CRITICAL IMPACT ENERGY FOR LOCAL IMPACT DAMAGE OF HARD PROJECTILE ON CONCRETE SLAB

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ABSTRACT

Concrete is a common construction material used to build conventional, unconventional, and sensitive structures. Great demand exists for efficient designing of concrete as protective structures against impact loading generated by natural disasters and consciously engendered unpleasant incidents etc. When hard projectile collides with concrete wall it is the impact energy of the projectile that makes concrete target to deform, which means impact energy is the dominant cause of damage in impact accidents. Hard missile impact can generate both local (penetration, scabbing, and perforation) and global impact damage. Local damage studies normally fall into three categories, i.e. empirical formulation, idealised analytical models, and numerical simulations. The present study is curiously focused on the required critical impact energy for occurrence of local impact damage in concrete structures generated by hard projectile, via three categories i). Numerical simulation, ii). Analytical modelling, and iii). Empirical formula.

The numerical simulations were conducted to determine the critical impact energy of ogive nose hard projectile which causes maximum penetration in to the concrete structures. The effects of diameter and CRH ratio of ogive nose hard projectile on critical impact energy were also analysed. An analytical model is developed to predict the required critical impact energy for spalling, tunnelling and penetration in concrete target. A nose shape factor ($N_i$) also has been introduced with empirical friction factor ($N_f$) in Chen and Li nose shape factor ($N^*$), to analyze the effects of nose shape on critical impact energy. Furthermore, an empirical formula also has been developed.

The early stage scabbing phenomenon has been observed through the wave propagation in simulations with fully elastic model assumptions. The critical impact energy required for scabbing of concrete target and the effects of diameter of
projectile \((d)\) and the target thickness \((H)\) on critical impact energy has been observed. An analytical model is developed based on 1-Dimensional with reflected wave propagation, and shear assumptions. Furthermore, an empirical formula also has been introduced.

For perforation, the penetration numerical simulations have been further extended to achieve perforation in deep concrete against impact of ogive nose hard projectile with CRH = (3.0, 4.25, and 6.0). The required critical impact energy and residual impact energy has been analysed. Furthermore, the modifications in Li and Reid (2006) perforation model also have been done. In addition a new empirical formula also has been introduced.

The outcome of this study can be used for making design recommendation and design procedures for determining the dynamic response of the concrete target to prevent local impact damage.
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<th>Description</th>
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<tr>
<td>(X) or (x)</td>
<td>Penetration depth (mm or m) and (Inches or feet)</td>
</tr>
<tr>
<td>(K_p)</td>
<td>Concrete penetrability co-efficient of Petry formula</td>
</tr>
<tr>
<td>(K)</td>
<td>Modified concrete penetrability co-efficient of Petry formula</td>
</tr>
<tr>
<td>(A_p)</td>
<td>Missile section pressure (psi)</td>
</tr>
<tr>
<td>(d)</td>
<td>Diameter of missile (mm or m) and (Inches or feet)</td>
</tr>
<tr>
<td>(M)</td>
<td>Mass of projectile (kg)</td>
</tr>
<tr>
<td>(V_o)</td>
<td>Impact Velocity (m/sec) and (ft/sec)</td>
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<tr>
<td>(e)</td>
<td>Perforation limit (mm or m) and (Inches or feet)</td>
</tr>
<tr>
<td>(h_s)</td>
<td>Scabbing limit (mm or m) and (Inches or feet)</td>
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<tr>
<td>(f_c)</td>
<td>Unconfined compressive strength of concrete (MPa) and (psi)</td>
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<tr>
<td>(BRL)</td>
<td>Ballistic Research Laboratory</td>
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<tr>
<td>(ACE)</td>
<td>Army Corp Engineers</td>
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<tr>
<td>(S.I)</td>
<td>S.I unit system</td>
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<tr>
<td>(F.P.S)</td>
<td>Imperial unit system</td>
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<tr>
<td>(NDRC)</td>
<td>US National Defense Research Committee</td>
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<tr>
<td>(H) or (H_o)</td>
<td>Thickness of target (mm or m)</td>
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<tr>
<td>(E_k)</td>
<td>Kinetic energy of impact (Joule or KJ)</td>
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<td>(E_{ck})</td>
<td>Critical kinetic energy of impact (Joule or KJ)</td>
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<tr>
<td>(E_{cs})</td>
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<tr>
<td>(E_{cp})</td>
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<tr>
<td>(a)</td>
<td>Aggregate size of concrete (mm or m)</td>
</tr>
<tr>
<td>(E)</td>
<td>Young’s modulus of elasticity (GPa) and (psi)</td>
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<tr>
<td>(E_s)</td>
<td>Young’s modulus of elasticity of steel (GPa) and (psi)</td>
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<tr>
<td>(\rho_c) or (\rho)</td>
<td>Unit weight of concrete ((w/v)) (kg/m(^3))</td>
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<tr>
<td>(V_p)</td>
<td>Ballistic limit velocity (m/sec) and (ft/sec)</td>
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<tr>
<td>(P)</td>
<td>Cross sectional perimeter of missile in CEA – EDF formula (mm or m)</td>
</tr>
<tr>
<td>(r)</td>
<td>Percentage of reinforcement (%)</td>
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$c_r$ - Rebar spacing of reinforcement (mm or m)

