

Chapter 2

Projectile Impact Phenomena and Existing Studies

2.1 Local Response of Concrete Targets Under Projectile Impact

For the local response of the concrete target hit by a non-deformable projectile, three successive phenomenological responses are usually observed in test with the gradually increasing of the initial striking velocity V_0 of the projectile, as illustrated in Fig. 2.1.

- (i) *Penetration*, shown in Fig. 2.1a, a projectile penetrates into the concrete target with a certain distance, the so-called spalling takes place in the vicinity of the impacted location due to the extrusion of the projectile, while the distal face (opposite to the impacted face) of the target has not any minor cracks.
- (ii) *Scabbing*, shown in Fig. 2.1b, the projectile penetrates into the concrete target with a certain distance, and the scabbing of fragments occurs on the rear face of the target.
- (iii) *Perforation*, shown in Fig. 2.1c, the projectile passes through the target with certain residual velocity, and the fragments induced by shear plugging form simultaneously ahead of the projectile.

For the thick concrete target, the whole perforation process consists of the following three stages: impact cratering, tunneling, and rear shear plugging, such as shown in Fig. 2.2a. For the thin concrete target, as shown in Fig. 2.2b, the cratering process is followed directly by the rear shear plugging.

The mainly concerned terminal ballistic parameters during the projectile penetration and perforation processes are the depth of penetration h_{pen} (DOP, the normal depth of the projectile penetrates into the target), scabbing limit thickness h_{scab} (the minimum thickness of the target required to prevent the scabbing at the rear face for a given projectile striking velocity), perforation limit thickness h_{per} (the minimum thickness of the target required to prevent the perforation for a given projectile striking velocity), the ballistic limit velocity V_{BL} (the minimum initial impact

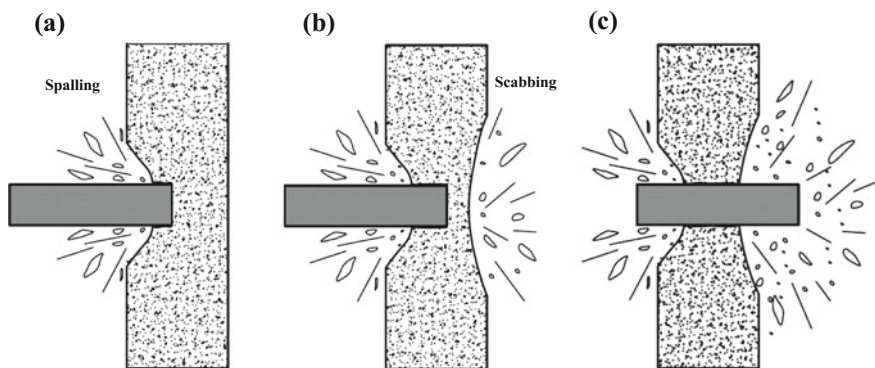


Fig. 2.1 Projectile impact on the concrete target **a** penetration **b** scabbing **c** perforation

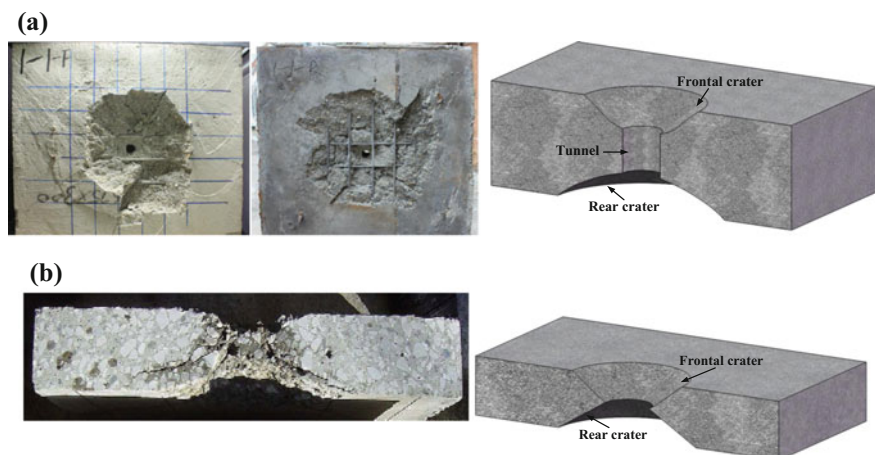


Fig. 2.2 Frontal and rear faces and axial section plane view of **a** thick concrete slab **b** thin concrete slab (Wu et al. 2015a; Beppu et al. 2008)

velocity of the projectile to perforate the target with the constant target thickness), and the residual velocity of the projectile V_r (the remaining exit velocity of the projectile after perforating a target).

In fact, the overall structural response of concrete targets has definite influence on the perforation process of projectiles, which can be referred to Li et al. (2007). However, this book mainly concerns with the local impact response of the concrete target under projectile impact.

Generally, based on the field prototype or laboratory reduce-scaled projectile shooting tests, the empirical (phenomenological), (semi-)analytical penetration/perforation models as well as numerical simulations are the three main approaches in the projectile impact investigations.

2.2 Empirical Models

The empirical models are usually obtained by the curve fitting of projectile shooting test data, thus the applications of the empirical models are dependent on the parametric ranges covered in tests. For concrete targets, Kennedy (1976), Li et al. (2005), and Ben-Dor et al. (2013) conducted detailed reviews and assessments on the existing empirical penetration and perforation models. For instance, Ben-Dor et al. (2013) assessed the validations of the empirical models by comparing the prediction results with the projectile penetration data of 94 shots and projectile perforation data of 102 shots.

In this section, several widely used empirical models which were proposed until the end of the year 2014 are listed in the SI form. Limited by the length of this book and to avoid the reduplication of the existing studies, the originations and modifications of the models are simplified, which can be found in Li et al. (2005), Ben-Dor et al. (2013), and Ranjan et al. (2014).

2.2.1 Modified Petry Formula (Petry 1910; Samuely 1939)

$$\frac{h_{\text{pen}}}{d} = k \frac{M}{d^3} \log_{10} \left(1 + \frac{V_0^2}{19,974} \right) \quad (2.1)$$

Originally, in Petry I formula, k is taken as 6.36×10^{-4} for massive plain concrete, 3.39×10^{-4} for normal reinforced concrete, and 2.26×10^{-4} for specially reinforced concrete. In the modified Petry II formula, $k = 0.0795k_p$ and Walter and Wolde-Tinsae (1984) proposed that

$$k_p = 6.34 \times 10^{-3} \exp(-0.2973 \times 10^{-7} f_c) \quad (2.2)$$

Amirikian (1950) further proposed that

$$\frac{h_{\text{per}}}{d} = 2 \frac{h_{\text{pen}}}{d} \quad (2.3)$$

$$\frac{h_{\text{scab}}}{d} = 2.2 \frac{h_{\text{pen}}}{d} \quad (2.4)$$

Amde et al. (1997) proposed that

$$V_r = V_0 \sqrt{1 - (0.5H/h_{\text{pen}})} \quad (2.5)$$

where H and f_c are the thickness and unconfined compressive strength of concrete targets, respectively. M and d represent the mass and diameter of the projectile, respectively.

