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A REVIEW – LOCAL FAILURE ON CONCRETE TARGET DUE TO PROJECTILE IMPACT

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ABSTRACT

Extensive work has been carried out to investigate the effects of the impact of rigid projectiles on concrete targets. Many of this research investigation have concluded with presenting empirical formulae that correlate – to the best possible extent – some of the variables of the phenomena with the results of the experimental work. This paper presents a review on the validity and limitations of empirical formulae adopted in the design of nuclear structures in USA and UK to predict a local impact effects in concrete targets struck by hard projectiles. These formulae are used to determine the penetration depth, scabbing thickness and perforation thickness of the concrete target. Failure mechanisms are classified based primarily on experimental evidence. An energy approach and numerical modeling with finite element for investigating the penetration of concrete by rigid missiles and the associated phenomena are also presented. Criticisms are made on the validity and limitations of the empirical formulae. The future trend of the analysis and design of concrete penetration by hard missiles impact are predicted.

KEYWORDS : Local impact; Penetration; Perforation; Scabbing; Empirical formulae; Energy approach; Numerical model; Hard missile

1. Introduction

Nuclear power plant structures are normally constructed using reinforced concrete due to the benefits of inertia effects of concrete mass, low cost, high rigidity and high thermal resistance of concrete. The nuclear structures are designed to resist impact and blast loading in the event of accident or planned attacks. The nuclear power plant is always the main target in the wartime as the destruction of nuclear power plant not only disrupts the power supply but also destroy the life form in that area. The failure of the nuclear structures in Fukushima serves as a warning that the design of nuclear structures still requires more research to improve the level of safety.

As a developing country, Malaysia plans to construct its first ever nuclear power plant by 2022, to meet the increasing demand for the electricity and sustain the growth of country's economy. As the reserve of natural resources such as petroleum, coal and gas is depleting, the choice of nuclear power is inevitable. Therefore it is the responsibility of the civil engineers especially structural engineers to ensure the nuclear structures are designed at high level safety and have sufficient resistance to withstand impact and blast loading. Since the impact phenomenon on structures is relatively new among the local engineers community in Malaysia, this paper is intended to provide an insight regarding the impact physics, the formulae applied for the design of nuclear structures in the developed countries and current research on the impact response on concrete structures.

2. Classification Of Impact Phenomenon And Impact Response Of Reinforced Concrete Structures

Impact can be classified based on (i) relative stiffness between the striking object and the struck body, and (ii) velocity of the striking object. For the first classification, when the stiffness of the striking object is significantly higher than the struck body, the kinetic energy from the striking object can be assumed fully dissipated by plastic deformation of the struck body. In this case, where the striking object is assumed rigid is termed as 'hard impact'. In the context for the nuclear structures design, the hard impact scenario is the missiles attack with the intention to breach the structures. The hard impact scenario on the reinforced concrete structures will be the focus of this paper as it will cause the most severe damage on structures. On the other hand, if the stiffness of striking object is significantly lower than the stiffness of struck body, the striking object will deform plastically and it is termed as the 'soft impact'. An example of soft impact is when a vehicle crashes into a thick reinforced concrete wall and then the vehicle deforms plastically.

Impact scenario can also be classified into low velocity impact and high velocity impact. In the case of velocity of striking body is less than or equal to 10 m/s, it is classified as low velocity impact, otherwise it is classified as high velocity impact. According to Dancygier (1997), the nuclear structures are designed to resist impact loading caused by projectile or missiles travelling up to 1000 m/s.

The response of reinforced concrete structures under impact loading is different from the static loading especially in the case of high velocity impact of rigid projectile. For impact velocities up to 10 ms^{-1}, the failure modes are generally the same as the static failure, except there is increased tendency for local damage or shear failure to occur. Kennedy (1979) and Li et al. (2005) reviews the progress in the in concrete design aimed at resisting missile impact effects, the terminology used when describing local missile impact effects was clarified and the empirical formulae commonly used to predict the local missile impact effects were summarized. Seven failure modes associated with missile impact effects on concrete targets are listed below and followed by schematic illustration of failure modes as shown in Figure 1.

i. *Penetration:* Tunnelling effect into the target by the projectile path (the length of the tunnel is called the penetration depth).
ii. *Cone cracking and plugging:* Formation of a cone-like crack under the projectile at the distal face and the possible subsequent punching-shear plug.
iii. *Spalling:* Ejection of target material from the proximal face of the target.
iv. Radial cracking: Global cracks radiating from the impact point and appearing on either the proximal or distal face of the concrete slab or both, when cracks develop through the target thickness.
v. *Scabbing*: Ejection of fragments from the distal face of the target.
vi. *Perforation:* Complete passage of the projectile through the target with or without a residual velocity.
vii. *Overall structural responses and failures:* Global bending, shear and membrane responses as well as their induced failures throughout the target.

In this paper, the design of nuclear structures to resist three local failure modes, penetration, scabbing and perforation will be discussed in details in the following section.