$k_c$ - Unconfined compressive strength of concrete UKAEA formula (MPa)

$C$ - Dimensional co-efficient for Stone Webster formula

$u$ - Reference velocity for Chang formula (m/sec) and (ft/sec)

$I_a$ - Halder and Hamieh Impact factor

$N^*$ - Nose Shape factor

$N_h$ - Hughes nose shape factor

$I_h$ - Hughes Non-dimensional impact factor

$f_t$ - Tensile strength of concrete (Mpa) and (psi)

$S$ - Hughes ($DIF$) Dynamic Increase Factor

$H_r$ - Reference or assumed thickness of the concrete slab (mm or m)

$\sigma_i$ - Rate dependent characteristic strength of concrete

$d_r$ - Diameter of the reinforcing steel bar (mm)

$r_t$ - Total bending reinforcement (% EWBF)

$h$ - Length of nose of the projectile (mm or m)

$N$ - Geometry function

$I$ - Impact function

$F_R$ - Resultant Force (N)

$C_d$ - Drag co-efficient, for granular medium

$V_{cc}$ - The impact velocity to initiate through-thickness cone cracking, (m/sec)

$DIF$ - Dynamic increase factor

$\sigma_c$ - Uni-axial compressive strength of concrete target (Mpa).

$\sigma_t$ - Uni-axial tensile strength of concrete target (Mpa).

$V_f$ - Impact velocity of projectile for tunnelling (m/sec).

$N_f$ - Empirical nose shape frictional factor.

$N_i$ - Nose shape factor (Imran and Ismail)

$\Psi$ - CRH ratio (S/d).

$S$ - Dimensionless empirical constant

$H/d$ - Relative target thickness and missile diameter ratio

$kd$ - Depth of initial conical crater (mm or m).

$H_{eff}$ - Effective target thickness (mm or m).

$\delta$ - Angular directional change

$\beta$ - Initial obliquity angle
\( \tau_f \) - Shear strength of concrete (Mpa) and (psi)
\( \alpha \) - Cone slope angle
\( A_s \) - Surface area of cone plug (mm\(^2\) or m\(^2\))
\( H' \) or \( H^* \) - Remaining plug thickness of concrete after penetration (mm or m).
\( F_S \) - Shear force (N)
\( H'_{BL} \) - Remaining plug thickness of concrete for ballistic limit (mm or m).
\( I_{BL} \) - Impact factor for ballistic limit of concrete
\( I^* \) - Residual impact factor after ballistic of concrete.
\( V_{BL} \) - Ballistic limit velocity for concrete
\( V^* \) - Residual velocity after ballistic of concrete
\( R_d \) - Radius of cross-section or rear plug
\( \rho_s \) - Reinforcement ratio \( (f_s/f_c) \)
\( f_s \) - uni-axial tensile strength of steel reinforcement
\( \Theta \) - Reinforcement factor
\( \chi \) - Dimensionless thickness of concrete
\( \chi_c \) - Critical dimensionless thickness of concrete
\( \sigma_n \) - Normal penetration resistance
\( \sigma_y \) - Dynamic strength of the projectile
\( I_{c1} \) - Upper limit for the rigid projectile regime
\( I_{c2} \) - Lower limit of impact function for the semi-hydrodynamic regime
\( \sigma_q \) - Quasi-static strength of the projectile material.
\( EWEF \) - Each Way Each Face
\( \sigma_y \) - Yield strength of the target material
\( FE \) - Finite element
\( FD \) - Finite differences
\( DE \) - Discrete Elements
\( L_e \) - Characteristic element dimension
\( \varepsilon_{c}^{pl} \) - Compressive plastic strain (%)
\( \varepsilon_{c}^{in} \) - Compressive inelastic strain (%)
\( \varepsilon_{t}^{pl} \) - Tensile plastic strain (%)
\( \varepsilon_{t}^{ck} \) - Tensile cracking strain (%)
\( d_c \) - Compressive damage parameter
\( d_t \) - Tensile damage parameter
\( \delta_c \) - Compressive stiffness recovery stress state function
\( \delta_t \) - Tensile stiffness recovery stress state function
\( E_{io} \) - Initial (Undamaged) modulus of elasticity (Gpa).
\( \varepsilon_c \) - Total compressive strain (%)
\( \varepsilon_t \) - Total tensile strain (%).
\( \sigma_{to} \) - Uni-axial tension failure stress
\( \sigma_{co} \) - Uni-axial initial yield compression stress
\( \sigma_{cu} \) - Ultimate compressive stress
\( \varepsilon_{p_l} \) - Equivalent plastic strain in tension
\( \varepsilon_{c_l} \) - Equivalent plastic strain in compression
\( w_c \) - Compression stiffness recovery parameter
\( w_t \) - Tensile stiffness recovery parameter
\( \varepsilon_{in} \) - An inelastic strain in compression
\( E_{ct} \) - Critical impact energy for tunnelling process (J or KJ).
\( E_{exp} \) - Critical impact energy for spalling (J or KJ).
\( E_{rs} \) - Residual impact energy after spalling (J or KJ).
\( E_{rp} \) - Residual impact energy after penetration/perforation (J or KJ).
\( E_{cBL} \) - Critical impact energy for Ballistic limit (J or KJ).
\( E_{rBL} \) - Residual impact energy after Ballistic limit (J or KJ).
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CHAPTER 1