2.2.2 Ballistic Research Laboratory (BRL) Formula (Beth 1941; Chelapati et al. 1972; Gwaltney 1968; Adeli and Amin 1985)

The modified BRL formula was proposed by Gwaltney (1968) and Adeli and Amin (1985) based on the original form proposed by Beth (1941) and Chelapati et al. (1972) as follows

$$\frac{h_{\text{pen}}}{d} = \frac{1.33 \times 10^{-3}}{\sqrt{f_c}} \left(\frac{M}{d^3} \right) d^{0.2} V_0^{1.33} \quad (2.6)$$

Chelapati et al. (1972) and Linderman et al. (1973) further proposed that

$$\frac{h_{\text{per}}}{d} = 1.3 \frac{h_{\text{pen}}}{d} \quad (2.7)$$

$$\frac{h_{\text{scab}}}{d} = 2 \frac{h_{\text{pen}}}{d} \quad (2.8)$$

2.2.3 Army Corps of Engineers (ACE) Formula (ACE 1946; Chelapati et al. 1972)

$$\frac{h_{\text{pen}}}{d} = \frac{3.5 \times 10^{-4}}{\sqrt{f_c}} \left(\frac{M}{d^3} \right) d^{0.215} V_0^{1.5} + 0.5 \quad (2.9)$$

$$\frac{h_{\text{per}}}{d} = 1.32 + 1.24 \frac{h_{\text{pen}}}{d} \quad \text{for} \quad 1.35 < \frac{h_{\text{pen}}}{d} < 13.5 \quad \text{or} \quad 3 < \frac{h_{\text{per}}}{d} < 18 \quad (2.10)$$

$$\frac{h_{\text{scab}}}{d} = 2.12 + 1.36 \frac{h_{\text{pen}}}{d} \quad \text{for} \quad 0.65 < \frac{h_{\text{pen}}}{d} \leq 11.75 \quad \text{or} \quad 3 < \frac{h_{\text{scab}}}{d} \leq 18 \quad (2.11)$$

The above Eqs. (2.10) and (2.11) are regressed from the impact tests of the large-caliber (37–155 mm) penetrators, while for the 0.5 caliber bullets, they have

$$\frac{h_{\text{per}}}{d} = 1.23 + 1.07 \frac{h_{\text{pen}}}{d} \quad (2.12)$$

$$\frac{h_{\text{scab}}}{d} = 2.28 + 1.13 \frac{h_{\text{pen}}}{d} \quad (2.13)$$

2.2.4 *Modified National Defense Research Committee (NDRC) Formula (NDRC 1946; Kennedy 1966)*

$$\begin{cases} \frac{h_{\text{pen}}}{d} = 2G^{0.5} & \text{for } G \leq 1 \\ \frac{h_{\text{pen}}}{d} = G + 1 & \text{for } G > 1 \end{cases} \quad (2.14)$$

in which

$$G = 3.8 \times 10^{-5} \frac{N^* M}{d \sqrt{f_c}} \left(\frac{V_0}{d} \right)^{1.8} \quad (2.15)$$

where N^* is the projectile nose geometry factor, which equals to 0.72, 0.84, 1.0, and 1.14 for flat, hemispherical, blunt, and very sharp projectile noses, respectively.

$$\begin{cases} \frac{h_{\text{per}}}{d} = 3.19 \left(\frac{h_{\text{pen}}}{d} \right) - 0.718 \left(\frac{h_{\text{pen}}}{d} \right)^2 & \text{for } \frac{h_{\text{pen}}}{d} \leq 1.35 \quad \text{or} \quad \frac{h_{\text{per}}}{d} \leq 3 \\ \frac{h_{\text{per}}}{d} = 1.32 + 1.24 \left(\frac{h_{\text{pen}}}{d} \right) & \text{for } 1.35 < \frac{h_{\text{pen}}}{d} < 13.5 \quad \text{or} \quad 3 < \frac{h_{\text{per}}}{d} < 18 \end{cases} \quad (2.16)$$

$$\begin{cases} \frac{h_{\text{scab}}}{d} = 7.91 \left(\frac{h_{\text{pen}}}{d} \right) - 5.06 \left(\frac{h_{\text{pen}}}{d} \right)^2 & \text{for } \frac{h_{\text{pen}}}{d} \leq 0.65 \quad \text{or} \quad \frac{h_{\text{scab}}}{d} \leq 3 \\ \frac{h_{\text{scab}}}{d} = 2.12 + 1.36 \left(\frac{h_{\text{pen}}}{d} \right) & \text{for } 0.65 < \frac{h_{\text{pen}}}{d} \leq 11.75 \quad \text{or} \quad 3 < \frac{h_{\text{scab}}}{d} \leq 18 \end{cases} \quad (2.17)$$

2.2.5 *Ammann and Whitney Formula (Kennedy 1976; Ben-Dor 2013)*

For the penetration of explosively generated high-speed fragments ($V_0 > 300$ m/s).

$$\frac{h_{\text{pen}}}{d} = \frac{6 \times 10^{-4}}{\sqrt{f_c}} N^* \left(\frac{M}{d^3} \right) d^{0.2} V_0^{1.8} \quad (2.18)$$

2.2.6 Whiffen Formula (Whiffen 1943)

Whiffen formula was suggested by British Road Research Laboratory as

$$\frac{h_{\text{pen}}}{d} = \left(\frac{2.61}{\sqrt{f_c}} \right) \left(\frac{M}{d^3} \right) \left(\frac{d}{d_{a,\text{max}}} \right)^{0.1} \left(\frac{V_0}{533.4} \right)^{\frac{97.51}{f_c^{0.25}}} \quad (2.19)$$

where $d_{a,\text{max}}$ is the maximum size of coarse aggregate in concrete. The application ranges are $V_0 < 1127.8 \text{ m/s}$, $5.52 \text{ MPa} < f_c < 68.95 \text{ MPa}$, $0.136 \text{ kg} < M < 9979.2 \text{ kg}$ and $12.7 \text{ mm} < d < 965.2 \text{ mm}$.

2.2.7 Kar Formula (Kar 1978)

Aiming to the nuclear power plant protection and considering the projectile materials and the coarse aggregate size of concrete targets, Kar proposed the following formula based on the NDRC formula

$$\begin{cases} \frac{h_{\text{pen}}}{d} = 2G^{0.5} & \text{for } G \leq 1 \\ \frac{h_{\text{pen}}}{d} = G + 1 & \text{for } G > 1 \end{cases} \quad (2.20)$$

in which

$$G = 3.8 \times 10^{-5} \left(\frac{E}{E_s} \right)^{1.25} \frac{N^* M}{d \sqrt{f_c}} \left(\frac{V_0}{d} \right)^{1.8} \quad (2.21)$$

$$\begin{cases} \frac{h_{\text{per}} - \bar{d}_a}{d} = 3.19 \left(\frac{h_{\text{pen}}}{d} \right) - 0.718 \left(\frac{h_{\text{pen}}}{d} \right)^2 & \text{for } \frac{h_{\text{pen}}}{d} \leq 1.35 \\ \frac{h_{\text{per}} - \bar{d}_a}{d} = 1.32 + 1.24 \left(\frac{h_{\text{pen}}}{d} \right) & \text{for } 1.35 < \frac{h_{\text{pen}}}{d} \leq 13.5 \end{cases} \quad (2.22)$$

$$\begin{cases} \left(\frac{h_{\text{scab}} - \bar{d}_a}{d} \right) \left(\frac{E_s}{E} \right)^{0.2} = 7.19 \left(\frac{h_{\text{pen}}}{d} \right) - 5.06 \left(\frac{h_{\text{pen}}}{d} \right)^2 & \text{for } \frac{h_{\text{pen}}}{d} \leq 0.65 \\ \left(\frac{h_{\text{scab}} - \bar{d}_a}{d} \right) \left(\frac{E_s}{E} \right)^{0.2} = 2.12 + 1.36 \left(\frac{h_{\text{pen}}}{d} \right) & \text{for } 0.65 < \frac{h_{\text{pen}}}{d} < 11.75 \end{cases} \quad (2.23)$$

where $\bar{d}_a$ denotes a half of the coarse aggregate size, E and E_s are Young's moduli of the projectile material and steel, respectively.