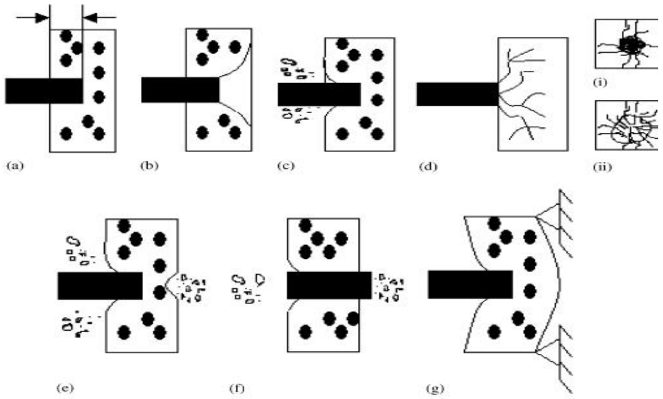


Fig.(1) Missile impact effects on concrete target, (a) Penetration, (b) Cone cracking, (c) Spalling, (d) Cracks on (i) Proximal face and (ii) Distal face, (e) Scabbing, (f) Perforation, and (g) Overall target response. [Li et al. (2005)]

3. Design Codes Adopted In USA And UK For Nuclear Structures

The codes of practice adopted empirical formulae for the design of nuclear structures in the United States and United Kingdom. Empirical formulae based on experimental data are especially important in this field due to the complexity of the phenomena. The empirical formulae for penetration depth, scabbing and perforation limits, are often formulated by curve-fitting test data and most of them are unit-dependent and only being applicable strictly within the limits of the tests from which the data were acquired. The limited parameters in the experiments are: (1) mass of the missiles, (2) geometry (shape and diameter) of the missile, (3) velocity of the missile, and (4) concrete strength. Both small-scale lab tests and full-scale prototype tests have been used to study impact on concrete targets. These have led to various empirical formulae as discussed in details in the following section. The major empirical formulae available in this paper are reproduced from a review provided by Li et al. (2005) and Guirgis and Guirgis (2009). The notation used for repeatedly mentioned symbols and their respective units in SI units is given in Table 1.

Table (1) Some of the quantities used in penetration depth formulae and their units.

Symbol	**Quantity**	**Units (SI)**
x	Penetration depth measured from the proximal face of the concrete target	m
V_o	Projectile impacting velocity	m/s
M	Mass of the projectile	kg
d	Diameter of projectile	m
A	Projectile cross-sectional area	m^2
e	Perforation limit	m
h_s	Scabbing limit	m
H_o	Thickness of target	m
f_c	Unconfined compressive strength of concrete	MPa

*N**	Nose shape factor	–

3.1. The U.S. Army Corps of Engineers (ACE) formula [ACE (1946) and Kennedy (1979)]

The US Army manual, TM-5-855-1 recommends the use of ACE formula to predict penetration depth on reinforced concrete structures. While the Air Force manual, ESL-TR-87-57, recommends the ACE formulae for perforation and scabbing. Based on experimental results prior to 1943, the ACE developed the following formula for penetration depth:

$$\frac{\boldsymbol{x}}{\boldsymbol{d}} = \frac{\mathbf{3.5\ x\ 10^{-4}}}{\sqrt{\boldsymbol{f_c}}} \left(\frac{\boldsymbol{M}}{\boldsymbol{d^3}}\right) \boldsymbol{d}^{\mathbf{0.215}}\, \boldsymbol{V_o^{1.5}} + \mathbf{0.5} \quad \textbf{(SI units)}$$

Based on the above penetration depth given above the perforation and scabbing limits were given by:

$$\frac{e}{d} = 1.32 + 1.24 \left(\frac{x}{d}\right) \ \text{for}\ \ 1.35 < \frac{x}{d} < 13.5 \ \text{or}\ \ 3 < \frac{e}{d} < 18$$

$$\frac{h_s}{d} = 2.12 + 1.36 \left(\frac{x}{d}\right) \ \text{for}\ 0.65 < \frac{x}{d} \leq 11.75 \ \text{or}\ 3 < \frac{h_s}{d} \leq 18$$

The above perforation and scabbing formulae are based on regression analyses of data from ballistic tests on 37 mm, 75 mm, 76.2 mm and 155 mm steel cylindrical missiles. Additional data for 0.5 caliber bullets were obtained in 1944 and the above formulae were modified to:

$$\frac{e}{d} = 1.23 + 1.07 \left(\frac{x}{d}\right) \ \text{for}\ \ 1.35 < \frac{x}{d} < 13.5 \ \text{or}\ \ 3 < \frac{e}{d} < 18$$

$$\frac{h_s}{d} = 2.28 + 1.13 \left(\frac{x}{d}\right) \ \text{for}\ 0.65 < \frac{x}{d} \leq 11.75 \ \text{or}\ 3 < \frac{h_s}{d} \leq 18$$

This empirical formula was developed for ordinary concrete and impact velocities of less than 310 m/s [Martin SQ 1994].

3.2. The modified formula of the National Defense Research Committee [NDRC (1946) and Kennedy (1979)]

The modified NDRC was adopted in 1946 by the US National Defense Research Committee based on the ACE formulae. This formula was the first to consider the effect of missile shape on the response of reinforced concrete structures. It was found that missiles with shape noses require less energy to perforate concrete structures than missiles with flat noses. While the hemispherical nosed projectiles with a diameter approximately equal to the target thickness showed that such projectiles required up to 30% higher velocities to perforate a reinforced concrete target than a flat-faced projectile having the same mass and diameter (Li et al., 2005). The design manual of the US Department of Defense Explosive Safety Board, ARLCD-SP-8400, recommended modified NDRC formulae.

