is 20.3-cm (8-inches) thick. The right circular cylindrical projectile shown is 16-cm long by 3.184-cm in diameter, 1000-g with L/D=5. Rebar placement is standard as described in ITOP 5-2-503 [27].](image)

Table 2. Permutations of parameters examined. All are steel projectile impacting SAM-35 concrete target except last line (with asterisk), which is steel projectile impacting RTC concrete.

<table>
<thead>
<tr>
<th>Mass (g)</th>
<th>Impact Position</th>
<th>L/D</th>
<th>Length (cm)</th>
<th>Diameter (cm)</th>
<th>Presented Area (cm²)</th>
<th>Impact Location</th>
<th>Impact Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>End</td>
<td>0.88</td>
<td>5</td>
<td>5.696</td>
<td>25.48</td>
<td>0 Rebar</td>
<td>500 800 1000 1200 1500</td>
</tr>
<tr>
<td>1000</td>
<td>End</td>
<td>0.88</td>
<td>5</td>
<td>5.696</td>
<td>25.48</td>
<td>2 Rebar</td>
<td>500 800 1000 1200 1500</td>
</tr>
<tr>
<td>1000</td>
<td>End</td>
<td>2.48</td>
<td>10</td>
<td>4.027</td>
<td>12.74</td>
<td>0 Rebar</td>
<td>500 800 1000 1200 1500</td>
</tr>
<tr>
<td>1000</td>
<td>End</td>
<td>2.48</td>
<td>10</td>
<td>4.027</td>
<td>12.74</td>
<td>1 Rebar</td>
<td>500 800 1000 1200 1500</td>
</tr>
<tr>
<td>1000</td>
<td>End</td>
<td>2.48</td>
<td>10</td>
<td>4.027</td>
<td>12.74</td>
<td>2 Rebar</td>
<td>500 800 1000 1200 1500</td>
</tr>
<tr>
<td>1000</td>
<td>End</td>
<td>5.03</td>
<td>16</td>
<td>3.184</td>
<td>7.96</td>
<td>0 Rebar</td>
<td>500 800 1000 1200 1500</td>
</tr>
<tr>
<td>1000</td>
<td>End</td>
<td>5.03</td>
<td>16</td>
<td>3.184</td>
<td>7.96</td>
<td>2 Rebar</td>
<td>500 800 1000 1200 1500</td>
</tr>
<tr>
<td>1000</td>
<td>End</td>
<td>9.81</td>
<td>25</td>
<td>2.547</td>
<td>5.10</td>
<td>0 Rebar</td>
<td>500 800 1000 1200 1500</td>
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<tr>
<td>1000</td>
<td>End</td>
<td>9.81</td>
<td>25</td>
<td>2.547</td>
<td>5.10</td>
<td>2 Rebar</td>
<td>500 800 1000 1200 1500</td>
</tr>
<tr>
<td>1000</td>
<td>Side</td>
<td>5.03</td>
<td>16</td>
<td>3.184</td>
<td>7.96</td>
<td>0 Rebar</td>
<td>500 800 1000 1200 1500</td>
</tr>
<tr>
<td>1000</td>
<td>Side</td>
<td>5.03</td>
<td>16</td>
<td>3.184</td>
<td>7.96</td>
<td>1 Rebar</td>
<td>500 800 1000 1200 1500</td>
</tr>
<tr>
<td>1000</td>
<td>Side</td>
<td>5.03</td>
<td>16</td>
<td>3.184</td>
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<td>2 Rebar</td>
<td>500 800 1000 1200 1500</td>
</tr>
<tr>
<td>1000</td>
<td>Side</td>
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<td>25</td>
<td>2.547</td>
<td>5.10</td>
<td>0 Rebar</td>
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<tr>
<td>1000</td>
<td>Side</td>
<td>9.81</td>
<td>25</td>
<td>2.547</td>
<td>5.10</td>
<td>2 Rebar</td>
<td>500 800 1000 1200 1500</td>
</tr>
</tbody>
</table>
concret es, as demonstrated by Hanchak et al. [3] by testing 48 MPa (7 ksi) and 140 MPa (20 ksi) strength concrete, and the validation is therefore only truly appropriate for the particular con cretes tested by Hanchak et al. [3]. The Hanchak et al. [3], similar experimental data (cf. Cargile et al. [4], Jinzhu et al. [5]), and, to this author’s knowledge, all open literature concrete perforation data is for ogive-nosed and truncated ogive-nosed projectiles. Prior related work by this author [20–22] has suggested that it is necessary to characterize the material of interest, parameterize an appropriate constitutive model with this characterization data, and validate the constitutive model parameters with penetration and perforation experimental data all prior to considering a model predictive for the set of conditions for which the model was validated. Of course, such an approach is often unfeasible. As the present work is an attempt to provide insight into the energy of perforation of generalized concrete by a generalized projectile, this highly specific model validation is obviously not possible. Although the subject work makes use of mechanical characterization and experimental test data for concretes tested by the U.S. Army, these concretes are a small set of possible concretes tested elsewhere. Therefore, the subject work would benefit from addition of as much experimental data and as many validated constitutive material models and parameter sets as possible, but this is a goal for future work since such a goal is extensive, requires considerable effort and resources, and is therefore impractical in the context of the present study. So the reader should view the subject work as an early exploration of the topic that will perhaps provide insight rather than a final and conclusive model of reinforced concrete perforation. Therefore also, future work should include running a similar series of simulations using different constitutive models and different materials, validated if possible, to explore if there is any effect due to these variables or if the behavior is the same for perforation of any reinforced concrete.