INTRODUCTION

1.1 Background

Impact events occur in a wide variety of circumstances, from the everyday occurrence of striking a nail with hammer to the natural & man made disasters. We frequently see the results of these disasters affecting our environment. Especially, through media reports on impact accidents in conventional and un-conventional structures caused by natural disasters, or collision impact & explosions occur either accidently or deliberately. Thus, the safety of public is growing concerned, including the nuclear accidents.

Impact damage is a matter of growing concern in many fields of study such as nuclear, chemical, civil, mechanical, electrical, and other engineering disciplines. In general, the dynamics of impact is an important consideration in the design of conventional structures, and sensitive and un-conventional structures in particular, such as nuclear plants, power plants, military structures, weapon industries, weapons storage places, bunkers, water retaining structures (dams, barrages, etc.), chemical and local industries, highway and railway bridges, tunnels, flyways, barriers & etc. These kinds of conventional, sensitive and un-conventional structures should have to be designed as self protective structures against impact and explosive loading generated by any natural disaster (tsunami, hurricane, tornado, wind storm, sand storm and earthquakes etc.), consciously engendered unpleasant incidents (terrorist attacks etc), or/and against accidently occur incidents in nuclear plants, weapon
industries, weapon storage places, local industries, and collision of air crafts, buses, trains with buildings, etc.

The materials which are used to construct those kind of conventional, sensitive, and un-conventional structures including brick, concrete, ductile, and brittle metals, ceramics, and polymer composites are emerging anxiety against the impact scenarios. Among all of them since mid of 18th century concrete is often used as economical construction material with confidence, for the military and civilian above mentioned conventional, sensitive and unconventional structures. As most of the structures are constructed with normal strength and high strength concrete so it is vital to have a good knowledge of the behaviour of concrete against impact and explosive loading for the designing of high-quality protective structures.

Local impact damage can be simplified as the impact damage caused by vehicle/train collision, aircraft/missile, and drop-weights, free falling bodies on concrete structures, except explosion. In local impact damage, vehicles, trains, aircrafts, missiles, drop-weights, and free falling bodies are considered as impact projectiles. Projectile may exists in a long diversity in sizes, shapes, velocity, weight, density, etc such as bullets, fragments, tornado, missile, explosive bomb, steel rod, flying objects at high speed, etc. The impacting projectile (missile) can be classified as ‘Hard’ and ‘Soft’ in nature, depending upon the implication of its deformation with respect to the deformation of target. Hard missile impact can generate both local impact damages and global damages on concrete structures.

An impact at diverse scenarios generates various kinds of effects, depending upon nature of impact, target structure, impact scenarios, and boundary conditions etc. The projectile generated by wind storm, hurricane cyclone, vehicle collisions, aircraft crash, missile, fragments, explosion, can cause different damage effects on concrete structures depending upon structural construction such as underground structures, under sea structures, structures on ground and etc. The angle at which projectile hit at the concrete structures is another complexity of the impact scenarios. Respectively, structural response of structure also varies depending upon the boundary conditions of structure and position of projectile at which it collide with structure.
In this study interest was paying attention on response of concrete target against local impact effects caused by hard projectile, bearing in mind that projectile collision is directly hitting the structure at perpendicular direction above ground, considering failure criteria, contact mechanics, material model, and parametric analysis (velocity of missile, weight of missile, size and shape of missile, normal direction of impact, density of missile and target, thickness of structure, strength of concrete).

Due to intricacy of the local impact effects and complex behaviour of concrete, investigations are generally carried out based on experimental data. Conclusions of the experimental observations are then used to develop engineering models. It is observed from literature that, the local impact effect of hard projectile on concrete targets normally can be studied by three engineering techniques using experimental observations:

- Empirical analysis based on experimental data by fitting curve,
- Idealised analytical modelling based on physical laws, and
- Numerical simulations based on computational mechanics and material models.

In some situation, several of these methods are considered as expensive or may be impractical within limited resources. However, since there have been noteworthy development in technology, numerical simulation techniques become more accepted method for determining the detailed response of non-linear analysis, and are considered as one of the cost effective methods.

Therefore, the present study was mainly focused on finding the critical impact energies due to local impact effects such as penetration, perforation and scabbing caused by hard missile impact on concrete structures in normal direction, via
Empirical formulae based on curve fitting on existing data,

Analytical Modelling, based on physical laws, and

Numerical simulation by using finite element dynamic explicit analysis engineering technique on Concrete Damaged Plasticity model in ABAQUS Version 6.9 software.