The modified NDRC penetration depth formula is given by:

$$\boldsymbol{G = \frac{3.8 \text{ x } 10^{-5}}{d\sqrt{f_c}} N^{*}M \left(\frac{V_o}{d}\right)^{1.8}} \quad \text{(SI units)}$$

where N^* is a nose shape factor equal to 0.72, 0.84, 1.0 and 1.14 for flat, blunt, hemispherical and very sharp noses respectively.

The function G is given by:

$$G = \left(\frac{x}{2d}\right)^2 \text{ for } \frac{x}{d} \le 2 \,; \qquad \frac{x}{d} = 2G^{0.5} \text{ for } G \ge 1$$

$$G = \frac{x}{d} - 1 \text{ for } \frac{x}{d} > 2 \,; \qquad \frac{x}{d} = G+1 \text{ for } G < 1$$

Perforation limit to thin targets [Kennedy (1979)]

$$\frac{e}{d} = 3.19\left(\frac{x}{d}\right) - 0.718\left(\frac{x}{d}\right)^2 \text{ for } \frac{x}{d} \le 1.35 \text{ or } \frac{e}{d} \le 3$$

$$\frac{e}{d} = 1.32 + 1.24\left(\frac{x}{d}\right) \text{ for } 1.35 < \frac{x}{d} < 13.5 \text{ or } 3 < \frac{e}{d} < 18$$

Scabbing limits to thin targets [Kennedy (1979)]

$$\frac{h_s}{d} = 7.91\left(\frac{x}{d}\right) - 5.06\left(\frac{x}{d}\right)^2 \text{ for } \frac{x}{d} \le 0.65 \text{ or } \frac{h_s}{d} \le 3$$

$$\frac{h_s}{d} = 2.12 + 1.36\left(\frac{x}{d}\right) \quad for\ 0.65 < \frac{x}{d} \le 11.75 \ or\ 3 < \frac{h_s}{d} \le 18$$

This empirical formula was developed for ordinary concrete and impact velocities of less than 310 m/s [Martin 1994].

3.3. The CEA–EDF perforation formula [Berriaud et al. (1978)]

CEA and EDF in France started a large program in 1974 to develop reliable predictions on ballistic performance of reinforced concrete slabs under missile impact [Berriaud et. al. (1978)]. Based on a series of drop-weight and air gun tests, CEA–EDF suggested a perforation limit formula

$$\frac{e}{d} = 0.82\frac{M^{0.5}V_o^{0.75}}{\rho_c{}^{0.125}f_c{}^{0.375}d^{1.5}} \qquad \text{(SI units)}$$

Where: (ρ_c) is the density of the concrete.

The ballistic limit for a pressurized structure (including non-pressurized liquid and gas storage structures) should be the minimum impact velocity for through-thickness radial cracking and perforation. The ballistic limit V_p (m/s) is given by

$$Vp = 1.3\,\rho_c{}^{1/6}f_c{}^{0.5}\left(\frac{dH_o^2}{M}\right)^{2/3} \qquad \text{(SI units)}$$

Fullard et. al.(1991) extended the above equation of ballistic limit to non-circular missile cross-section and included the parameter of percentage of reinforcement. When perforation is considered, the influence of the reinforcing mesh will be introduced in the ultimate mode of deformation, when a failure surface (crack) occurs, and activates a dowel action of the reinforcement (Dancygier, 1997).

$$Vp = 1.3\,\rho_c{}^{1/6}f_c{}^{0.5}\left(\frac{\rho H_o^2}{\pi M}\right)^{\frac{2}{3}}(r + 0.3)^{0.5}$$

where H_0 is the thickness of the target, p is the perimeter of the missile cross-section and r is the percentage of reinforcement each way in each face is valid for $20<V_0< 200$(m/s) [Berriaud et al.. (1978)]

3.4. The United Kingdom Atomic Energy Authority (UKAEA) formula [Barr (1990)]

The most recent British Army manual uses UKAEA formulae for penetration and scabbing and the CEA–EDF formula for perforation. Based on extensive studies conducted for the protection of nuclear power plant structures in the UK, Barr (1990) suggested the following further modification to the NDRC formula, directed mainly toward the lower impact velocities more relevant to the nuclear industry:

$$\boldsymbol{G = 3.8 \text{ x } 10^{-5} \frac{N^{*}M}{d\sqrt{f_c}} \left(\frac{V_o}{d}\right)^{1.8}} \quad \text{(SI units)}$$

where the *G*-function is defined by

$$\frac{x}{d} = 0.275 - [0.0756\text{-}G]^{0.5} \text{ for } G \leq 0.0726$$

$$\frac{x}{d} = [4G - 0.242]^{0.5} \text{ for } 0.0726 \leq G \leq 1.0605$$

$$\frac{x}{d} = G + 0.9395 \text{ for } G \geq 1.0605$$

The parameter ranges of this formula are 25 < V_o < 300 (m/s), 22 < f_c < 44 (MPa) and 5000 < M/d^3 < 200,000 (kg/m^3). This formula could predict the penetration depth within 20% of accuracy when x/d is > 0.75. The accuracy of the formula reduces significantly (+100% to -50%) when the x/d < 0.75.

