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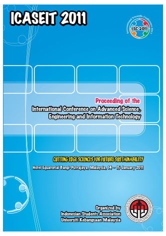

Ogive Nose Hard Missile Penetrating Concrete Slab Numerical Simulation Approach

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***Abstract*— Great demand exists for more efficient design to protect delicate and serious structures such as nuclear plants, Power plants, Weapon Industries, weapons storage places, water retaining structures, & etc, against impact of kinetic missiles generated both accidentally and deliberately such as dynamic loading, incident occurs in nuclear plants, terrorist attack, Natural disasters like tsunami and etc., in various impact and blast scenarios for both civilian and military activities. In many cases, projectiles can be treated as rigid bodies when their damage and erosion are not severe. Due to the intricacy of the local impact damages, investigations are generally based on experimental data. Conclusions of the experimental observations are then used to guide engineering models. Local damages studies normally fall into three categories, i.e. empirical formulae based on data fitting, idealised analytical models based on physic laws and numerical simulations based on computational mechanics and material models. In the present study, 2D asymmetrical numerical simulation have done on concrete slab against the impact of ogive nose hard missile of 26.90mm and 76.20mm diameter with CRH ratio 2.0 and 6.0 respectively, for penetration by using Concrete Damaged Plasticity Model, and ABAQUS/Explicit dynamic analysis in ABAQUS. It is found that the strains/stresses are induced in the concrete slab and a very nicely propagation of the stresses inside the concrete slab in the form of waves, which is a clear indication for vibrations of the concrete. The lack of failure criterion in concrete damaged plasticity model does not allow the removal of elements during the analyses. This means that spalling, scabbing, and perforation cannot be modelled with the Concrete Damage Plasticity Model. The penetration depth results shows that the deeper penetration requires higher critical impact kinetic energies, and comparison shows the simulation results are more accurate than other formulae predicted results.**

***Keywords*— Penetration, concrete, local impact, Kinetic energy, Numerical simulation, Ogive Nose, Hard Missile, CRH.**

I. INTRODUCTION

Over the years, concrete is commonly used construction material for the defensive and civil applications, to protect structures from local and explosive impact loads. For the designing of high-quality protective structures it is crucial to have a good knowledge about behaviour of concrete against impact or explosive loading conditions. Projectile exists in a long range with variation in sizes, shapes, velocity, weight, density, hardness, such as aircraft crashes, fragments generated by accidental explosions and other events (e.g., failure of a pressurized vessel, failure of a turbine blade or other high speed rotating machines), flying objects due to natural forces (tornado, meteoroid), bullets, fragments, etc. The projectile 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 ([1], [2], [12]). 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 ([1], [2], [12]). Local impact effect is briefly sub-divided in below explained processes:

Radial Cracking: When projectile colloids with concrete target with certain velocity, it results radial cracks originated from the point of impact within the target in every direction [2].

Spalling: The ejection of material of target from front face (impacted face) due to impact of hard projectile is called spalling. 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 ([1], [2]).

Penetration: Penetration is defined as the digging of missile into the target body afar from the thickness of spall crater. The lengthwise measurement of dig is called penetration depth ([1], [2]).

Cone cracking & Plugging: During penetration missile colloids with rear border of target and generates curved shear cracks in the shape of bell plug is called cone cracking. And than missile continues penetrating through target, it forces plug and shears-off the surrounding material of target is called plugging. This process generates rapid change into the behaviour of target [2].

Scabbing: Ejection of target material from back face of target is called scabbing ([1], [2]).

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 ([1], [2]).

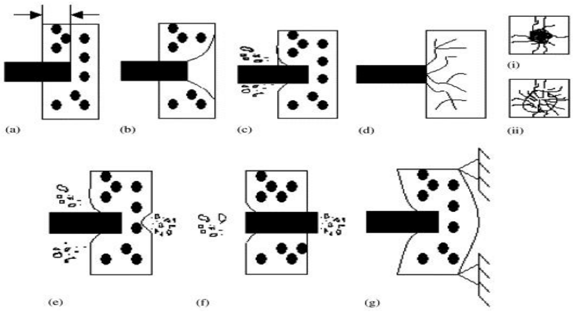

Fig.1. Explains the local impact phenomena caused by hard projectile [2]. (a) Penetration, (b) Cone cracking and Plugging, (c) Spalling, (d) Radial cracking, (e) Scabbing, (f) Perforation, and (g) Global phenomena.

