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# Local Damage of Plain and Reinforced Concrete Targets under Impact Load

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## ABSTRACT

In the present study, simplified models for calculating the penetration depth, scabbing, and perforation thicknesses for concrete targets have been proposed. These models consider the dynamic strain rate effect in the estimation of penetration parameters. The results of proposed model have been compared with the experimental data.

**Keywords:** Missile penetration, axisymmetric impact, projectiles, concrete targets, impact load, damage assessment

## NOMENCLATURE

| | |
|---|---|
| $m$ | Missile mass |
| $d$ | Missile diameter |
| $V$ | Impact velocity |
| $E$ | Modulus of elasticity |
| $f_t$ | Concrete tensile strength |
| $f_i(.)$ | Some unknown function ($i$ = 1, 2, 3, ...) |
| $x_t$ | Depth of penetration |
| $s$ | Scabbing thickness |
| $e$ | Perforation thickness |
| $C_i$ | Model parameters ($i$ = 1, 2, 3, ...) |
| $f'_{td}$ | Dynamic tensile strength of concrete |
| $\dot{\varepsilon}_d$ | Dynamic strain rate |
| $\dot{\varepsilon}_s$ | Static strain rate |

## 1. INTRODUCTION

Reinforce cement concrete (RCC) is the most widely used material in civil and strategic structures. The safety or destruction of these structures under missile impact depends on missile penetration, partial or full, into RCC members, such as slab or wall. Owing to this reason, estimation of penetration depth in concrete targets, reinforced or plain, has been the area of interest for many investigators world-wide. In the last four decades, a number of empirical, semi-empirical, analytical, and numerical models have been proposed for the prediction of damage in different types of targets[1-10]. However, a review of the past investigations reveals that the effect of dynamic strain rate in the estimation of penetration parameters is not reported widely. In the present study, simplified models for calculating the penetration depth, scabbing, and perforation thicknesses for concrete targets have been proposed. These models consider the dynamic strain rate effect in the estimation of damage. The results of the proposed models have been compared with the

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experimental data and in some cases, improvement from equations available in the literature is observed. Few parametric studies have also been included to obtain the results of field interest.

## 2. PROBLEM FORMULATION

### 2.1 Penetration Depth

Consider the impact of a hard, flat nose and cylindrical missile, which results in penetration. For the estimation of penetration depth $x_t$ in the RCC target, it has been assumed that the depth of penetration depends on the missile mass $m$, missile diameter $d$, impact velocity $V$, modulus of elasticity $E$, and concrete tensile strength $f_t$. It follows that some function $f_1$ exists so that[7]

$$\frac{x_t}{d} = f_1[I] \tag{1}$$

where $f_1$ is some unknown function and

$$I = \frac{mV^2}{f_t d^3} \tag{2}$$

The impact parameter $I$ is a measure of the damage potential of a missile; large values correspond to greater damage potential.

### 2.2 Scabbing & Perforation Thicknesses

In a similar way it can be shown that the scabbing thickness $s$, and perforation thickness $e$, may be given by

$$\frac{s}{d} = f_2[I] \tag{3}$$

and

$$\frac{e}{d} = f_3[I] \tag{4}$$

where $f_2$ and $f_3$ are some unknown functions that correspond to scabbing and perforation thicknesses. Two different approaches have been adopted in the present study for estimating the depth of penetration. In the first approach (model 1), depth of penetration has been related to the dynamic strain rate, and the dynamic strain rate is related to both the missile parameters and the density of target material. In the second approach (model 2), dynamic strain rate has been related to the time taken in penetration.