Scabbing limit given by Barr (1990) is

$$h_s/d = 5.3\, G^{0.33}$$

The validity of the parameters are 29<V_o<238 (m/s), 26<f_c<44 (MPa), and 3000 <M/d^3<222200 (kg/m^3). The accuracy for the formula is within 40% for 2<h_s/d<5.56.

3.5. The R3-UMIST formula [Reid and Wen (2001), BNFL.(2003)]

UK Nuclear Electric (NE) initiated a major research program on the impact behaviour of reinforced concrete structures in 1985. A collection of empirical formulae were proposed to predict critical kinetic energies of missiles for identified local impact effects on reinforced concrete slabs. The UMIST formulae can be used for predicting penetration depth, scabbing and perforation limits of concrete targets subjected to lower to intermediate impact velocity range. The penetration depth in this formula is given by

$$\boldsymbol{\frac{x}{d} = \frac{2}{\pi}\left(\frac{N^{*}}{0.72}\frac{MV_o^2}{\sigma_t d^3}\right)}$$

where N^* is the nose shape factor which equals to 0.72 for a flat nose, 0.84 for a hemispherical nose, 1.0 for a blunt nose and 1.13 for a sharp nose, and σ_t is the rate-dependent characteristic strength of concrete defined by

$$\sigma_t\ (\mathrm{Pa}) = 4.2 f_c\ (\mathrm{Pa}) + 135.0\times10^6 + [0.014 f_c\ (\mathrm{Pa}) + 0.45\times10^6] V_o\ (\mathrm{m/s})$$

The formula has been verified for the following parameter ranges: $50 < d < 600$ (mm), $35 < M < 2500$ (kg), $0 < x/d < 2.5$ and $3 < V_o < 66.2$ (m/s).

The critical kinetic energies of the projectile to cause cone cracking (E_c), scabbing (E_s) and perforation (E_p) are given as follows. The R3-UMIST formulae were derived with a minimum H_o/d value of 0.5, therefore where assessments are required for $H_o/d<0.5$, the derived critical energies must be treated with cautious. The perforation formulae were developed based on flat-nose missiles, it is recommended to use these formulae to when there exist insufficient data on missile nose shape effects to formulate nose specific empirical correlations.

i. $H_o/d < 5$

Cone cracking is an important local failure mode that should be considered if the concrete structure is used to store pressurized gases or liquids. Critical kinetic energy of cone cracking is:

$$\frac{E_c}{\eta\sigma_t d^3} = -0.00031\left(\frac{H_o}{d}\right) + 0.00113\left(\frac{H_o}{d}\right)^2 \quad for\ \left(0 < \frac{H_o}{d} \le 2\right)$$

$$\frac{E_c}{\eta\sigma_t d^3} = -0.00325\left(\frac{H_o}{d}\right) + 0.00130\left(\frac{H_o}{d}\right)^3 \quad for\ \left(2 < \frac{H_o}{d} < 5\right)$$

Critical kinetic energy of scabbing is

$$\frac{E_s}{\eta\sigma_t d^3}\frac{N^*}{0.72} = -0.005441\left(\frac{H_o}{d}\right) + 0.01386\left(\frac{H_o}{d}\right)^2$$

Critical kinetic energy of perforation is

$$\frac{E_p}{\eta\sigma_t d^3} = -0.00506\left(\frac{H_o}{d}\right) + 0.01506\left(\frac{H_o}{d}\right)^2 \quad for\ \left(0 < \frac{H_o}{d} \le 1\right)$$

$$\frac{E_p}{\eta\sigma_t d^3} = -0.01\left(\frac{H_o}{d}\right) + 0.02\left(\frac{H_o}{d}\right)^3 \quad for\ \left(1 \le \frac{H_o}{d} < 5\right)$$

ii. $H_o/d \ge 5$

$$\frac{\boldsymbol{E_c}}{\boldsymbol{\sigma_t d^3}} = \frac{\pi}{4}\left[\left(\frac{\boldsymbol{H_o}}{\boldsymbol{d}}\right) - 4.7\right]$$

$$\frac{\boldsymbol{E_s}}{\boldsymbol{\sigma_t d^3}}\frac{\boldsymbol{N^*}}{0.72} = \frac{\pi}{4}\left[\left(\frac{\boldsymbol{H_o}}{\boldsymbol{d}}\right) - 4.3\right]$$

and

$$\frac{\boldsymbol{E_p}}{\boldsymbol{\sigma_t d^3}} = \frac{\pi}{4}\left[\left(\frac{\boldsymbol{H_o}}{\boldsymbol{d}}\right) - 3.0\right]$$

where η is determined by

$$\boldsymbol{\eta} = \begin{cases} \frac{3}{8}\left(\frac{\boldsymbol{d}}{\boldsymbol{C_r}}\right)\boldsymbol{r_t} + 0.5 \quad \boldsymbol{if}\ \left(\frac{\boldsymbol{d}}{\boldsymbol{C_r}} < \sqrt{\frac{\boldsymbol{d}}{\boldsymbol{d_r}}}\right) \\ \frac{3}{8}\left(\sqrt{\frac{\boldsymbol{d}}{\boldsymbol{d_r}}}\right)\boldsymbol{r_t} + 0.5 \quad \boldsymbol{if}\ \left(\frac{\boldsymbol{d}}{\boldsymbol{C_r}} \geq \sqrt{\frac{\boldsymbol{d}}{\boldsymbol{d_r}}}\right) \end{cases}$$