In general, the local impact effect of hard missile on concrete structures can be studied in three ways, (i). Empirical Studies (predict empirical formula based on experimental data), (ii). Analytical Studies (create formula based on physical laws), and (iii), Numerical Simulation (based on computer based material model). Numerical simulation study is fast developed approach to calculate the dynamic behaviour of concrete against local impact effects, and it become more reliable and economical because of its rapid growth. In this paper a numerical simulation study is conducted to overcome the shortcomings of other modes of studies, and to provide a better understanding of ABAQUS Explicit dynamic analysis based on concrete damaged plasticity model with the analysis of required critical impact kinetic energies for maximum penetration.

II. LITERATURE REVIEW

The effects of the local impact of hard missile on concrete structures have been studied since the mid of 17th century because of continuous military interest in designing of high performance missiles and high performance protective barriers [2]. A review of previous research work exposed that peak studies on concrete structures against dynamic loading were conducted from the early 1940s [5]. However, most of the research work ceased shortly after World War – II and were not resumed until 1960s [5]. The intensive study on concrete targets against local impact effects of hard missiles in the nuclear industry re-initiated since five decades ago. Kennedy (1976) provided an early review of the concrete response against local impact effects of hard missile for nuclear industries and recommended impact force time history theory [2]. Various studies were conducted to specify the local impact effects of hard missile on concrete structures, a review of these studies were discussed intensively in previous publications, Kennedy (1976), Bangash (1993), Williams (1994), Corbett et al. (1996) [2].

With the rapid developments of computational tools, computational mechanics and material constitutive models, the numerical simulation of local missile impact effects becomes more reliable and economical. The major differences between a quasi-static constitutive model and a dynamic one of concrete are encapsulated by the needs to understand inertia effects and the effects of strain rate on the deformation and failure of the concrete target. Extensive simulation studies were conducted in past to analyse local impact effects of hard missile on concrete structures.

T.L Teng et. al. (2004) simulates 2D local impact effects of ogive nose missile impacted on reinforced concrete walls perpendicularly, and impacted at 50° oblique with the equivalent inclusion method considering reinforced concrete as homogeneous material. He suggested the equivalent matrix for homogenized material and equivalent material moduli for finite element analysis by using Mori – Tanaka's average strain theory. The FEM proposed model simulates very close results as compared to the experiment considering residual velocity and ricochet limit of projectile [6].

C.Y. Tham (2005) investigated the penetration and perforation of reinforced concrete with 3D hydro-code in AUTODYN and examined the influence of constant-yield strength, pressure-dependent yield strength, and pressure-dependent yield strength + damage + strain-rate hardening. Except for the low velocity regime, the results for the case of the constitutive model with pressure-dependent yield function exhibit strong correlation with experimental residual velocities, and the result from the constitutive model that includes strain-rate and damage with a pressure-dependent yield surface showed relatively good agreement with the experimental residual velocities. The damage contours at the impact and exit surface from the simulation were also consistent with the post-test damage results [9].

Z. L. Wang et. al. (2006) improved and implemented the Taylor-Chen-Kuszmaul (TCK) continuum damage model into the dynamic finite element code, LS – DYNA, with erosion algorithm. The results of impact, exit crater (scabbing), and as well as residual velocity shows good understanding with experimental data. In addition the effect of CRH ratio of ogive nose projectile on impact craters was also investigated, which shows that the higher CRH creates smaller size of crater [5].

M. Polanco - Loria et. al. (2007) investigated Holmquist–Johnson–Cook (HJC) model for concrete with some modifications in pressure shear behaviour, the strain rate sensitivity term, and damage description. The Ballistic limit assessments with deviations under 8% when compared to the experimental results were observed [10].

Wenjie Shiu et. al. (2008) developed a 3D model based on discrete element method (DEM) to predict the penetration depth in to reinforced concrete slab caused by flat nose hard missile. Further simulations were conducted with varying shapes for missile nose, which shows when the ratio of target thickness to missile diameter (H/d) is approximately 1 than the simulation results predicts more reliable results as compared to Chen and Li formulae. Further when the (H/d) increased numerical simulation results agree with Chen and Li formulae [11].