### 4. Results and Discussion

As described earlier, comparing the initial energy divided by the presented area of a projectile with the residual velocity of the projectile provides a means of evaluating a projectile’s effectiveness at perforating a reinforced concrete target. These results from the parametric numerical simulations are presented in Figure 2. Examination of this chart suggests a trend in the data. The data are closely grouped for smaller residual velocities, perhaps related to the ballistic limit velocity of the target-penetrator system, but the scatter of the data increases among larger residual velocities.

If we make the assumption that penetration is a function of the target-penetrator material system, and plot all of the data on a single chart, as we have done in Figure 2, and if we normalize the penetrator energy per unit area by the target resistance to penetration, which is defined as the target density, \( \rho_T \), times the target sound speed, \( C_T \), squared times the target thickness, \( h \), then we can fit a curve to the data and extract two empirical parameters. We will assume here that these two parameters apply to all target-penetrator material systems, which may not be a bad assumption considering that the data from the RTC concrete target simulations fit with the majority of the data but with residual velocity shifted slightly depending on the previously defined penetration resistance of the material. Note that we are using the same rebar material in all cases since it is assumed here that, in the Eulerian case, the rebar provides little resistance to penetration relative to the concrete since, in similar Eulerian simulations of the same target material and penetrator material but without rebar, the resulting residual velocity is only slightly different than simulations with rebar.

Equation 1 provides a fit (\( R^2 = 0.866 \)) to the data presented in Figure 2. Equation 1 includes two empirical parameters, \( A \) and \( B \), which were determined for the fit to the data in Figure 2. The parameters used to fit Equation 1 to the data in Figure 2 are provided in Table 3.
In Equation 1, projectile energy per presented area (numerator of Equation 1) is normalized by target resistance to penetration (denominator of Equation 1) defined earlier. The parameter $B$ incorporates a projectile shape factor, $1/4$ for cylindrical projectiles or $1/6$ for spherical projectiles. Equation 1 may be rewritten as Equation 2, which is equivalent. The projectile kinetic energy divided by the projectile presented area and normalized by the target resistance to penetration as defined earlier may be more clearly seen in Equation 2.

\begin{align}
\nu_r &= A \ln \left( \frac{B \rho_p d v_0^2}{\rho_T C_T^2 h} \right) \quad (1) \\
\nu_r &= A \ln \left( \frac{B m v_0^2}{2 d \rho_T C_T^2 h} \right) \quad (2)
\end{align}

Table 3. Empirical parameters, material parameters, and geometry for Equation 1 from the empirical fit in Figure 2. $A$ and $B$, are empirical parameters derived from the Equation 1 fit from data for SAM-35 concrete perforated by a 4340 steel projectile. $\rho_p$ is projectile density, $\rho_T$ is target density, $C_T$ is sound wave velocity in the target material (note that these target parameters are provided in Table 1), $d$ is projectile diameter, and $h$ is target thickness.
Note that this work examines blunt projectile impacts to reinforced concrete targets, but the preponderance of experimental data available examines ogive or similarly sharp projectile impacts to concrete and is typically concerned with depth of penetration into concrete. Thus, no experimental data is compared with the numerical data in the present work, but experimental validation is obviously an important subject for future exploration. Again, this work was intended as an initial exploration into the kinetic energy per presented area required to perforate reinforced concrete and thus to provide a means of estimating whether a given projectile design will perforate reinforced concrete at a given impact velocity.

5. Conclusions

Using numerical simulations, a parametric study was conducted to determine the energy per unit area required to perforate a double reinforced concrete target with a right circular cylindrical projectile. An empirical equation was fit to the data from the numerical simulations. This equation may potentially be used to design projectiles for perforating reinforced concrete.

Much work is still needed in this effort. Building on the Eulerian numerical methods used here, future work should include Lagrangian numerical methods for target perforation. Future work should include examination of the contribution of the rebar to the penetration resistance. Exploration of the empirical fit to the data should be conducted to determine any dependence of empirical parameters on the target-penetrator material system, and future work should include running a similar series of simulations using different constitutive models and different materials, validated if possible, and perhaps at other projectile orientations to explore if there is any effect due to these variables. Comparisons with experimental data found in the literature for ogive-nosed and truncated ogive-nosed projectiles are possible, but experimental data for right circular cylinder target perforation with residual velocity measurement are also needed to validate these results.

Acknowledgements

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References


<table>
<thead>
<tr>
<th>$A$ (m/s)</th>
<th>$B$</th>
<th>$\rho_P$ (kg/m$^3$)</th>
<th>$\rho_T$ (kg/m$^3$)</th>
<th>$C_T$ (m/s)</th>
<th>$d$ (m)</th>
<th>$h$ (m)</th>
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<tbody>
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<td>312.5</td>
<td>106.2</td>
<td>8,050</td>
<td>2,242</td>
<td>3,730</td>
<td>.02</td>
<td>0.20</td>
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</table>


[26] RTC concrete data provided by S.A. Akers, 2011, U.S. Army Corps of Engineers Engineer Research and Development Center, Geotechnical and Structures Laboratory, Vicksburg, MS.