The results obtained from this study can be used for making design recommendation and design procedures for determining the dynamic response of the concrete target in order to prevent local impact damage.

1.2 Problem Definition and Need for this Research

Natural disaster such as tsunami, earthquake, wind, hurricane vehicle collision, aircraft crash, accident in nuclear and local industries, can generate local impact damage in concrete structures by generating projectile such as flying objects during wind storm, hurricane, cyclones etc can colloids with concrete structure at certain speed which can initiate the local impact damage. The impact waves with 120ft height of tsunami certainly cause lifting of objects and colloids with buildings also can be reason of local impact damage of concrete structures. An earthquake can cause the free falling impact on buildings which also counted as the reason of local impact damage in concrete structures. An air plane crash or vehicle collision in to the building either accidentally or deliberately (terrorist attack) also generate local impact damage of conventional, unconventional, and sensitive structures.

In general, the security and safety is become the major concern of the public because of increasing number of natural disaster which causing death causalities and impact damage on conventional, unconventional, and sensitive structures such as Indian Ocean tsunami in South Asia 2004, Cyclone Nargis in Myanmar 2008, in 2010 Salang avalanches Afghanistan and Kohistan avalanche in Pakistan, 2008 Afghanistan blizzard, 2008 Chinese winter storm, Hurricane Katrina, 2010 Haiti
earthquake, 2011 Tohoku earthquake tsunami causing accident in nuclear plant in Japan, Rio de Janeiro flood and landslide 2011, 2008 Santa Catarina floods and mudslides, and etc.. The statistical survey shows that the death toll and structural damage caused by natural disasters is much higher as compared to the causalities and structural damage of both World Wars. Natural disasters are considered deadliest because the structural damage is much greater as compared to the death tolls. The last decade was the deadliest ever decades of occurrence of natural disasters. Among all the countries in the world, Asian region was more affected as compared to other parts of World (2011 Statistical Yearbook for Asia and the Pacific, Economic and Social Commission for Asia and Pacific ESCAP, United Nations UN).

The growing number of terrorist attacks around the world is another eye catching figure to realise the problem of security and safety of general public, and structural damage of conventional, unconventional, and sensitive structures. According to NCTC (National Counterterrorism Center) WITS (World Incident Tracking System), since 2005 to 2010 in last five years 73,866 terrorist incidents have been recorded. The statistical report of NCTC shows that the most of the terrorist attacks are happened in the region of Asia. In 2007 highest number of terrorist attacks was counted (2010 Report on Terrorism, National Counter Terrorism Centre). Thus, in general it is worthy to study dynamics of impact loading, and behaviour of the concrete target.

For this study, In particular, the versatility of concrete as a building material demands advanced research for improving the practical techniques of designing as a self protective structure against above mentioned impact loading issues with different aspects. Concrete subjected to impact loading involves the dynamic of structures, and dynamics of structures which depends upon the impact energy. It means that the ‘impact energy’ is the dominant cause of damages occurs due to moving objects. When hard projectile collides with concrete target, it is the impact energy of the projectile that makes concrete target to deform. It was observed from literature review on local impact damage of concrete structure against impact of hard projectile that the only limited number of researchers investigated the local impact effects of hard missile on concrete targets incorporating impact energy. Based on the impact energy theory, the aim of this research was to estimate the critical impact energy
required for penetration, scabbing and perforation of concrete target subjected to
hard projectile impact.

The empirical studies are always important for local impact effects because of
the complex behaviour of concrete target. Huge work has been done by many
researchers based on empirical studies but these were very less efforts made to study
the critical impact energy. According to literature, Li and Reid (2006) modified the
NDRC and UMIST formula in terms of required critical impact energy for scabbing
and perforation of concrete for flat nose hard missile. Furthermore, Li and Reid
(2006) suggested an empirical formula based on experimental data to determine the
critical impact energy for scabbing and perforation of concrete against impact of flat
nose hard missile. Therefore, it is vital to develop empirical formulae based on
experimental data by curve fitting to determine the required critical impact energy
for penetration, scabbing, and perforation of concrete target impacted with hard
projectile, and compared with previous work.