where d is the diameter of the projectile, d_r is the diameter of the reinforcing steel bar, C_r is the rebar spacing and r_t is the total bending reinforcement ($r_t = 4r$ with r being % EWEF, defined as $r = \pi d_r^2/4H_2C_r$,where H_0 is the thickness of the concrete target). The scabbing and perforation models are applicable for $22< d < 600$(mm), $1 < M < 2622$(kg), $0 < V_0 < 427$(m/s), $19.9 < f_c < 78.5$(MPa), $0 < r < 4$(% EWEF) and $50.8 < H_0 < 640$(mm).

4. Comparison of empirical formulae and discussion

Comparison of the various empirical penetration and perforation formulae adopted in the code of practice in USA and UK are given in Figure 2 and Figure 3 which indicates a considerable spread of predicted results against impact velocity. As mentioned earlier in this paper, empirical formulae for penetration depth into a concrete target are normally formulated from curve-fitting test data. The results obtained using many of the different formulae available in the literature may vary considerably and in many cases the variation range is very wide making the obtained estimates of penetration depth unreliable.

Most of the empirical formulae have one or more of the following deficiencies:

i. limited range of applicability, usually; the same as the range of test variables,

ii. not all variables which make significant contribution to the results are included,

iii. the formula is unit-dependent with dimensionally non-homogeneous quantities or constants,

iv. the formula is not based on a theory or an analytical model, and

v. the formula does not distinguish between the different phases of the penetration process.

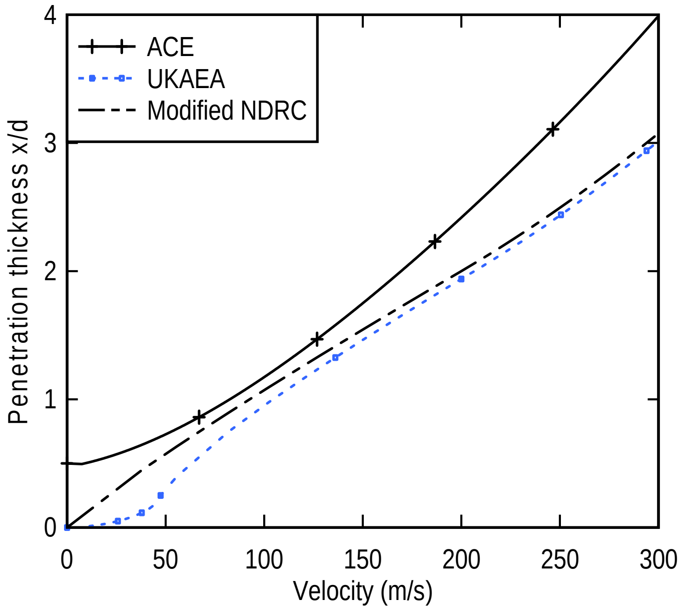


Figure (2) Comparison between various empirical penetration formulae [reproduced from Yankelevsky (1997)].

The differences between empirical results can be mainly attributed to the large number of independent variables involved and the uncertainty regarding the exact effect each has on the final result. According to Guirgis and Guirgis (2009), some of these different variables are:

i. Projectile variables: projectile mass, diameter, nose shape, cross-sectional area, initial speed, modulus of elasticity and deformation of projectile material, projectile striking obliquity, possible ricochet. The deformable body impact is significant and is relatively new area of study.

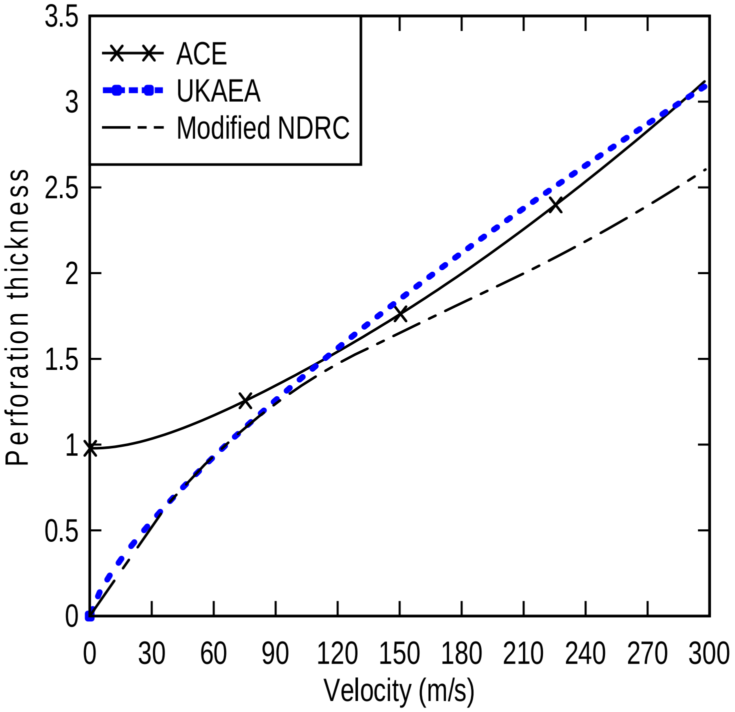


Figure. 3. Comparison between various empirical peroration formulae [reproduced from Yankelevsky (1997)].