G. Shiqiao .et al. (2008) proposed a fuzzy model for predicting the penetration resistance of concrete against rigid missile. The results of deceleration show good agreement with experimental data [13].

Review of previous work reveals that only limited work have done by researchers in terms of numerical simulations on the local impact effects of hard missile on concrete targets with the vision of impact kinetic energy. The majority of researchers carried out numerical simulation studies on other material models with modification to used for concrete and reinforced concrete subjected to impact loading. Therefore, this numerical simulation study has been carried out to explore and further improve the prognostic simulation models for local impact effects (Penetration) of hard missile on concrete targets footed on impact kinetic energies. The significant task of this research is to classify the benefits and limitations of numerical simulation techniques by using Concrete Damaged Plasticity model with non-linear Abaqus/Explicit impact analysis in ABAQUS software. Furthermore the analysis has been done on required critical impact kinetic energy for maximum penetration of concrete targets together with comparison of penetration depth.

III. CONCRETE DAMAGED PLASTICITY MODEL

Concrete is typically brittle and non-homogeneous in composition. The concrete damaged plasticity model is a continuum, plasticity-based damage model. It assumes that the main two failure mechanisms are tensile cracking and compressive crushing of the concrete material.

The model assumes that the uni-axial tensile and compressive response of concrete is characterized by damaged plasticity. Under the uni-axial tension the stress- strain response follows a linear elastic relationship until the failure stress (σ_{to}) is reached. The failure stress corresponds to the onset of micro-cracking in the concrete material. Beyond the failure stress the formation of micro-cracks is represented macroscopically with a softening stress-strain response, which induces strain localization in the concrete structure [4].

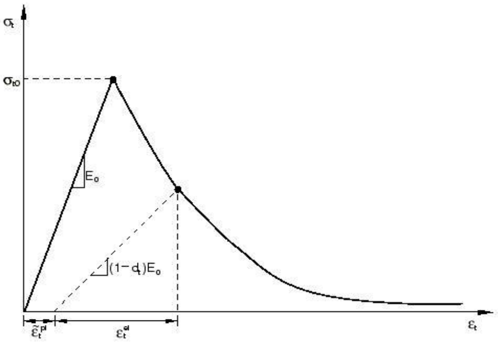

Fig. 2. Shows the tensile response of concrete under uni-axial loading [4].

Under uni-axial compression the response is linear until the value of initial yield stress (σ_{co}). In the plastic regime the response is typically characterized by stress hardening followed by strain softening beyond the ultimate stress (σ_{cu}). This representation, although somewhat simplified, captures the main features of the response of concrete [4].

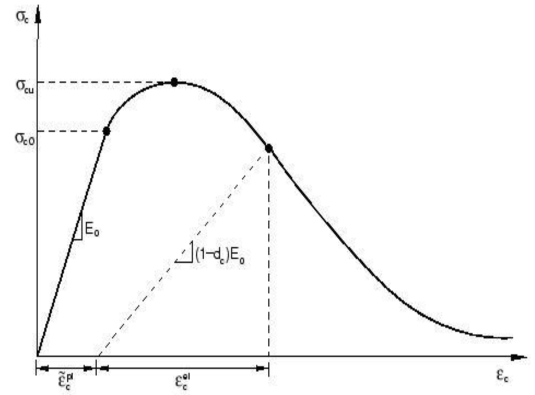

Fig. 3. Shows the Compressive response of concrete under uni-axial loading [4].

In the strain softening branch of the stress-strain curves, the unloading response of concrete is weakened: the elastic stiffness of the material appears to be damaged (or degraded). The degradation of the elastic stiffness is characterized by two damage parameters, compressive damage parameter (d_c) and tensile damage parameter (d_t). If E_o is the initial (undamaged) elastic stiffness of the material, the stress-strain relations under uni-axial tension and compression loading are, respectively [4]:

$$\sigma_t = (1 - d_t)E_o(\varepsilon_t - \varepsilon_t^{pl}) \tag{1}$$

$$\sigma_c = (1 - d_c)E_o(\varepsilon_c - \varepsilon_c^{pl}) \tag{2}$$

Under uni-axial cyclic loading conditions the degradation mechanisms are quite complex, there is some recovery of the elastic stiffness as the load changes sign during a uni-axial cyclic behavior, this stiffness recovery effect, also known as the “unilateral effect”. The effect is usually more pronounced as the load changes from tension to compression, which results in the recovery of the compressive stiffness. The concrete damaged plasticity model assumes that the reduction of the elastic modulus is given in terms of a scalar degradation variable (d) as [4]:

$$E = (1-d)E_o \tag{3}$$

Where E_o is the initial (undamaged) modulus of the material, and the stiffness degradation parameter (d), is a function of the stress state and the uni-axial damage parameters, (d_t) and (d_c) [4]. For the uni-axial cyclic conditions ABAQUS assumes that:

$$(1-d) = (1-\delta_t d_c)(1-\delta_c d_t) \tag{4}$$

The post-failure behavior of concrete in tension and compression can be defined by tension stiffening and compression hardening in terms of cracking strain and an inelastic compressive strain respectively [4].

$$\varepsilon_t^{pl} = \varepsilon_t^{ck} - \frac{d_t}{(1-d_t)}\frac{\sigma_t}{E_o} \tag{5}$$

$$\varepsilon_c^{pl} = \varepsilon_c^{in} - \frac{d_c}{(1-d_c)}\frac{\sigma_c}{E_o} \tag{6}$$

In addition with above mentioned stress-strain parameters of concrete the Density, Young's modulus, Poisson's ratio, Dilation angle, Flow potential eccentricity, Bi-axial/Uni-axial compression plastic strain ratio, Invariant stress ratio, and Viscosity values of concrete is required.

IV. NUMERICAL SIMULATION

The number of simulations have been carried out on three kind of plain concrete slabs (1220mm x 1830mm), (1370mm x 1220mm) and (1370mm x 760mm) impacted in normal direction with ogive nose hard missile of 26.90mm diameter, in case of CRH = 2.0. For the case of CRH = 6.0, concrete slabs of (1830mm x 1830mm) used against the normal impact of ogive nose missiles having diameter of 76.20mm, figure 4 (a) and (b) shows the projectile geometry respectively. The mechanical properties of both concrete slabs and missile are as follows:

$2040 \leq$ Density of concrete (ρ) ≤ 2370 (kg/m^3), $23 \leq$ Unconfined Compressive strength of concrete (F_c) ≤ 108.30 (Mpa), $24.123 \leq$ Young's Modulus (E) ≤ 40.432 (Gpa). $8.35 \leq$ Mass of Projectile (M) ≤ 35.20 (kg), $238.40 \leq$ Velocity of Projectile (V) ≤ 800 (m/sec).

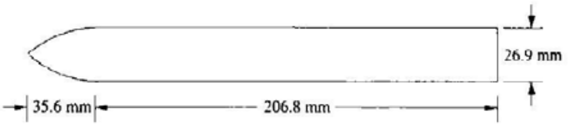

Fig. 4 (a) Projectile geometry for $\psi = 2.0$.

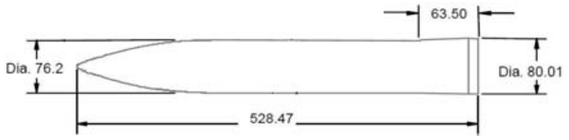

Fig. 4 (b) Projectile geometry for $\psi = 6.0$, all dimensions are in mm.

For the explanation one of the above mentioned simulations is described in detail here. The FE model for ax-symmetric consideration, the concrete slab is defined as block of (685mm x 1220mm) having density 2340 kg/m^3, 35.2Mpa unconfined compressive stress, and 27.79Gpa young's modulus. For mesh of concrete slab quad type standard linear solid elements (ABAQUS elements) are used with Lagrangian formulation. The solid quad elements have a dimension of approximately (27.40mm x 27.11mm), making the mesh of the concrete slab reasonably fine to produce stable time for simulation. The hard missile of 26.9mm in diameter having mass 0.907kg, impacted with 561/m/sec velocity is modelled as a rigid body, in order to avoid excessive simulation times caused by heavy distortion of the elements at the projectile nose. Care was exercised to make sure that the projectile impacted on slab at 90°.