Once the phenomenon is understood accurately, an analytical model can
predicts the most realistic behaviour by application of physical laws. It is most
efficient and economical method used to predict the penetration, scabbing and
perforation of concrete targets under impact of hard missile. As observed in literature
that the Kennedy (1976) applied the concept of conservation of energy for
determining the penetration depth. Later on, Shiqiao et al. (2004) suggested an
analytical formula to calculate scabbing on rear face of concrete target, in dynamic
penetration equation Shiqiao et al. put assumptions of mass, momentum, and energy
conservation. S. Guirguis and E. Guirguis (2009) suggested an energy approach
based on volumetric crushing energy density to predict penetration depth. However,
it is found that Li and Reid (2006) suggested an analytical model to predict the
critical impact energy required to perforate concrete target, when it is impacted with
flat nose hard missile. Therefore, it is suggested that a comprehensive analytical
study have to be carry out to overcome the previous studies in terms of required
critical impact energy for penetration, scabbing and perforation of concrete target
against impact of hard missile.
Numerical simulation analysis is generally sophisticated and therefore needs experience and access to well-equipped facilities. It is observed from literature that the majority of researchers carried out numerical simulation studies using different ‘material models’ with implementation of ‘strain rate effect’ for predicting the penetration, scabbing, and perforation of concrete and reinforced concrete subjected to hard projectile impact. In numerical simulation very little work has been found on critical impact energy of hard projectile required to causing penetration, scabbing, and perforation in concrete structures against hard projectile impact. Another controversial gap in numerical simulation models for concrete against impact loading has been highlighted. According to Li and Meng (2003) the dynamic uni-axial compressive strength enhancement of concrete occurs because of lateral confinement of concrete rather than a genuine strain-rate effect. According to Li et al. (2005) unfortunately, importance of the ‘lateral confinement’ in the measured enhancement of the uni-axial compressive strength of concrete in a Split Hopkin pressure Bar Test (SHPB) has not been completely understood, or seriously addressed in previous publications. It is continuously being interpreted as a strain-rate enhancement in almost all experimental publications, and has been frequently implemented into concrete models for numerical simulation. It may lead to overestimates of the dynamic strength of a concrete structure and to dangerous design since the measured dynamic enhancement of the uni-axial compressive strength of concrete could actually be due to the lateral confinement and this enhancement might have already been accounted for in other parts of the concrete model. Therefore, a numerical simulation study also have been conducted to determine the critical impact energy of hard projectile causing against penetration, scabbing, and perforation of concrete targets using ABAQUS software with the help of Concrete Damaged Plasticity model, and dynamic explicit analysis.

1.3 Objectives of Research

The principal aim of this research was to rigorously analyse the prognostic empirical formulae, numerical simulations, and analytical models to be able to predict comprehensive behaviour of concrete protective structures against local impact
effects (Penetration, Scabbing, and Perforation) due to hard missile classify on critical impact energies. Based on the aim of this research, following objectives were for investigation:

- To investigate the true behaviour of concrete protective structures against local impact effect (penetration, scabbing and perforation) based on critical impact energy approach.

- To identify the benefits and limitations of numerical simulation techniques, by using Concrete Damaged Plasticity model with the help of dynamic explicit analysis using ABAQUS software version 6.5.

- To determine the required critical impact energy of ogive nose hard missile to penetrate the concrete target together with the effect of diameter and CRH ratio by numerical simulation, in case of CRH ratio = 2.0, 3.0, 4.25, 6.0).

- To determine the required critical impact energy of ogive nose hard missile to perforate the concrete target, and residual impact energy after perforation by numerical simulation (CRH ratio = 3.0, 4.25, 6.0).

- To determine the required critical impact energies of flat nose hard missile to scab the concrete target together with the effect of diameter and target thickness by numerical simulation.

- To develop the new analytical model and empirical formulae for the prediction of required critical impact energy which can initiate the penetration, perforation and scabbing in concrete targets with flat and ogive nose shape hard missile.
1.4 Scope of Investigations

Within limited resources and available data, scope of investigations is defined in detail to achieve the above mentioned aims and objectives of this research. The critical impact energy is set to be determine for penetration and perforation with the effect of diameter of projectile ranging from 12.92mm to 76.20mm and CRH ratio ranging from 2.0 to 6.0, within the range of 1225m/sec by three ways of studies i) Empirical, ii) analytical, and iii) Numerical simulation. Residual energy also has been determined at perforation within same above mentioned scope. The critical impact energy required to produce scabbing in concrete target on the impact of flat nose hard missile also have been determined by all three means of study. Furthermore, the assessment of reliability of Concrete Damaged Plasticity model in ABAQUS Version 6.5 software for the development of numerical simulation solutions of non-linear impact analysis has been conducted. The key realization of this study is the finding of critical impact energies required to produce or initiate the local impact effects (penetration, scabbing, and perforation) in concrete protective structures with the assumption of hard missile in normal direction, which further instigate improvements in the previous studies.

1.5 Thesis Layout

This study of critical impact energy of hard projectile for local impact effect (penetration, scabbing, and perforation) of concrete protective structures is illustrated into seven (7) chapters in following manner:

Chapter One: Introduction, containing introduction of research topic with background proceeds to outline the problem statement and need of this research based on literature review, followed by the primary objectives, scope of the study with introductory remarks.

Chapter Two: Contains the literature review of published research work on experimental, empirical, analytical, and numerical simulations of local impact effects
(penetration, scabbing, and perforation) of hard missile on concrete and reinforced concrete protective targets. The simulation modelling techniques, methods and material models is also included. Furthermore, basics of Impact and concepts of local impact effects, hard and soft missile,

Chapter Three: Illustrates about the available experimental data, mechanical properties of concrete and projectile, initial and boundary conditions, and methodology used for this research. A brief explanation of Dynamic Explicit algorithm, and Concrete Damaged Plasticity Model for performing dynamic simulation in ABAQUS Version 6.5 is also presented in detail in Appendix – F, and Appendix – G as part of this chapter.