i. *Concrete target variables*: concrete density, aggregate sizes and gradation, aggregate materials, relative volume of aggregate and paste, method of curing of concrete, concrete temperature, concrete compressive and tensile strength, strain rate effects on concrete strength, pre-stressing or post-tensioning of concrete targets and reinforcement types, ratio and details such as rebar diameter and spacing, overall target response is normally neglected and all models focus on local impact analysis. All empirical formulae totally ignore the strain rate effect in their explicit expression.

ii. *Impact incident variables*: friction coefficient between missile and concrete, concrete wall thickness and wall boundary conditions. Not all variables which make significant contribution to the results are included.

Despite extensive experimental investigation, most of the empirical formulae did not include the effect of reinforcing bars on penetration/perforation/scabbing. Only some individual cases e.g Barr (1990) or UKAEA, the effect of reinforcing bars have been taken into account in the perforation formulae, which fitted the experimental data. UMIST formula include the effect of reinforcement when the dimensionless thickness H/d <5, but the formulae were derived based on the minimum value H/d of 0.5, and they should be used cautiously.

5. Energy Approach For Studying Penetration Depth

In the energy approach, the amount of energy required to convert a specific volume of concrete to separate particles taking following factors into account: (1) the characteristics of the concrete and its constituents, (2) the gradation of the separate particles, and (3) the mode of failure of concrete. In the factor (1), the properties of the constituent of concrete such as the materials of which the aggregates are composed, the amount, size and distribution of the aggregate components and the relative volumes of aggregate and water–cement paste should also have a considerable effect on this amount of energy. For the gradation of the separate particles, the total exposed surface area of the separate particles increases as the fineness of the gradation of the particles increases, therefore the energy required for creating this surface increases as well. But this factor is difficult to consider in the analysis. Under high velocity impact, the failure mode of concrete is different from the static loading. The failure of the concrete volume impacted by the missile may require the creation of cracks through particles of the coarse aggregate which should require higher amount of energy.

Guirgis and Guirgis (2009) proposed the new measure to be used to represent concrete resistance, termed as *Volumetric Crushing Energy Density of Concrete*” or $G^{\#}$ where the superscript refers to the specific gradation criteria. This term represent the energy required for converting a unit volume of concrete to separate particles under compressive loading so that the particles of the crushed volume meet certain gradation criteria. $G^{\#}$ is measured in stress units and its value should be dependent on the gradation criteria and should increase for the same concrete as the fineness of particles increases.

This energy approach considered a two-stage model (Yankelevsky, 1997) for response of concrete under hard missile impact. The first stage is dynamic penetration, and the second stage is plug formation and the shear-out of the plug. Transition from stage one to stage two occurs when the total penetration resistance in front of the projectile nose equals the shear resisting force offered by the remaining thickness of the target.

Guirgis and Guirgis (2009) proposed the following formula using the energy approach;

$$\frac{M}{2} v_I^2 = \mathrm{H_I G_I^{\#} S x^2 d} \qquad \mathbf{for\ x \le 2d}$$

$$\frac{M}{2} v_I^2 = \mathrm{H_{II} G_{II}^{\#} S A (x - d)} \qquad \mathbf{for\ x > 2d}$$

where $G_1^{\#}$ is volumetric crushing energy density of concrete at the beginning of the phase 1, V_1 is the missile velocity at the beginning of the phase 1, H_I and H_{II} are constant, A is the cross-sectional area of the part of the missile embedded into the target.

The modification factor S can be calculated from the following relation:

$$S = S^c S^d S^V S^N S^E S^P S^H \ldots$$

Where S^c is the compressive strength modification factor,

S^d; missile diameter modification factor which account for the scale effect,

S^V; missile velocity modification factor, which accounts for the strain rate effect,

S^N; missile nose shape modification factor,

S^E; missile modulus of elasticity modification factor,

S^P; concrete pre-stress modification factor, and

S^H; concrete curing method modification factor.

More modification factors could be added to those mentioned above allowing the inclusion of the effect of other variables of the phenomena. Moreover, some of the modification factors could have different values during each phase, for instance the missile velocity modification factor should have a decreased value during the second phase to reflect the reduced velocity of the missile at the beginning of this phase. The nose shape modification factor could have different values in each phase as well. Furthermore, the effect of steel reinforcement can be included by accounting for the energy required to rupture the steel reinforcement within the crushed volume of concrete in calculating the penetration depth.

Using the experimental data presented by Forrestal et al., (1994,2003), the energy approach was used to estimate the penetration resistance for the concrete targets utilized in these tests. Figure 3 shows the ratio between the values of penetration depth obtained by the energy approach relative to test results. The corresponding values obtained by the modified NDRC formula are also shown in the same figure. Obviously, the NDRC formula has under estimated the penetration depth values because of the higher values of $H_I G^{\#}_{\mathrm{I}}$ and $\mathrm{H}_{\mathrm{II}}\ \mathrm{G}^{\#}_{\mathrm{II}}$ implied in the NDRC formula.