#### 2.2.1 *Model* 1

Considering the effect of dynamic strain rate $\dot{\varepsilon}_d$, the following model has been proposed for the penetration depth:

$$\frac{x_t}{d} = C_1 + C_2 I_{m1} \tag{5}$$

where $I_{m1}$ is the modified value of $I$ and $C_1$, $C_2$ are the model parameters. It is to be noted that in the estimation of $I_{m1}$, dynamic tensile strength of concrete, $f_{td}'$ has been considered instead of static tensile strength of concrete ($f_t$), thus one gets:

$$I_{m1} = \frac{mV^2}{f_{td}' \, d^3} \tag{6}$$

where

$$f_{td}' = \sqrt{f_c}\,exp(C_3 e^{C_4}) \tag{7}$$

in which $$e = \log_{10}\left(\frac{\dot{\varepsilon}_d}{\dot{\varepsilon}_s}\right) \tag{8}$$

The static strain rate $\dot{\varepsilon}_s$ remains the same as $10^{-7}$/s and the dynamic strain rate is:

$$\dot{\varepsilon}_d = C_5\left[\frac{mV^2}{\gamma . d^4}\right] \tag{9}$$

Having known the penetration depth $x_t/d$, one can easily find the scabbing and perforation thicknesses from the following relations:

$$\frac{s}{d} = C_6\left[\frac{x_t}{d}\right] + C_7 \tag{10}$$

$$\frac{e}{d} = C_8\left[\frac{x_t}{d}\right] + C_9 \qquad (11)$$

The model parameters $C_1$, $C_2$, $C_3$, $C_4$, $C_5$, $C_6$, $C_7$, $C_8$, and $C_9$ can be determined[7] by regressional analysis.

#### 2.2.2 *Model 2*

This model has been developed for predicting the penetration depth only. Scabbing and perforation thicknesseses are not considered in this model. This model is almost the same as model 1, with only change in the calculation of dynamic strain rate which is taken as a function of impact velocity ($V$) of missile, and penetration depth $x_t$, that is

$$\dot{\varepsilon}_d = f\left(\frac{V}{x_t}\right) \qquad (12)$$

By this concept, the equation changes to the following form:

$$\frac{x_t}{d} = C_1 + C_2 I_{m2} \qquad (13)$$

where $C_1$ and $C_2$ are the model parameters, and $I_{m2}$ is the modified form of $I$, which is given by

$$I_{m2} = \frac{mV^2}{f'_{td} d^3} \qquad (14)$$

in which $f'_{td}$ may be estimated by combining Eqn (12) with Eqns (7) and (8) as

$$f'_{td} = \sqrt{f_c}\, exp\left(C_3\left(log_{10}\left(\frac{V/x_t}{\dot{\varepsilon}_s}\right)\right)^{C_4}\right) \qquad (15)$$

The model parameters $C_1$, $C_2$, $C_3$, and $C_4$ can again be determined[7] by regressional analysis.

## 3. ESTIMATION OF MODEL PARAMETERS

### 3.1 Model 1

For model 1, parameters $C_1$ to $C_8$ have been determined by regression analysis using the test results of Sliter[10]. The model parameters are:

$C_1 = 0$, $C_2 = 49.577$ for $I_{mt} \le 0.01$

$C_1 = 0.364$, $C_2 = 13.150$ for $I_{m1} > 0.01$

$C_3 = 12.000$, $C_4 = 0.060$

$C_5 = 11.000$

$C_6 = 5.558$, $C_7 = 0$ for $\frac{x_t}{d} \le 0.50$

$C_6 = 1.491$, $C_7 = 2.034$ for $\frac{x_t}{d} > 0.50$

$C_8 = 3.535$, $C_9 = 0$ for $\frac{x_t}{d} \le 0.50$

$C_8 = 0.823$, $C_9 = 1.356$ for $\frac{x_t}{d} > 0.50$

### 3.2 Model 2

For model 2, parameters $C_1$ to $C_4$ have been determined again by regression analysis using the test results of Sliter[10]. The model parameters are:

$C_1 = 0.5014$, $C_2 = 2.0990$, $C_3 = 11.0000$, $C_4 = 0.0600$

## 4. RESULTS & DISCUSSION

Using the whole data sets given by Sliter, 12 groups have been formed in which all parameters except the velocity are the same. These groups are listed in Table 1.

Figures 1 and 2 show a comparison of estimated penetration depth ($x_t/d$) with experimental values. These figures show that the proposed simplified models (model 1 and model 2) predict penetration depth equally well as the other popular existing models (eg, NDRC, ACE, A&W, and BRL) predict.