Chapter Four: This chapter contains the brief explanation of course of entire action of numerical simulations. The stand alone results of simulations are explained and discussed briefly.

Chapter Five: In this chapter development of new empirical formulae, which are newly proposed for prediction of local impact effects within their valid ranges. And the development of proposed analytical models for required critical impact energy to penetration, scabbing, and perforation concrete targets based on assumptions of physical law’s are explained.

Chapter Six: Validation, verification and Discussion about the fallout of numerical simulations and the domino effects of newly developed analytical models, and empirical formulae. It also shows the comparison of the results of this study with some high profile analytical and empirical formulae predictions.

Chapter Seven: The final chapter discussed about the conclusion achieved from this study with counselling for probable advance perfections by keeping in view the core principles, and objectives of this study. Furthermore, the limitations of newly developed empirical formulae, analytical model and numerical simulations also have been presented. The recommendations for future work also have been discussed based on this research.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The concrete behaviour firstly examined in the mid 17th century, against the local impact effect of hard projectile (Li et al., 2005). Since than until now, the studies are carried because of continuous modification in the performance and capability of destructive military application that accordingly need to upgrade the concrete protective structures.

A review of research works revealed that peak studies of concrete structures against dynamic loadings were conducted from the early 1940s (Wang et al., 2007). However, most of the research work ceased shortly after World War – II and was not resumed until 1960s because losses of World War II caused reduction of interest (Wang et al., 2007). The intensive study of the impact effects of hard missiles on concrete targets in the nuclear industry started about three and half decades ago. Kennedy (1976) provided an early review of the concrete design against missile local impact effects of hard projectile for nuclear industry. This and other research described several phenomena associated with local impact effects on concrete targets, including penetration, cone cracking and plugging, spalling, scabbing, and perforation, etc., which have been discussed intensively in previous publications, e.g., Kennedy (1976), Bangash (1993), Williams (1994), Corbett et al. (1996), and Li et al. (2005).
There’re three ways to study local impact effect of hard missile on concrete structures. Empirical methods based on experimental data, Analytical methods based on physical laws, and third one numerical simulation methods based on computer based material model. Experimental data is always important for understanding and making comparison with other methods.

A comprehensive review of empirical, analytical and simulation studies of local impact effect of hard missile on concrete and reinforced concrete targets are presented and discussed in section (2.16), (2.17), (2.18).

2.2 Impact and Explosion

An impact is defined as the collision of one body with another body. The force or impetus with which one body hits another or with which two objects collides, transmitted by a collision is sudden time-dependent load. Whereas, an explosion is defined as the release of mechanical, chemical, or nuclear energy in sudden and often violent manner subjected to heat, friction, and detonation (undergoes a very rapid chemical change) which exerts pressure in surrounding medium (concrete wall, steel, brick, soil, air, water, etc.)

2.3 Conventional Projectiles (Missiles) or Impactors

Natural disaster such as tsunami, earthquake, wind, hurricane vehicle collision, aircraft crash, accident in nuclear and local industries, etc., can generate local impact damage in concrete structures by generating projectile. A projectile in form of missile is first given an initial velocity and it is then possible to assume that it is moving under the action of its own weight.

For impact analysis and design, projectile generated by tornadoes, hurricanes and wind can be anything from roof tiles and planks to cars, Lorries, boats etc. Because of mechanical faults or for other reasons, components have been ejected
from parent structures with greater velocities and, acting as projectiles, have had devastating effects on the workforce and on structures.

In combat and terrorist attack situation, military weapons (missiles, bullets, explosion fragments), aircraft, helicopters, vehicles crashes are always in action to produce projectile effects and local impact damage on conventional, sensitive and un-conventional structures on ground, underground or in the sea etc. The breakaway rotors, engines, wings and tails themselves act as high-speed missiles. Vehicles ships tankers and high speed boats collide with vital installations and consequently are major hazards.

On environmental side, falling trees, high speed water jets, ejecting material from barriers (as fragments) during spalling, penetration, scabbing and perforation process, water waves, snow/ice loads impacting on structures and projectile, fragments generated by blasts and explosion due to gas leaks and nuclear detonations are part of a wider aspect of impact problems.

2.4 Hard and Soft Projectiles and its Impact

Projectile may exists in a long diversity in sizes, shapes, velocity, weight, density, etc such as bullets, fragments, tornado, missile, explosive bomb, steel rod, air plane, flying objects at high speed, etc.