2.2.8 CEA-EDF Perforation Formula (Berriaud 1978)

Commissariat à l'Energie Atomique-Electricité de France (CEA-EDF) proposed that

$$\frac{h_{\text{per}}}{d} = 0.82 \frac{M^{0.5} V_0^{0.75}}{\rho_0^{0.125} f_c^{0.375} d^{1.5}} \quad (2.24)$$

$$V_{\text{BL}} = 1.3 \rho_0^{1/6} f_c^{0.5} \left(\frac{dH^2}{M} \right)^{2/3} \quad (2.25)$$

Furthermore, by considering the non-circular missile cross section and reinforced concrete targets, Fullard et al. (1991) proposed

$$V_{\text{BL}} = 1.3 \rho_0^{1/6} f_c^{0.5} \left(\frac{pH^2}{\pi M} \right)^{2/3} (r + 0.3)^{0.5} \quad (2.26)$$

where p is the perimeter of the projectile cross section and r represents the reinforcement ratio. The application ranges are $V_0 < 200$ m/s, $23 \text{ MPa} < f_c < 46 \text{ MPa}$, $20 \text{ kg} < M < 300 \text{ kg}$, $0.35 < H/d < 4.17$.

2.2.9 UK Atomic Energy Authority (UKAEA) Formula (Barr 1990)

$$\begin{cases} \frac{h_{\text{pen}}}{d} = 0.275 - (0.0756 - G)^{0.5} & \text{for } G \leq 0.0726 \\ \frac{h_{\text{pen}}}{d} = (4G - 0.242)^{0.5} & \text{for } 0.0726 \leq G \leq 1.0605 \\ \frac{h_{\text{pen}}}{d} = G + 0.9395 & \text{for } G \geq 1.0605 \end{cases} \quad (2.27)$$

where

$$G = 3.8 \times 10^{-5} \frac{N^* M}{d \sqrt{f_c}} \left(\frac{V_0}{d} \right)^{1.8} \quad (2.28)$$

The application ranges are $25 \text{ m/s} < V_0 < 300 \text{ m/s}$, $22 \text{ MPa} < f_c < 44 \text{ MPa}$, $5000 \text{ kg/m}^3 < M/d^3 < 200,000 \text{ kg/m}^3$.

$$\frac{h_{\text{scab}}}{d} = 5.3 G^{0.33} \quad (2.29)$$

The application ranges are $29 \text{ m/s} < V_0 < 238 \text{ m/s}$, $26 \text{ MPa} < f_c < 44 \text{ MPa}$, $3000 \text{ kg/m}^3 < M/d^3 < 222,200 \text{ kg/m}^3$.

$$\begin{cases} V_{BL} = V_a & \text{for } V_a \leq 70 \text{ m/s} \\ V_{BL} = V_a \left[1 + \left(\frac{V_a}{500} \right)^2 \right] & \text{for } V_a > 70 \text{ m/s} \end{cases} \quad (2.30)$$

in which

$$V_a = 1.3 \rho_0^{1/6} k_c^{1/2} \left(\frac{pH^2}{\pi M} \right)^{2/3} (r + 0.3)^{1/2} \left[1.2 - 0.6 \left(\frac{c_r}{H} \right) \right] \quad (2.31)$$

where c_r is the rebar spacing distance, r is reinforcement ratio % (each-way-each-face, EWEF), and $k_c = f_c$ for $f_c < 37$ MPa, and $k_c = 37$ MPa for $f_c \geq 37$ MPa. The application ranges are $11 \text{ m/s} < V_{BL} < 300 \text{ m/s}$, $22 \text{ MPa} < f_c < 52 \text{ MPa}$, $0.33 < H/(p/\pi) < 5$, $0 < r < 0.75\%$, $0.12 < c_r/H < 0.49$, $150 \text{ kg/m}^3 < M/(p^2 H) < 10^4 \text{ kg/m}^3$. When $c_r/H > 0.49$, Eq. (2.26) should be used instead.

2.2.10 Bechtel Formula (BPC 1974; Rotz 1976; Sliter 1980; Bangash 1993)

Bechtel Power Corporation (BPC 1974; Rotz 1976; Sliter 1980; Bangash 1993) proposed the scabbing limit for solid and hollow steel projectiles, respectively, as

$$\frac{h_{scab}}{d} = 38.98 \left(\frac{M^{0.4} V_0^{0.5}}{f_c^{0.5} d^{1.2}} \right) \quad (\text{solid projectile}) \quad (2.32)$$

$$\frac{h_{scab}}{d} = 13.63 \left(\frac{M^{0.4} V_0^{0.65}}{f_c^{0.5} d^{1.2}} \right) \quad (\text{hollow projectile}) \quad (2.33)$$

2.2.11 Stone and Webster Formula (Sliter 1980; Jankov et al. 1976)

$$\frac{h_{scab}}{d} = \left(\frac{M V_0^2}{(0.013H/d + 0.33)d^3} \right)^{1/3} \quad (2.34)$$

The application ranges are $1.9 \text{ kg} < M < 12.8 \text{ kg}$, $27 \text{ m/s} < V_0 < 157 \text{ m/s}$, $20.7 \text{ MPa} < f_c < 31 \text{ MPa}$, $11.4 \text{ cm} < H < 15.2 \text{ cm}$ and $1.5 < h_{scab}/d < 3$.

2.2.12 Degen Perforation Formula (Degen 1980)

$$\begin{cases} \frac{h_{\text{per}}}{d} = 2.2 \left(\frac{h_{\text{pen}}}{d} \right) - 0.3 \left(\frac{h_{\text{pen}}}{d} \right)^2 & \text{for } \frac{h_{\text{pen}}}{d} < 1.52 \quad \text{or} \quad \frac{h_{\text{per}}}{d} < 2.65 \\ \frac{h_{\text{per}}}{d} = 0.69 + 1.29 \left(\frac{h_{\text{pen}}}{d} \right) & \text{for } 1.52 \leq \frac{h_{\text{pen}}}{d} \leq 13.42 \quad \text{or} \quad 2.65 \leq \frac{h_{\text{per}}}{d} \leq 18 \end{cases} \quad (2.35)$$

where the penetration depth h_{pen} is determined by the modified NDRC formula (Eq. 2.14). The application ranges are $28.4 \text{ MPa} < f_c < 43.1 \text{ MPa}$, $25 \text{ m/s} < V_0 < 311.8 \text{ m/s}$, $0.15 \text{ m} < H < 0.61 \text{ m}$ and $0.1 \text{ m} < d < 0.31 \text{ m}$.

2.2.13 Chang Formula (Chang 1981)

For a flat ended projectile, Chang (1981) proposed the dimensionless formulae as

$$\frac{h_{\text{per}}}{d} = \left(\frac{61}{V_0} \right)^{0.25} \left(\frac{MV_0^2}{f_c d^3} \right)^{0.5} \quad (2.36)$$

$$\frac{h_{\text{scab}}}{d} = 1.84 \left(\frac{61}{V_0} \right)^{0.13} \left(\frac{MV_0^2}{f_c d^3} \right)^{0.4} \quad (2.37)$$

where the application ranges are $16 \text{ m/s} \leq V_0 \leq 311.8 \text{ m/s}$, $0.11 \text{ kg} \leq M \leq 342.9 \text{ kg}$, $50.8 \text{ mm} \leq d \leq 304.8 \text{ mm}$ and $22.8 \text{ MPa} \leq f_c \leq 45.5 \text{ MPa}$.