The variation of penetration depth with striking velocity of missile has been shown in Figs 3-6 for

**Table 1. Groups of data to study the effect of variation of impact velocity**

| S.No | Missile parameters: Weight (kN) | Diameter (mm) | Velocity (m/s) | Target parameters: Thickness (mm) | Compressive strength of concrete (MPa) | Observed penetration depth (mm) | $x_f/d$ | Type of damage* |
|---|---|---|---|---|---|---|---|---|
| | | | | **Group 1** | | | | |
| 1 | 2.220 | 304.80 | 110.0300 | 400 | 40 | — | — | P |
| 2 | 2.220 | 304.80 | 89.9200 | 400 | 40 | 170.180 | 0.56 | S |
| 3 | 2.220 | 304.80 | 106.0700 | 400 | 40 | — | — | P |
| 4 | 2.220 | 304.80 | 96.9300 | 400 | 40 | 185.420 | 0.61 | S |
| | | | | **Group 2** | | | | |
| 1 | 1.880 | 304.80 | 122.8344 | 400 | 34 | — | — | P |
| 2 | 1.880 | 304.80 | 110.0328 | 400 | 34 | 238.760 | 0.78 | S |
| 3 | 1.870 | 304.80 | 93.8784 | 400 | 34 | 99.060 | 0.33 | S |
| | | | | **Group 3** | | | | |
| 1 | 2.220 | 304.80 | 117.0432 | 500 | 34 | 223.520 | 0.73 | S |
| 2 | 2.220 | 304.80 | 106.9848 | 500 | 34 | 149.860 | 0.49 | S |
| | | | | **Group 4** | | | | |
| 1 | 1.560 | 304.80 | 147.8280 | 500 | 34 | 175.260 | 0.58 | S |
| 2 | 1.560 | 304.80 | 76.8096 | 500 | 34 | 20.320 | 0.07 | S |
| | | | | **Group 5** | | | | |
| 1 | 1.880 | 304.80 | 143.8656 | 500 | 39 | — | — | P |
| 2 | 1.880 | 304.80 | 78.9432 | 500 | 39 | 30.480 | 0.10 | S |
| 3 | 1.880 | 304.80 | 119.7864 | 500 | 39 | 134.620 | 0.44 | S |
| | | | | **Group 6** | | | | |
| 1 | 1.560 | 304.80 | 172.8216 | 600 | 36 | 228.600 | 0.75 | S |
| 2 | 1.560 | 304.80 | 142.9512 | 600 | 36 | 78.740 | 0.26 | S |
| | | | | **Group 7** | | | | |
| 1 | 0.330 | 277.88 | 147.8280 | 210 | 38 | 149.860 | 0.54 | S |
| 2 | 0.330 | 277.88 | 101.8032 | 210 | 38 | 35.560 | 0.13 | S |
| | | | | **Group 8** | | | | |
| 1 | 0.056 | 76.20 | 30.7848 | 152 | 26 | 3.8100 | 0.05 | N |
| 2 | 0.056 | 76.20 | 55.7784 | 152 | 30 | 9.3980 | 0.12 | N |
| | | | | **Group 9** | | | | |
| 1 | 0.036 | 25.40 | 64.9224 | 152 | 41 | 40.640 | 1.60 | N |
| 2 | 0.036 | 25.40 | 67.0560 | 152 | 41 | 50.800 | 2.00 | N |
| | | | | **Group 10** | | | | |
| 1 | 0.011 | 45.00 | 165.8112 | 230 | 33 | 42.926 | 0.95 | N |
| 2 | 0.011 | 45.00 | 209.7024 | 230 | 33 | 54.864 | 1.22 | N |
| | | | | **Group 11** | | | | |
| 1 | 0.022 | 45.00 | 156.9720 | 230 | 40 | 70.866 | 1.58 | N |
| 2 | 0.022 | 45.00 | 202.9968 | 230 | 40 | 105.918 | 2.36 | N |
| 3 | 0.022 | 45.00 | 311.8104 | 230 | 40 | — | — | P |
| | | | | **Group 12** | | | | |
| 1 | 0.004 | 40.00 | 163.9824 | 400 | 40 | 30.988 | 0.78 | N |
| 2 | 0.004 | 40.00 | 291.0840 | 400 | 40 | 43.942 | 1.10 | N |