The impacting projectile (missile) may be classified as ‘Hard’ and ‘Soft’ depending upon deformability of projectile with respect to target’s deformation. Deformation of hard missile is considerable smaller or negligible compared with target’s deformation. Almost in all cases hard missiles are considered as non – deformable or rigid. However, ‘Soft’ missile deforms itself considerably well as compared to target’s deformation (Kennedy 1976), (Li et al. 2005), and (Koechlin and Potapov 2009). The respective impact caused according with classification of missile is considered as Hard Impact and Soft Impact.
2.5 Theory of Local Impact damage on concrete

Local impact damage of concrete can be defined as the damage caused by projectile with its physical parameters because of collision (vehicle/train collision, aircraft/missile, and drop-weights, free falling), not because of explosion is known as
local impact damage. Local impact effect is further briefly sub-divided in below explained processes:

- Radial cracking,
- Spalling,
- Penetration,
- Cone cracking and plugging,
- Scabbing, and
- Perforation.

### 2.5.1 Radial Cracking

When projectile thump the target with very low velocities, in the result projectile become rebound without producing any local damage to target except just only hair cracks on impacted area. The increase in velocity cause local impact damage on the impacted surface of target, the impact generates global cracks combined with cone cracks right under the face of projectile, global cracks originated from cone cracks (under the point of impact), as process goes these global cracks broaden into the target in every direction, first along impacted face, and along thickness of target and finally on back face of target. Radial cracking generates rapid change into the behaviour of concrete target and causes complexity because of rapid increase in strain (Li et al. 2005).

![Figure 2.3](image)  
**Figure 2.3** Radial cracking in local impact phenomena caused by hard projectile.
2.5.2 Spalling

The further increase in velocity cause more impact, it cause ejection of material of target from front face (impacted face). Due to impact of hard projectile, spalling produces spall crater in the surrounding area of impact. Spall crater is the total damaged portion of peeling off material from target on impacted face. Generally spall crater have greater area than the cross-sectional area of projectile. Spalling and spall crater depends upon the shape, velocity, cross-sectional area, mass, and nose shape of projectile. Normally the projectile have velocity within the medium range creates more spalling and form greater spall crater. However high velocity causes low spalling and spall crater (Kennedy 1976), and (Li et al. 2005).

![Figure 2.4](image-url)  
Figure 2.4 Spalling in local impact phenomena caused by hard projectile.

2.5.3 Penetration

Tunnelling is defined as the infiltration or digging of projectile into the concrete target beyond the depth of spall crater. The tunnelling forms a hole inside the target having slightly greater diameter than the diameter of projectile. Penetration can be defined as the combined depth of spall crater + tunnelling depth. Penetration further can be explained as when the missile goes through in a semi-infinite medium of target, it causes no effect on rear face (Kennedy 1976), and (Li et al. 2005).
2.5.4 Cone Cracking and Plugging

Cone cracking and plugging of concrete is another complex response against the impact of hard missile. Cone cracking and plugging occurs during transition process from penetration to scabbing. When missile with plastic shocks having larger vigour than the elastic wave’s colloids with rear border of concrete targets it generates curved shear cracks in the shape of bell plug is called cone cracking and plugging (Li et al. 2005).
2.5.5  Scabbing

Scabbing occurs when the dynamic force in shape of waves generated by projectile within the target become equal or greater than the tensile strength of target and force bell plug and shears-off the surrounding material of target from back face of target. Generally the zone of scabbing is wider than the zone of spalling, however zone of spalling have greater depth than the depth of scabbing. Once the scabbing instigates in target, it means there is no further strength remains in concrete target to resist further local impact effects (Kennedy 1976), and (Li et al. 2005).

![Figure 2.7](image)

**Figure 2.7**  Scabbing in local impact phenomena caused by hard projectile.

2.5.6  Perforation

The last process of damage due to hard missile impact is perforation. Perforation means complete passage or complete crossing of projectile through the target. It causes missile to extend penetration hole through scabbing crater and exit from the rear face of target (Kennedy 1976), and (Li et al. 2005).
Among these six local impact effects of hard missiles on concrete targets, penetration, scabbing, and perforation are frequently used to quantify for the designing of protective structure.

2.6  Global Impact Damage

The global impact effect is considered as the overall concrete wall collapse caused by the impact of hard missile. Mostly the global impact of concrete target during impact of hard missile occurs because of three types of failure mechanism or either by combination of these three failure mechanisms. Punching shear failure, membrane induced tensile failure, and bending induced tensile failure. In terms of energy the global impact effect (overall concrete target collapse) can be prevented by designing the wall to have reserve strain energy capacity greater than the total absorbed energy to which it is subjected (Kennedy 1976), and (Li et al. 2005).
2.7 Concrete Behaviour Under Impact Loading

The behaviour of concrete differs in dynamic loading compared to static loading. The initial stiffness, as well the ultimate strength, increases in both compression and tension. Furthermore, the concrete strain capacity is extended in dynamic loading. Concrete will crush and crack and the structure will shake and vibrate. The pressure at the front of the nose of the projectile is several times higher than the static uni-axial strength of concrete, also the lateral confining pressure. In addition, a stress wave is propagating from the tip of the nose of the projectile. In front of the nose of projectile, the impact may cause crushing. Since concrete is very weak in tension, the tensile wave obtained when the compressive wave hits the backside of the wall may cause scabbing at the backside, and cracking in the lateral direction. Both the compressive strength and the tensile strength of concrete are important parameters for the penetration, scabbing, and perforation. Moreover, the crater size depends on the tensile strength.