2.2.14 Haldar–Hamieh Formula (Haldar and Hamieh 1984)

Introducing the impact factor $I_a = MN^* V_0^2 / f_c d^3$, Haldar and Hamieh (1984) suggested that

$$\begin{cases} \frac{h_{\text{pen}}}{d} = -0.0308 + 0.2251 I_a & \text{for } 0.3 \leq I_a \leq 4.0 \\ \frac{h_{\text{pen}}}{d} = 0.6740 + 0.0567 I_a & \text{for } 4.0 < I_a \leq 21 \\ \frac{h_{\text{pen}}}{d} = 1.1875 + 0.0299 I_a & \text{for } 21 < I_a \leq 455 \end{cases} \quad (2.38)$$

2.2.15 Adeli–Amin Formula (Adeli and Amin 1985)

$$\begin{cases} \frac{h_{\text{pen}}}{d} = 0.0416 + 0.1698I_a - 0.0045I_a^2 & \text{for } 0.3 < I_a < 4.0 \\ \frac{h_{\text{pen}}}{d} = 0.0123 + 0.196I_a - 0.008I_a^2 + 0.0001I_a^3 & \text{for } 4.0 \leq I_a < 21 \end{cases} \quad (2.39)$$

$$\frac{h_{\text{per}}}{d} = 1.8685 + 0.4035I_a - 0.0114I_a^2 \quad \text{for } 0.3 < I_a < 21 \quad (2.40)$$

$$\frac{h_{\text{scab}}}{d} = 0.9060 + 0.3214I_a - 0.0106I_a^2 \quad \text{for } 0.3 < I_a < 21 \quad (2.41)$$

where the application ranges are $27 \text{ m/s} < V_0 < 312 \text{ m/s}$, $0.7 \leq H/d \leq 18$, $0.11 \text{ kg} \leq M \leq 342.9 \text{ kg}$, $d < 0.3 \text{ m}$ and $h_{\text{pen}}/d \leq 2$.

2.2.16 Hughes Formula (Hughes 1984)

Similar with Haldar–Hamieh formula, by introducing the impact factor $I_h = MV_0^2/f_id^3$, Hughes (1984) suggested that

$$\frac{h_{\text{pen}}}{d} = 0.19 \frac{N_h I_h}{S_h} \quad (2.42)$$

$$\begin{cases} \frac{h_{\text{per}}}{d} = 3.6 \frac{h_{\text{pen}}}{d} & \text{for } \frac{h_{\text{pen}}}{d} < 0.7 \\ \frac{h_{\text{per}}}{d} = 1.58 \frac{h_{\text{pen}}}{d} + 1.4 & \text{for } \frac{h_{\text{pen}}}{d} \geq 0.7 \end{cases} \quad (2.43)$$

$$\begin{cases} \frac{h_{\text{scab}}}{d} = 5.0 \frac{h_{\text{pen}}}{d} & \text{for } \frac{h_{\text{pen}}}{d} < 0.7 \\ \frac{h_{\text{scab}}}{d} = 1.74 \frac{h_{\text{pen}}}{d} + 2.3 & \text{for } \frac{h_{\text{pen}}}{d} \geq 0.7 \end{cases} \quad (2.44)$$

where N_h describes the projectile nose shape, and it equals to 1.0, 1.12, 1.26, and 1.39 for flat, blunt, spherical, and very sharp noses, respectively. The parameter $S_h = 1.0 + 12.3 \ln(1.0 + 0.03I_h)$ reflects the strain rate effect on concrete targets during high-speed penetrations. The application range is $I_h < 3500$.

2.2.17 Healey and Weissman Formula (Bangash 1989)

This formula is very similar to the modified NDRC and the Kar formulae and has the form as

$$\begin{cases} \frac{h_{\text{pen}}}{d} = 2G^{0.5} & \text{for } G \leq 1 \\ \frac{h_{\text{pen}}}{d} = G + 1 & \text{for } G > 1 \end{cases} \quad (2.45)$$

where

$$G = 4.36 \times 10^{-5} \left(\frac{E}{E_s} \right) \frac{N^* M}{d \sqrt{f_c}} \left(\frac{V_0}{d} \right)^{1.8} \quad (2.46)$$

2.2.18 IRS Formula (Bangash 1993)

$$h_{\text{pen}} = 3703.376 f_c^{-0.5} + 82.152 f_c^{-0.18} \exp(-0.104 f_c^{0.18}) \quad (2.47)$$

The minimum shield thickness for total protection of a target against penetration, perforation, and scabbing is

$$H_{\text{min}} = 3913.119 f_c^{-0.5} + 132.409 f_c^{-0.18} \exp(-0.104 f_c^{0.18}) \quad (2.48)$$

2.2.19 CRIEPI Formula (Kojima 1991)

The Central Research Institute of Electric Power Industry (CRIEPI) proposed

$$\frac{h_{\text{pen}}}{d} = \frac{0.0265 N^* M d^{0.2} V_0^2 \left(114 - 6.83 \times 10^{-4} f_c^{2/3} \right)}{f_c^{2/3}} \left[\frac{(d + 1.25 H_r) H_r}{(d + 1.25 H) H} \right] \quad (2.49)$$

$$\frac{h_{\text{per}}}{d} = 0.9 \left(\frac{61}{V_0} \right)^{0.25} \left(\frac{M V_0^2}{d^3 f_c} \right)^{0.5} \quad (2.50)$$

$$\frac{h_{\text{scab}}}{d} = 1.75 \left(\frac{61}{V_0} \right)^{0.13} \left(\frac{M V_0^2}{d^3 f_c} \right)^{0.4} \quad (2.51)$$

where $H_r = 0.2$ m is the reference thickness of the concrete slab.

2.2.20 TM 5-855-1 Formula (TM 5-855-1 1986)

For the standard explosive formed fragment, the depth of penetration is expressed as

$$h_{\text{pen}} = \begin{cases} \frac{0.027M^{0.37}V_0^{0.9}}{f_c^{0.25}} & \text{for } V_0 \leq V_0^* \\ \frac{0.004M^{0.4}V_0^{1.8}}{f_c^{0.5}} + 0.395M^{0.33} & \text{for } V_0 > V_0^* \end{cases} \quad (2.52)$$

and

$$h_{\text{per}} = 0.0311h_{\text{pen}}M^{0.033} + 2.95M^{0.33} \quad (2.53)$$

$$h_{\text{scab}} = 0.0334h_{\text{pen}}M^{0.033} + 4.465M^{0.33} \quad (2.54)$$

$$V_r = \begin{cases} V_0 \left[1 - (H/h_{\text{per}})^2 \right]^{0.555} & \text{for } V_0 \leq V_0^* \\ V_0 \left[1 - (H/h_{\text{per}}) \right]^{0.555} & \text{for } V_0 > V_0^* \end{cases} \quad (2.55)$$

where

$$V_0^* = 5.13f_c^{0.278}/M^{0.044} \quad (2.56)$$

2.2.21 UMIST Formula (Reid and Wen 2001; BNFL 2003; Li et al. 2005)

$$\frac{h_{\text{pen}}}{d} = \left(\frac{2}{\pi} \right) \frac{N^*MV_0^2}{0.72\sigma_t d^3} \quad (2.57)$$

$$\sigma_t(\text{MPa}) = 4.2f_c(\text{MPa}) + 135 + [0.014f_c(\text{MPa}) + 0.45]V_0(\text{m/s}) \quad (2.58)$$

where the application ranges are $50 \text{ mm} < d \leq 600 \text{ mm}$, $35 \text{ kg} \leq M \leq 2500 \text{ kg}$, $h_{\text{pen}}/d \leq 2.5$ and $3 \text{ m/s} < V_0 < 66.2 \text{ m/s}$.