*P: Perforation; S: Scabbling; N: No scabbing

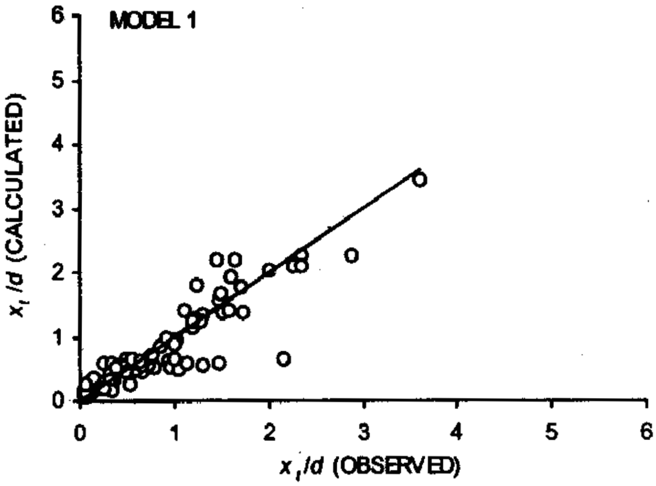


**Figure 1. Observed and predicted penetration depth (model 1).**

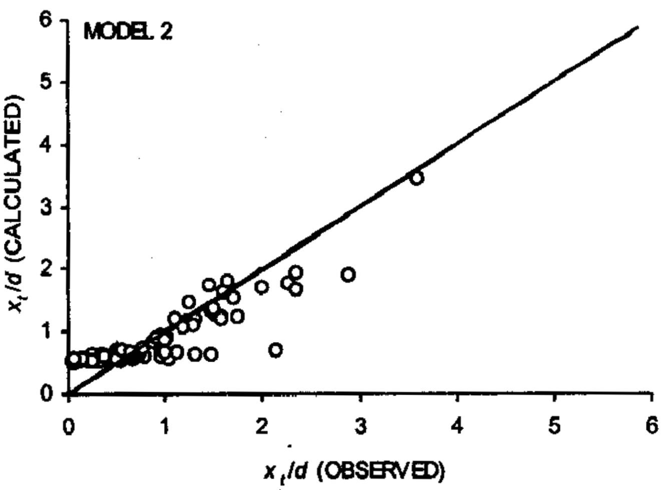


**Figure. 2 Observed and predicted penetration depth (model 2).**

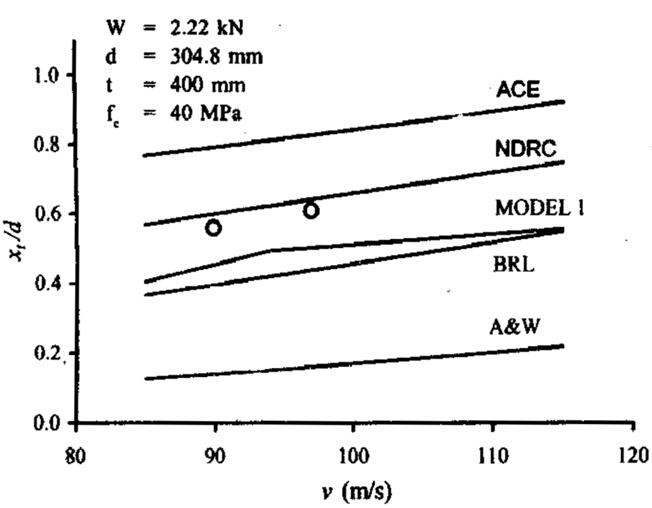


**Figure 3. Performance of penetration depth models for data group–1.**

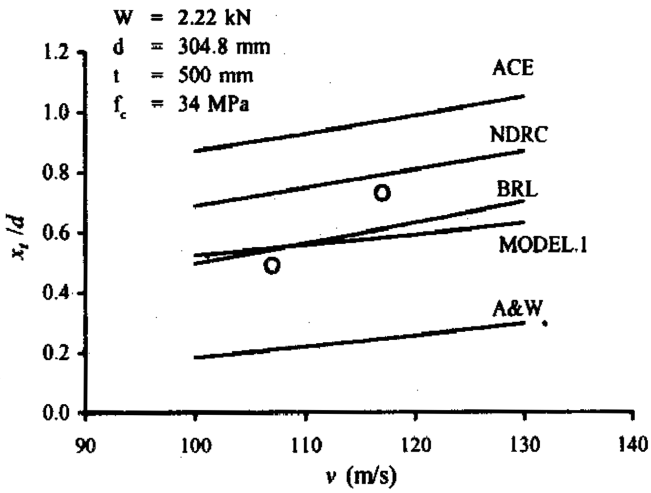


**Figure 4. Performance of penetration depth models for data group–3.**

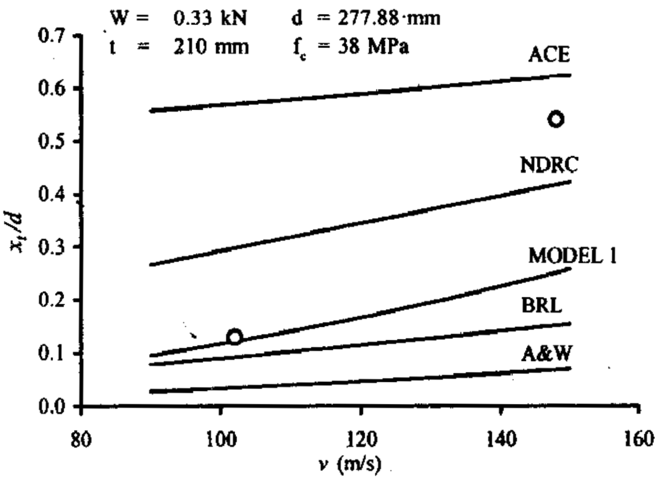


**Figure 5. Performance of penetration depth models for data group–7.**

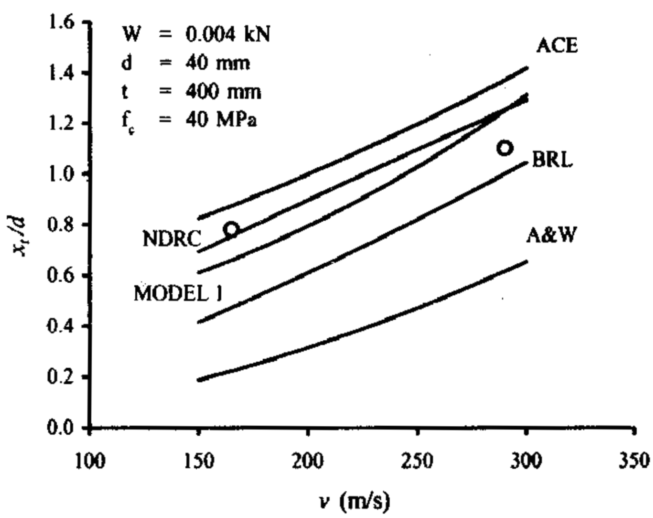


**Figure 6. Performance of penetration depth models for data group–12.**

various velocity ranges and values of other parameters. The increase in penetration depth with increase in velocity is observed in all the figures. It is also seen from these figures that the penetration depth from the prediction models of ACE and A & W are at the two extremes with A & W model being below the lower bound and ACE model at the upper bound. The proposed model 1 is almost between the NDRC and the BRL models and approximately a mean of the two extremes, thus making it the best model for the prediction of penetration depth. It is also seen from these figures that the predictions using existing models differ considerably from one another.

## 5. CONCLUSIONS

The two dimensionally homogeneous, semi-analytical models have been purposed to estimate the penetration depth in RCC targets of finite thickness impacted by hard missiles. The results obtained from the proposed models show a close proximity with the experimental values. The results also compare well with the existing models/equations, and for some range of impact velocity, the proposed models provide a better estimate than the existing models and equations.

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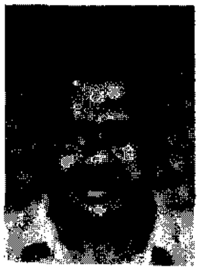

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