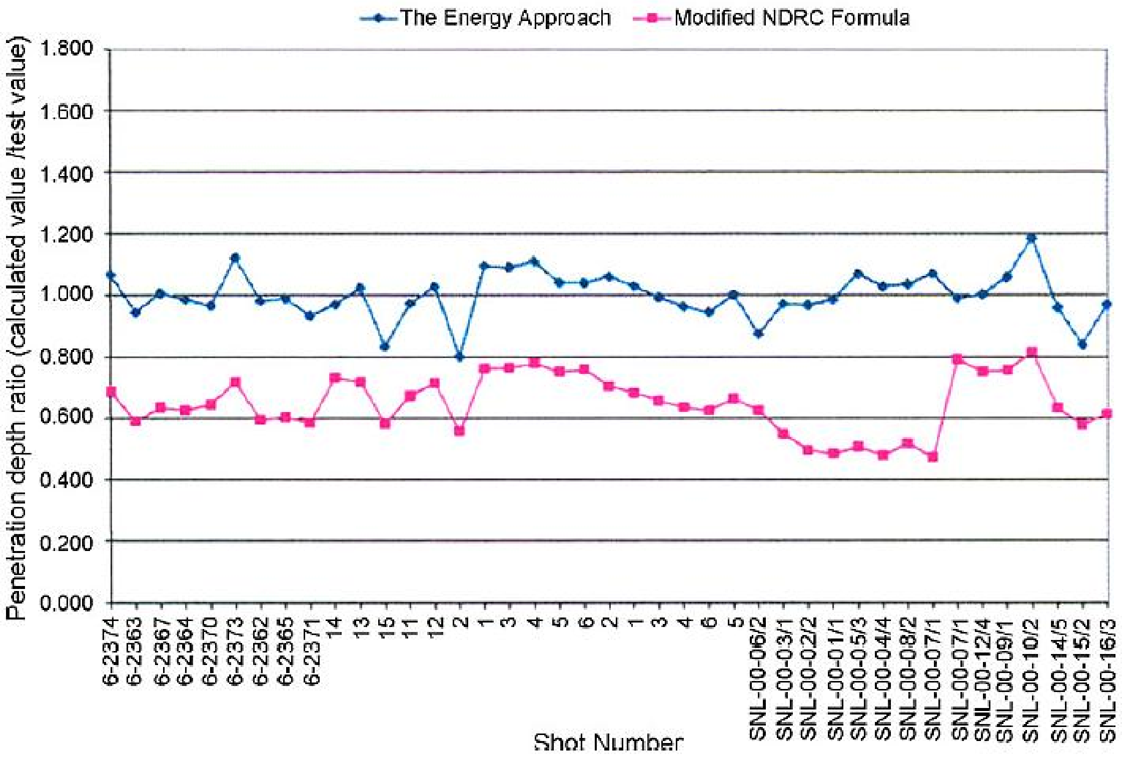


Fig (3): Using the energy approach with some experimental penetration results. (Guirgis and Guirgis, 2009)

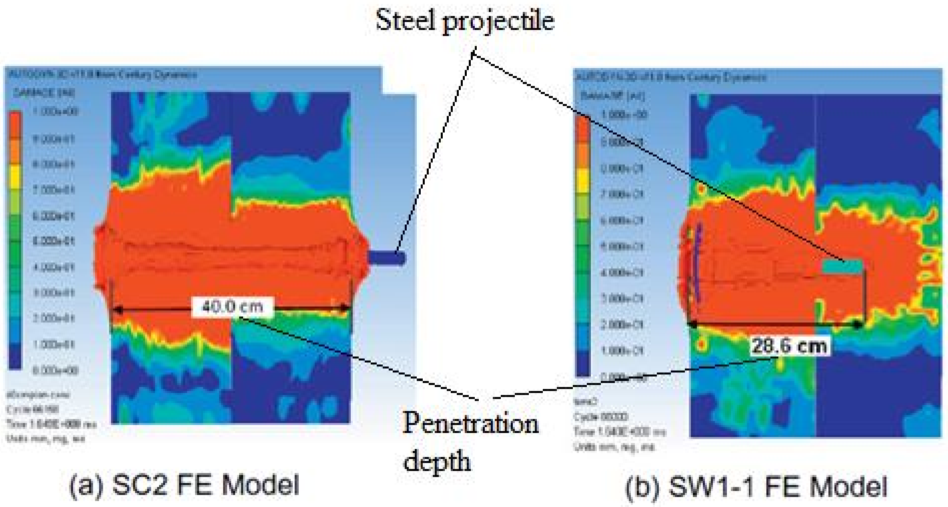
6. Numerical Modelling and Finite Element Approach

The high cost of undertaking experiments and the high parameter variation and dependency of the experimental setups and results, respectively, make it difficult to understand the local damage caused by projectile impact, which motivates the use of numerical simulations. This is growing more common as computing becomes faster, cheaper and more powerful, and as the material models become more reliable. These computer codes are representations of the conservation laws for a continuum using different numerical schemes.