Denoting the critical impact energies of a projectile causing through thickness cone cracking, scabbing, and perforation as E_{crack} , E_{scab} , and E_{per} , the following expressions are given

(i) $H/d < 5$

$$\begin{cases} \frac{E_{\text{crack}}}{\eta\sigma_t d^3} = -0.00031\left(\frac{H}{d}\right) + 0.00113\left(\frac{H}{d}\right)^2 & \text{for } 0 < \frac{H}{d} \leq 2 \\ \frac{E_{\text{crack}}}{\eta\sigma_t d^3} = -0.00325\left(\frac{H}{d}\right) + 0.00130\left(\frac{H}{d}\right)^3 & \text{for } 2 < \frac{H}{d} < 5 \end{cases} \quad (2.59)$$

$$\frac{E_{\text{scab}}}{\eta\sigma_t d^3} \frac{N^*}{0.72} = -0.005441\left(\frac{H}{d}\right) + 0.01386\left(\frac{H}{d}\right)^2 \quad (2.60)$$

$$\begin{cases} \frac{E_{\text{per}}}{\eta \sigma_t d^3} = -0.00506 \left(\frac{H}{d} \right) + 0.01506 \left(\frac{H}{d} \right)^2 & \text{for } 0 < \frac{H}{d} \leq 1 \\ \frac{E_{\text{per}}}{\eta \sigma_t d^3} = -0.01 \left(\frac{H}{d} \right) + 0.02 \left(\frac{H}{d} \right)^3 & \text{for } 1 \leq \frac{H}{d} < 5 \end{cases} \quad (2.61)$$

where

$$\eta = \begin{cases} 0.5 + \frac{3}{8} \left(\frac{d}{c_r} \right) r_t & \text{for } \frac{d}{c_r} < \sqrt{\frac{d}{d_r}} \\ 0.5 + \frac{3}{8} \sqrt{\frac{d}{d_r}} r_t & \text{for } \frac{d}{c_r} \geq \sqrt{\frac{d}{d_r}} \end{cases} \quad (2.62)$$

in which the total bending reinforcement ratio $r_t = 4r$ and $r = \pi d_r^2 / 4 H c_r$ is the reinforcement ratio in EWEF, c_r , and d_r represent the rebar spacing and rebar diameter, respectively.

(ii) $H/d \geq 5$

$$\frac{E_{\text{crack}}}{\sigma_t d^3} = \frac{\pi}{4} \left[\frac{H}{d} - 4.7 \right] \quad (2.63)$$

$$\frac{E_{\text{scab}}}{\sigma_t d^3} \frac{N^*}{0.72} = \frac{\pi}{4} \left[\frac{H}{d} - 4.3 \right] \quad (2.64)$$

$$\frac{E_{\text{per}}}{\sigma_t d^3} = \frac{\pi}{4} \left[\frac{H}{d} - 3.0 \right] \quad (2.65)$$

2.2.22 Wen Formula

Based on the UMIST formula, Wen and Yang (2014) and Wen and Xian (2015) proposed a unified approach for evaluating the terminal ballistic performance of projectiles as

$$\frac{h_{\text{pen}}}{d} = \left(\frac{2}{\pi} \right) \frac{M V_0^2}{\sigma d^3} \quad (2.66)$$

$$\sigma = \left(\alpha' + \beta' \sqrt{\frac{\rho_0}{Y} V_0} \right) Y \quad (2.67)$$

$$Y = \begin{cases} 1.4 f_c + 45 & \text{for } f_c \leq 75 \text{ MPa} \\ 150 & \text{for } 75 \text{ MPa} < f_c < 150 \text{ MPa} \\ f_c & \text{for } f_c \geq 150 \text{ MPa} \end{cases} \quad (2.68)$$

(i) For the thin target

$$\frac{E_{\text{crack}}}{\phi' \eta \sigma d^3} = 0.0003 \left(\frac{H}{d} \right) + 0.0003 \left(\frac{H}{d} \right)^4 \quad \text{for } 0 < \frac{H}{d} < 5 \quad (2.69)$$

$$\frac{E_{\text{scab}}}{\phi' \eta \sigma d^3} = -0.0066 \left(\frac{H}{d} \right) + 0.012 \left(\frac{H}{d} \right)^2 \quad \text{for } 0 < \frac{H}{d} < 5 \quad (2.70)$$

$$\begin{cases} \frac{E_{\text{per}}}{\phi' \eta \sigma d^3} = 0.0048 \left(\frac{H}{d} \right) + 0.0018 \left(\frac{H}{d} \right)^2 & \text{for } 0 < \frac{H}{d} \leq 1.3 \\ \frac{E_{\text{per}}}{\phi' \eta \sigma d^3} = -0.03 \left(\frac{H}{d} \right) + 0.022 \left(\frac{H}{d} \right)^3 & \text{for } 1.3 < \frac{H}{d} < 4 \end{cases} \quad (2.71)$$

(ii) For the thick target

$$\frac{E_{\text{crack}}}{\sigma d^3} = \frac{\pi}{4} \left(\frac{H}{d} - 4.7 \right) \quad \text{for } \frac{H}{d} \geq 5 \quad (2.72)$$

$$\frac{E_{\text{scab}}}{\sigma d^3} = \frac{\pi}{4} \left(\frac{H}{d} - 4.3 \right) \quad \text{for } \frac{H}{d} \geq 5 \quad (2.73)$$

$$\frac{E_{\text{per}}}{\sigma d^3} = \begin{cases} \frac{\pi}{4} \left(\frac{H}{d} - 3.0 \right) & \text{for } \frac{H}{d} \geq 4, \quad V_0 < 300 \text{ m/s} \\ \frac{\pi}{4} \left(\frac{H}{d} - 2.0 \right) & \text{for } \frac{H}{d} \geq 4, \quad V_0 \geq 300 \text{ m/s} \end{cases} \quad (2.74)$$

where α' , β' and ϕ' are projectile nose shape related parameters, and η is related with the projectile-nosed geometry and the arrangement of reinforcing steel mesh. The detailed expressions of the above parameters can be referred to Wen and Yang (2014) and Wen and Xian (2015).

2.2.23 Berezan Formula (Sagomonyan 1974)

Berezan formula was proposed as

$$\frac{h_{\text{pen}}}{d} = \lambda \frac{M}{10^3 d^3} V_0 \cos \alpha \quad (2.75)$$

where λ is the resistance coefficient which was given by Ben-Dor et al. (2013) for diversified targets, and α is angle between the normal to the target surface and the impact direction

2.3 Semi-analytical Models

2.3.1 Penetration

As illustrated in Sect. 2.1, the impact crater and the succeeding tunneling are formed for a rigid projectile penetrating into the semi-infinite concrete target, the schematic of which is shown in Fig. 2.3.

The resistance on a projectile during penetration process is commonly predicted by the dynamic spherical or cylindrical cavity expansion theory (introduced in Sect. 3.2). By using the onboard accelerometers, Forrestal et al. (2003a) measured the deceleration-time histories of a projectile during penetrating into a semi-infinite concrete target, shown in Fig. 2.4.