At Delft University, Zielinski (1982) followed a phenomenological approach where he compared static and impact tensions. He observed a changing geometry of the fracture plane. With increasing loading rate, the amount of aggregate fracture increased. Furthermore, multiple fractures were observed at high loading rates, as shown in figure (2.10).
2.8 Concrete Behaviour Under High lateral Pressure

When concrete is subjected to extremely high pressures, as in an impact situation, the lateral pressure suddenly becomes much higher. During fragment impacts, concrete is exposed to enormous confining pressures and behaves plastically, dissipating a large amount of energy. In addition, civil defence shelters have heavy reinforcement, which provides further confinement effects. The confining pressure in impact loading can be several hundred MPa. In a standard static tri-axial test, the ultimate strength of
concrete can increase greatly. Experiments by Bažant et al. (1996), with a uni-axial compressive strength of (46MPa), showed that the ultimate strength increased up to (800MPa), and the strains were extended as shown in figure (2.12).

![Stress-strain relationships for uni-axial compressive strength (46MPa) concrete at high lateral pressure based on tri-axial compression test data from Bažant et al. (1996).](image)

**Figure 2.12** Stress-strain relationships for uni-axial compressive strength (46MPa) concrete at high lateral pressure based on tri-axial compression test data from Bažant et al. (1996).

### 2.9 Fibre-Reinforced Concrete Behaviour Under Impact Loading

Though there are numerous types of fibres available, steel fibres are the most commonly used ones. Their common use is based on the considerations of costs, availability, stability at high temperatures, as well as overall improvement in mechanical properties.

Clifton (1982) reported in his review that investigations by Williamson (1966) on concretes subjected to explosives showed that the inclusion of fibres increased the shatter resistance of concrete with (80%) reduction in fragmentation and (20%) decrease in velocities of ejected fragments. Naus and Williamson (1976) qualitatively demonstrated that fibre-reinforced concrete was more resistant to penetration and to repeated impacts by small projectiles than plain concrete.
Experimental results of fibre-reinforced concretes subjected to high velocity projectile impacts by Anderson and Watson (1984) indicates that the penetration resistance of concrete, measured in terms of the penetration depth, is not greatly influenced by the fibre type (steel, polypropylene, or Aramid fibres), and by fibre content within a practical range. However, the results showed that greater fibre contents in the concrete leads to smaller crater volumes. Ramakrishnan et al. (1979) observed that the incorporation of one type of fibres with hooked ends increased shotcrete resistance by over (500%) in low velocity impact (by a 4.5 kg hammer falling 46 cm) compared to plain shotcrete. An increase in impact resistance of around (200%) was obtained using the hooked-end fibres in concrete compared to straight fibres (Clifton 1982).

A study of high velocity projectile impact on slurry infiltrated fibre Concrete (SIFCON) by Anderson and Watson (1992) shows that the incorporation of fibres reduces spalling and scab damage. It was also observed that the gravel used in the concrete was effective in preventing perforation of the specimens. Hence, it was suggested that a composite containing both gravel and fibres might provide an optimum solution to reduce overall impact damage.

Dancygier and Yankelevsky (1996) observed a reduced brittleness of high strength concrete with steel fibres under impact. A comparison of crater dimensions between the fibre-reinforced and plain concrete indicates that the fibres tend to arrest crack development and thus minimize the size of damaged area.

Conclusions drawn from an experimental study on impact penetration by O’Neil and Neeley (1999) reiterated some key points mentioned by Anderson and Watson (1984) as well as Dancygier and Yankelevsky (1996) that the incorporation of fibres does not significantly reduce the penetration depth of a given strength of concrete, though it does reduce the visible damage.
2.10 Effect of Impact Velocity on Local Impact Damage of Concrete

Impact loading has different velocity regimes and the response of the structure changes among these regimes. In fact, if the problem falls in low velocity regime (<250m/s) local indentation or penetrations are strongly related to the overall deformation of the structure, when it is in the intermediate velocity regime, (0.5-2km/s), instead of response of the whole system, behaviour of the material within the impact area 2-3 diameter of the projectile becomes dominant. Effects of velocity, geometry, material characteristics, and localized plastic flow, failure and strain rates are quite of importance and total incident time is defined in microseconds. Impact velocity of 2-3 km/s (upper limit of this range is the lower limit of the hypervelocity impact of 3-12 km/s) makes localized pressures above the strength of the material by an order of magnitude and colliding solids act like fluid in early stages of impact. For ultra-high velocity impact (>12km/s), explosive vaporization of the materials takes place because of very high strain rates. Zukas et al., (1982) Figure (2.13) explains the effect of impact with the method of loading and strain rate.

![Figure 2.13](image)

Figure 2.13 Effect of impact with method of loading and strain rate Zukas et al., (1982).

If material is shocked to very high pressures, it behaves like a fluid, but otherwise strength parameters control response of the material. Examples for responses can be given as follows: projectile making a deep tunnel in low strength...
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