Numerical modelling of concrete specimens under high loading rates in tension are been studied using *consistency viscoplastic model* by Barpi (2004). In the conclusion it is possible to obtain a good agreement in terms of the ratio between dynamic and static strength over a wide range of strain rates by choosing the value of viscosity m as a function of the strain rate. At the same time, this approach makes it possible to perform realistic simulations of high loading rate tests for impact loadings.

Simulation model of impact using finite element analyses on reinforced concrete slab have been proposed by Teng et. al (2004). The proposed model, based on the *equivalent inclusion method* is applied and considers the reinforced concrete as a homogeneous material, simplifying the finite element meshes and greatly reducing the computational cost of analyses. Using Mori–Tanaka's average strain theory, the equivalent stiffness matrix of the homogenized material and the associated equivalent material moduli are derived for finite element analyses. The residual velocity at which a projectile penetrates into an equivalent reinforced concrete slab is studied based on the strength of the equivalent material. The FEM computational results obtained using this method are very close to the test data, implying that the proposed method will be promising in future studies of impact analyses of reinforced concrete structures. Numerical results indicate the viability of the proposed model of the impact on reinforced concrete to be carried out for impact simulation both for normal and oblique impact of the projectiles.

Kamal and Eltehewy (2012) conducted experimental and numerical investigation of reinforced concrete blocks' penetration resistance. Investigation test was conducted experimentally using a steel blunt-nose projectile with a diameter of 23 mm and a mass of 175 g with striking velocity about 980 m/s hitting concrete blocks reinforced by different number of layers of woven wire steel mesh (Ferro-cement). A comparison was conducted between the results of the numerical model and the experimental test measurements and show relatively good agreement. Nystrom and Gylltoft (2011) conducted numerical study on the steel fibre-reinforced concrete and concluded that the scabbing crater can be reduced and prevented by using fibre-reinforced concrete.



(a) SC2 FE Model

(b) SW1-1 FE Model

Fig (4): Penetration depth in centimetre for different FE models.

7. Current Research On Improving The Ductility Of Concrete Under Impact Load

The concrete in the reinforced concrete structures will shatter under strong impact or blast loading, producing high speed secondary fragments which are hazardous to the building and its occupants. Cavill and Rebentrost (2006), Coughlin et al. (2010) and Nili and Afroughsabet (2010) showed that the ductility and toughness of the concrete can be increased by adding steel fibres into the concrete mix. Wu et al. (2009), Ngo et al. (2007) and Farnam et al. (2010) showed that the performance of concrete under blast loading can be improved significantly by using FRP and CFRP. Zhang et al. (2005) and Dancygier et al. (2007) showed that the high strength concrete performed better under impact loading conditions compared to the normal strength concrete. Millard et al. (2010) conducted experimental study on ultra high performance fibre-reinforced concrete and proposed a new dynamic increase factor for the flexural tensile strength for this concrete. Nystrom and Gylltoft (2011) conducted numerical study on the steel fibre-reinforced concrete and concluded that the scabbing crater can be reduced and prevented by using fibre-reinforced concrete.

Composite steel-concrete-steel (SCS) or double skin composite structures consist of a concrete core connected to two steel faceplates using mechanical shear connectors. This form of construction was originally conceived during the initial design stage for the Conwy river submerged tube tunnel in UK (Narayanan, 1994) and has received applications in building cores, gravity seawalls, nuclear structures and defence structures.

SCS panel is an effective means of protecting structures against extreme impact and blast loading due to its high strength and high ductility characteristics. Bowerman et al. (1999) developed Bi-Steel panel where steel bars are frictionally welded between two faceplates and then filled by concrete. Liew et al. (2009) developed double J-Hook connectors to interlock two steel faceplates and their uses are not limited by concrete core thickness.Young and Coyle (2002) showed that Bi-steel panels are able to withstand in-contact and close-in detonations of high explosives. The required wall thickness to prevent breach and spalling can be significantly reduced compared to reinforced concrete blast wall. The full scale barrier made of 300 mm thick Bi-steel panels can withstand explosions of 2 tonnes high explosive at a range of 2 metres. Then Redline 2 wall, which is a steel-concrete-steel wall, is considered to be more effective than an equivalent Bi-steel wall (in terms of thickness). The steel faceplates of Redline 2 wall are connected by steel hoops. Liew et al. (2009) performed low-velocity impact tests on the J-hook panels (one type of SCS panel) filled with lightweight concrete. The results showed that the J-hook panels resist the impact loading by flexural resistance, and the maximum displacement of the panels reduced as the number of shear connectors increased.

So far, extensive research has been conducted on composite SCS panel under blast loading very limited research has been carried out to high velocity impact. It is important to conduct high velocity impact test on the SCS panels in order to verify their performance under this loading condition.

8. CONCLUSIONS

In this paper empirical formulae and its limitations is presented to investigate the local penetration impact of concrete targets by rigid missiles. The penetration formula includes a large number of the variables of the phenomena with the possibility of extending the list of variables represented in the formula in future work. The wide variation of the penetration resistance may explain the wide variation of results obtained by the different formulae for the same values of the variables.

It is envisaged, with available computational efficiency and experimental data, that energy approach inclusive of finite element method with appropriate numerical modelling will be the trend in future investigations for local impact on concrete targets. Although energy approach and finite element method with correct numerical model will provide some theoretical and analytical basis to investigate the subject; it is still critical to validate the assumptions made experimentally.

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