Figure 2.4 shows that the resistance acted on the projectile increased nearly linearly in the cratering stage and maintained almost flat or a little decaying in the tunneling stage until penetration stops. Forrestal et al. (1993, 1996) demonstrated that the resistance on the projectile is proportional to the penetration depth during the cratering stage, and the crater depth H_{cf} is also proportional to the diameter of the projectile shank, e.g., $H_{cf} = kd$.

Forrestal et al. (1993, 1996) and Frew et al. (1998, 2006) suggested that $k = 2$ based on the test data and further proposed the prediction formulae for the depth of penetration (DOP) as

$$\begin{aligned} h_{pen} &= \frac{(L + 0.5k'd)}{2N} \left(\frac{\rho_p}{\rho_0} \right) \ln \left[1 + \frac{N\rho_0 V_1^2}{Sf_c} \right] + 2d \\ &= \frac{2M}{\pi d^2 \rho_0 N} \ln \left[1 + \frac{N\rho_0 V_1^2}{Sf_c} \right] + 2d \end{aligned} \quad (2.76a)$$

$$k' = \left(4\psi^2 - \frac{4\psi}{3} + \frac{1}{3} \right) (4\psi - 1)^{0.5} - 4\psi^2 (2\psi - 1) \sin^{-1} \left[\frac{(4\psi - 1)^{0.5}}{2\psi} \right] \quad (2.76b)$$

Fig. 2.3 Axial sectional schematic of projectile penetrating into the concrete target

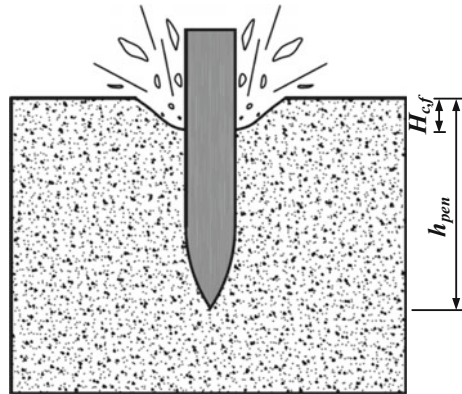
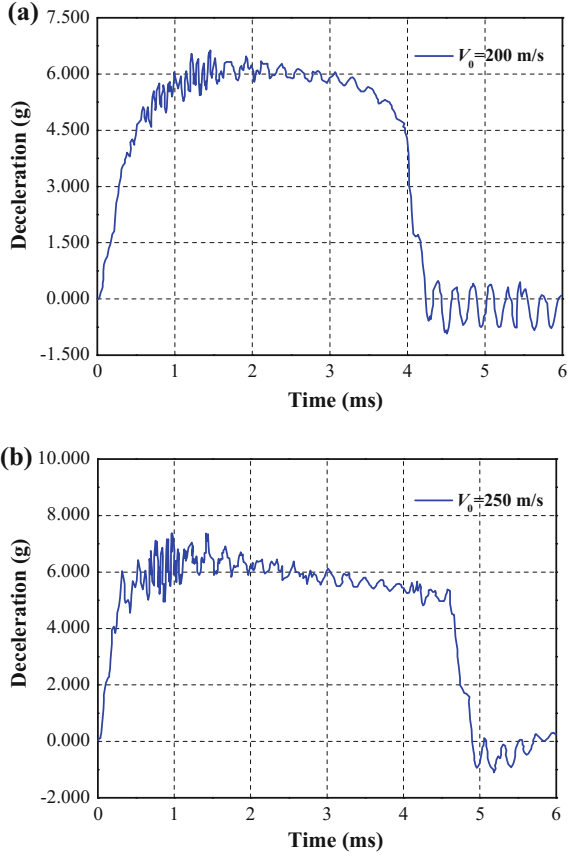


Fig. 2.4 Deceleration-time histories of projectile penetrating into the concrete target (Forrestal et al. 2003a)



$$N = \frac{8\psi - 1}{24\psi^2}; \quad V_1^2 = \frac{V_0^2 - \left(\frac{2d}{L + 0.5k'd}\right)\left(\frac{Sf_c}{\rho_p}\right)}{1 + N\left(\frac{2d}{L + 0.5k'd}\right)\left(\frac{\rho_0}{\rho_p}\right)}; \quad S = 82.6 \times (f_c \times 10^{-6})^{-0.544} \quad (2.76c)$$

where L is shank length of a projectile, $\psi = s/d$ and s are the caliber-radius-head (CRH) and circle radius of the ogival projectile nose, respectively.

In addition, by further considering the boundary influence of the target, Forrestal et al. (2003a) modified Eq. (2.76a, b, c) as

$$h_{\text{pen}} = \frac{2M}{\pi d^2 \rho_0 N} \ln \left[1 + \frac{N \rho_0 V_1^2}{R} \right] + 2d \quad h_{\text{pen}} > 2d \quad (2.77a)$$

$$N = \frac{8\psi - 1}{24\psi^2}; \quad V_1^2 = \frac{MV_0^2 - 0.5\pi d^3 R}{M + 0.5\pi d^3 N \rho_0} \quad (2.77b)$$

where V_1 is the velocity of the projectile at the transition from the cratering stage to the tunneling stage, and R is a concrete strength parameter similar to S in Eq. (2.76c), which can be regressed from the penetration test data according to the reverse expression of Eq. (2.77a).

$$R = \frac{N\rho_0 V_0^2}{\left(1 + \frac{0.5\pi d^3 N\rho_0}{M}\right) \exp\left[\frac{\pi d^2 (h_{\text{pen}} - 2d) N\rho_0}{2M}\right]} - 1 \quad (2.77c)$$

Equations (2.76a, b, c) and (2.77a, b, c) proposed by Forrestal et al. have been widely used. Nevertheless, Forrestal formulae are only applicable for ogive-nosed projectiles and the friction between the projectile and target during penetrations is neglected. Furthermore, the target strength parameter R in Eqs. (2.77a, b, c) must be confirmed by the projectile penetration tests, thus the prediction function of Eqs. (2.77a, b, c) is lost.

In addition, according to the two-stage (cratering + tunneling) penetration model, Chen and Li (2002), Li and Chen (2003), and Li et al. (2004) obtained the crater depth coefficient as $k = (0.707 + l_0/d)$ based on the slip-line field theory, in which l_0 is the projectile nose length. Introducing the dimensionless projectile-nosed geometry function N and impact factor I_0 , and neglecting the crater depth under the deep penetration, Eqs. (2.76a, b, c) was extended by Chen and Li (2002) and Li and Chen (2003) to the dimensionless form which can be applied for arbitrary-nosed projectiles.

$$\frac{h_{\text{pen}}}{d} = \frac{2}{\pi} N \ln\left(1 + \frac{I_0}{N}\right) \quad (2.78a)$$

$$I_0 = \frac{MV_0^2}{N_1 S f_c d^3}; \quad N = \frac{M}{N_2 \rho_0 d^3}; \quad S = 72.0 \times (f_c \times 10^{-6})^{-0.5} \quad (2.78b)$$

where N_1 and N_2 describe the influence of projectile nose geometry as well as the frictions between projectiles and targets. For an arbitrary-nosed projectile, N_1 and N_2 can be obtained by integrating the periphery function of projectile nose along the nose length. In Chen and Li (2002), the explicit expressions of N_1 and N_2 for ogive, conical, blunt, truncated ogive, hemispherical, and flat projectile nose were given.

Besides, Qian et al. (2000) introduced a resistance coefficient and target strength parameter to analyze the DOP of a truncated ogive-nosed projectile penetrating into concrete targets. However, the proposed formula is only valid when the length of the truncated part is less than 1/3 of the original nose length. Jan and Henrik (2004) extended the Forrestal formulae to the truncated ogive- and flat-nosed projectiles by modifying the resistance function based on the cavity expansion theory.

2.3.2 Perforation

As for the projectile perforation, the damage of a concrete slab is schematically shown in Fig. 2.5. Figure 2.6 shows the raw and low-pass filtered deceleration-time histories of a projectile perforating a 300-mm-thick concrete slab. Different from the decelerations of the projectile penetrating into the semi-infinite concrete target shown in Fig. 2.4, nearly no constant deceleration plateau is observed.

Based on the two-stage “tunneling + shear plugging” perforation model, Yankelevsky (1997) obtained the expression of perforation limit for the low speed ($V_0 < 200$ m/s) impact of the flat-nosed projectile. Chen and Li (2003), Li and Tong (2003), and Chen et al. (2004, 2008b) proposed the prediction formulae of perforation limit and ballistic limit for the reinforced concrete slab based on three stage “cratering + tunneling + shear plugging” perforation model. It was found that, if the projectile did not hit the rebar mesh, the relatively low reinforcement ratio (less than 4%) had nearly no effect on the ballistic limit of the projectile. Based on projectile perforation tests with 106 shots (Sliter 1980; Hanchak et al. 1992), the predicted accuracy of the above-mentioned perforation limit formulae for the damage modes of the concrete target (perforation, critical perforation and non-perforation) reached as high as 83% (Li and Tong 2003).

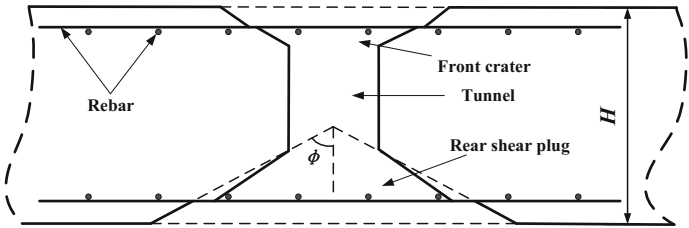
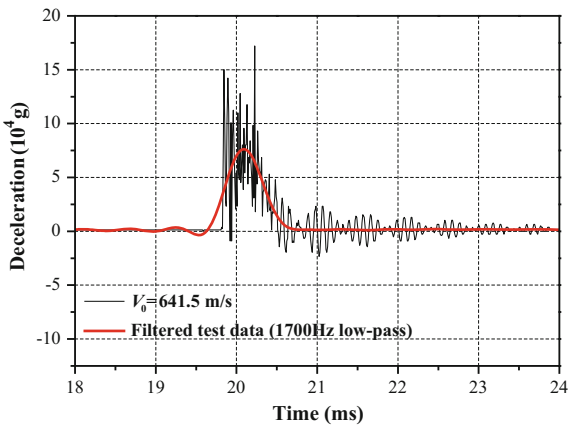


Fig. 2.5 Schematics of three-stage perforation model of the RC slab

Fig. 2.6 Deceleration-time history of projectile perforating the target (Wu et al. 2015a)



Perforation limit h_{per} was given by Chen and Li (2003), Li and Tong (2003), and Chen et al. (2004, 2008b) as

$$\frac{h_{\text{per}}}{d} = \frac{h_{\text{pen}}}{d} + \frac{\sqrt{1 + \sqrt{3}S \tan \phi} - 1}{2 \tan \phi} \quad \text{for} \quad \frac{h_{\text{pen}}}{d} > k \quad (2.79)$$

where h_{pen} and S are referred in Eqs. (2.78a, b), ϕ is the cone slope angle of the rear crater shown in Fig. 2.5. Dancygier (1998) proposed that $\tan \phi = 2.254$ and 4.108 for normal strength concrete (NSC) and high strength concrete (HSC), respectively.

Ballistic limit V_{BL} and the residual velocity V_r of the projectile can be obtained reversely from Eq. (2.79) as

$$V_{\text{BL}} = \sqrt{\frac{S f_c d^3 I_{\text{BL}}}{M}}; \quad I_{\text{BL}} = \frac{\pi}{2} \left(\frac{H}{d} - \frac{H_{\text{plug}}}{d} - \frac{k}{2} \right); \quad H_{\text{plug}} = \frac{\sqrt{1 + \sqrt{3}S \tan \phi} - 1}{2 \tan \phi} \quad (2.80a)$$

$$V_r = (V_0^2 - V_{\text{BL}}^2)^{0.5} \quad (2.80b)$$

Li et al. (2006) further obtained the critical impact kinetic energy of a projectile for perforating concrete slabs, which showed better agreements with the flat-nosed projectile perforation test data by comparing with the energy forms of UMIST and NDRC formulae as well as Eq. (2.79) for the perforation limit. Ben-Dor et al. (2010) obtained the perforation limit for the flat-nosed projectile by extending the two-stage model, which gave a good agreement with the experimental damage mode of the concrete target (Sliter 1980).

As for the projectile perforating on the segmented concrete targets, TM5-855-1 (1986) gives that a thick slab composed of several layers generally has a smaller perforation resistance than a monolithic slab with the same thickness. Ben-Dor et al. (2009) found theoretically that (i) the ballistic limit of multilayered concrete shield did not depend on the order of the slabs in the shield; (ii) the monolithic shield was superior to any layered shield with the same thickness; (iii) the largest decrease in the ballistic limit velocity occurred when a shield was divided into a number of slabs with the same thickness.

2.4 Numerical Simulation

Since the projectile penetration or perforation tests are difficult to perform and always expensive, numerical simulations of projectile penetration or perforation are playing an more and more important role. Numerical simulation approach can not only reproduce the transient phenomena of the projectile and target interaction, but also obtain numerical solutions (e.g., stress and strain) for the whole field. Besides,

it can provide the support and evidence for the establishment of analytical models and empirical formulae. As far as the terminal ballistics is concerned, Zukas (1990) conducted a comprehensive and informative survey of computer codes for impact simulations.

Numerical simulations of high velocity impact events usually use the so-called hydrocode, which can treat the complicate high pressure, high strain rate, and large deformation problems. Generally, the hydrocode is an efficient tool for solving the conservation equations for mass, momentum, and energy with the initial and boundary conditions. Based on different representations of the conservation laws for a continuum, it can be classified into Eulerian, Lagrangian, and Arbitrary Lagrangian–Eulerian approaches. For Eulerian approach, the mesh is fixed, while material flows through the mesh. The flow material through the fixed mesh determines the mass, pressure, velocity, and so on. The Eulerian approach is more suitable for drastic distorted materials. However, since only one material is allowed to exist in each element, the interface between the projectile and target is difficult to capture clearly. As for Lagrangian approach, the mesh is attached to the material and moves with it. Consequently, it is more appropriate for the material element that is less distorted and the interface between the projectile and target can be clearly observed. In addition, Arbitrary Lagrangian–Eulerian approach is a combination of Lagrangian and Eulerian approaches. For example, when a rigid projectile penetrates into a relatively soft target, the Lagrangian approach is used for the description of the projectile and the Eulerian approach for the soft target. Besides, based on different discretization methods, numerical simulations can be classified into finite difference method, finite element method and discrete element method, smoothed particle hydrodynamics method, and so on.

Lagrangian approach often suffers from mesh entanglement in the target that can prematurely terminate numerical computation. Therefore, the element erosion technique is introduced to address this issue, but the erosion criteria are usually empirical. In order to solve the above problems, Ortiz (1996) and Espinosa et al. (1998) developed an adaptive element method, in which the algorithms for correcting finite element mesh distortion through mesh rezoning, optimization, and refinement were presented. When the mesh distortion reaches a critical condition (usually represented by the accumulated equivalent plastic strain), rezoning and refinement of these elements are performed. Algorithm to automatically convert distorted finite elements into meshless particles is alternative selection, which was proposed by Johnson et al. (2002) and Johnson and Stryk (2003). In this method, when finite elements reach a user-specified plastic strain, they are converted to particles and linked to the adjacent finite element grid. This method allows for the use of accurate and efficient finite element approach in the lower distortion regions, and for the use of meshless particle approach in the higher distortion regions. The smoothed particle hydrodynamics (SPH) approach is also usually used to avoid the mesh entanglement. However, it is generally known that SPH approach is time-consuming and instable on the boundary. Recently proposed reproducing kernel particle method (RKPM) (Liu et al. 1995) can well solve the above problems and is successfully used in the projectile penetration simulations (Wu et al. 2012d;

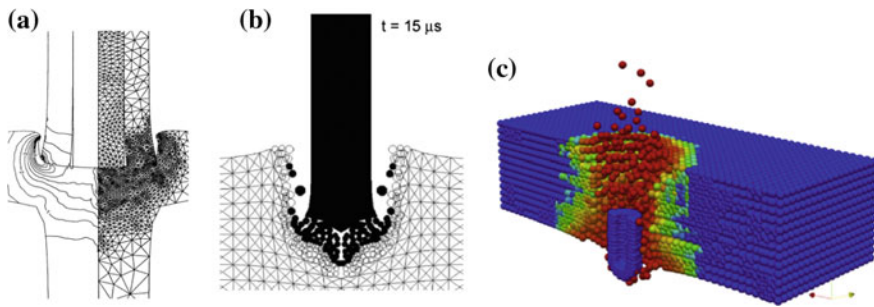


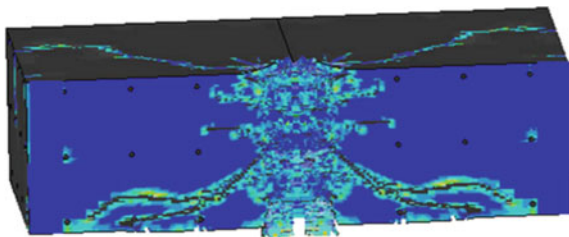
Fig. 2.7 Projectile penetration simulation results **a** adaptive element method (Espinosa et al. 1998) **b** F-M method (Johnson et al. 2002) **c** RKPM method (Wu et al. 2014c)

Wu et al. 2014c). Figure 2.7 presents the projectile penetration simulation results of adaptive element, converting distorted finite elements into meshless particles (F-M) and RKPM methods, respectively.

A proper material model is needed for correct simulation of projectile impact. The dynamic behavior of metal material under intense dynamic loading is relatively simple and Johnson–Cook model (Johnson and Cook 1983) is widely adopted. However, the dynamic behavior of brittle material (e.g., concrete and rock) is rather complex and is still the research hotspot.

Tu and Lu (2009) presented a comprehensive evaluation of several widely used concrete material models in commercial hydrocodes. Among them, Holmquist–Johnson–Cook (HJC) concrete model is widely used for impact simulation (Holmquist et al. 1993). In this model, two stress invariants are employed to formulate the current failure surface. Concrete is considered linear elastic before a prescribed maximum failure surface, beyond which the accumulated damage that depends on the equivalent plastic strain and plastic volume strain shifts the current failure surface to a residual state by reducing the cohesion strength value. In order to suppress the fracture by low magnitude tensile waves, a simple cutoff for the fracture strain (EFMIN) is adopted. HJC model does consider most of the important aspects of concrete behavior under impact loads, such as the pressure dependency, strain rate effect, damage cracking, and compaction (Polanco-Loria et al. 2008). However, from a critical point of view, many aspects are not taken into account, such as (i) the independence of the third stress invariant cannot capture the transition of the deviatoric section from the triangular shape at low pressures to the circular shape at high pressures; (ii) strain hardening is not considered; (iii) strain softening is only dependent on the fracture strain cutoff which is usually difficult to be determined; (iv) strain rate enhancement for compression and tension are identical, which is contrary to the available experiments [CEB-FIB Model Code 1990 (1993)]; and (v) tensile damage is not considered, which may play an important role in the simulation of the cratering and scabbing phenomena (Xu and Lu 2006; Li and Hao 2014).

Fig. 2.8 Tensile damage distribution during projectile perforating a concrete slab (Liu et al. 2009)



The previous modifications to HJC model are mainly focused on the compressive behavior (Polanco-Loria et al. 2008) and strain rate effect (Polanco-Loria et al. 2008; Islam et al. 2012), and they are still not suitable for the predictions of the cratering and scabbing phenomena. Liu et al. (2009) presented a modified version of HJC model, where they employed TCK model (Taylor et al. 1986) to describe the dynamic tensile behaviors of concrete, while the compressive behaviors of concrete were still governed by HJC model. Based on this model, Liu et al. (2009) gave reasonable predictions of the cratering and scabbing phenomena in concrete slabs, as shown in Fig. 2.8. However, the yield surface of the above modified model is discontinuous due to the separate treatment of compressive and tensile behaviors. Besides, TCK model has nine differential equations to be carefully integrated during a time step, which may cause numerical computation instability. In addition, some parameters, such as the volumetric strain rate experienced by concrete at fracture, are difficult to determine experimentally. Thus, a more reasonable concrete material model should be proposed for the projectile penetrating into concrete targets, and the shortcomings of HJC model discussed above should be well addressed, especially for the correct reproducing the cratering and scabbing phenomena observed in the experiments.

Gebbeken and Ruppert (2000) also proposed an extension form of HJC model for concrete, in which the third stress invariant was accounted in the definition of failure surface, the concrete damage was considered in the enlargement of failure surface with the strain rate effect, and the tensile failure was represented by a single parameter (Rankine criterion).

Riedel–Thoma–Hiermaier (RHT) model (AUTODYN 2003; Riedel et al. 1999) is also an extended version of HJC model, in which the third stress invariant is considered in the yield strength surface, but not in the residual strength surface. The description of damage is similar to HJC model, but independent on the plastic volume strain. Strain rate effect is taken into account by a dynamic amplification factor, which could become problematic in the simulation of high strain rate problems (Tu and Lu 2009). Tu and Lu (2010) presented several enhancements of RHT model, such as a modified residual strength surface dependent on the third stress invariant, as well as the improved tensile-to-compressive meridian ratio, dynamic tensile strength increasing factor, and bilinear softening model based on the fracture energy.

2.5 Summary

In this chapter, focusing on the local response of concrete targets under the impact of projectile, a state-of-the-art review of the relevant studies is presented. Firstly, local response of semi-infinite and finite thickness concrete targets under projectile penetration or perforation is roughly described by the two or three successive stages. Then, the frequently used empirical formulae, semi-analytical models, and numerical simulations for projectile impact are reviewed in detail. Total 23 sets prevalent empirical formulae proposed until the end of the year 2014 are listed in the SI form, which can be referred as a handbook. Also, the semi-analytical models (e.g., Forrestal series formulae, Li and Chen series formulae) for predicting the terminal ballistic parameters of projectiles impacting on concrete targets are summarized. Finally, different numerical simulation approaches, such as the Lagrangian, Eulerian, Arbitrary Lagrangian–Eulerian approaches, as well as the frequently used constitutive models of concrete material in hydrocodes are introduced and evaluated.

Concrete Structures Under Projectile Impact

Fang, Q.; Wu, H.

2017, XVII, 577 p. 445 illus., 370 illus. in color.,

Hardcover

ISBN: 978-981-10-3619-4