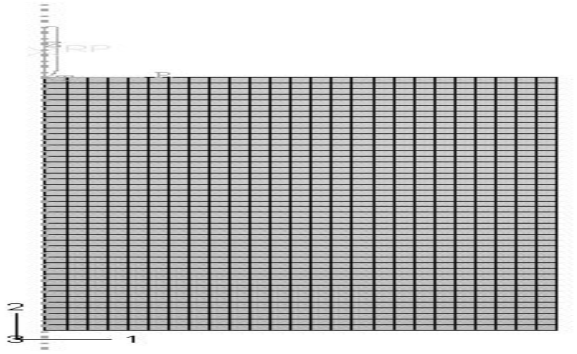

Fig. 5. Finite element grid for ax-symmetric simulation.

Defining the material properties and selection of model always plays important role when undertaking any kind non-linear finite element analysis. Concrete damaged plasticity model uses the concept of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity to represent the inelastic behaviour of concrete, which allows the definition of strain hardening in compression and can be defined to be sensitive to the straining rate, which resembles the behaviour of concrete more realistically. The Concrete Damaged Plasticity Model is designed for applications in which concrete is subject to cyclic loading with alternating tension compression loading, e.g. seismic problems. The model allows stiffness recovery during cyclic loading reversals. Beside of these complex parameters the general parameters like Young's Modulus (E), Poison Ratio (v), Dilation angle (Ø), Flow potential eccentricity (e), Bi-axial/Uni-axial compression plastic strain ratio, invariant stress ratio and viscosity also have to be taken in consideration with importance ([4], [14]).

In order to specify an accurate step analysis is integral to the modelling. In this research, ABAQUS commercial dynamic explicit step is used to analyse the penetration of hard missile in to concrete slab. Determining the dynamic explicit step is an essential task. It should be emphasis that any kind of explicit code is able to facilitate any kind of sophisticated analysis.

Contact interaction is always important for transforming the proper stresses across the common surfaces of two solid bodies and adjacent elements, by element to element so it can behave as natural as real. The fully constrained contact interaction is defined by using surface-to-surface contact technique in ABAQUS by defining the master and slave surfaces. Furthermore, the properties of contact interaction are defined as by penalty method, it provides the realistic stiffness behaviour into the model that can influence the stable time increments. Accordingly, in order to satisfy the constraint the normal contact is assigned as hard contact between missile and concrete target [14].

Appropriate boundary conditions are used for both missile and concrete target. The concrete slab is fixed only along the side edge, in such boundary condition missile also can perforate concrete slab. The missile is constraint to move only in one direction with initial impact velocity in normal direction to the concrete.

V. RESULTS AND DISCUSSION

The Concrete Damaged Plasticity Model clearly provides loading in the form of strains/stresses in the concrete slab due to the missile impact. Figure 6 show the stress distribution of the concrete slab at various moments in time for the impact of the hard missile, and a very nicely propagation of the stresses inside the concrete slab in the form of waves, which is a clear indication for vibrations of the concrete.

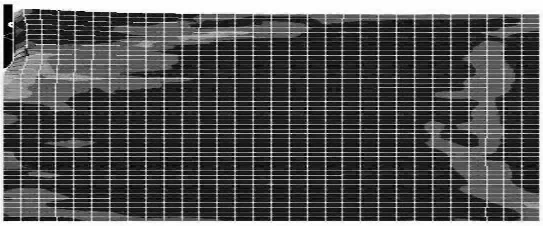

Fig. 6. Deformed mesh plot ax-symmetrical concrete slab against missile.

Figure (7) shows the time history of the position (penetration) of projectile into concrete target, and figure (8) shows the kinetic energy behaviour of missile into the concrete target during penetration with respect to the time for whole model. The missile is enormously slowed down during penetration of concrete slab as the curve for the kinetic energy of the missile reveals.

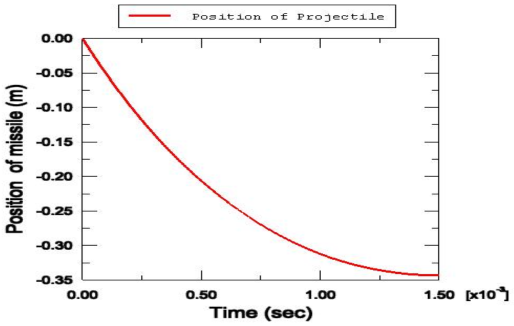

Fig. 7. Shows Position of Missile with respect to the time.

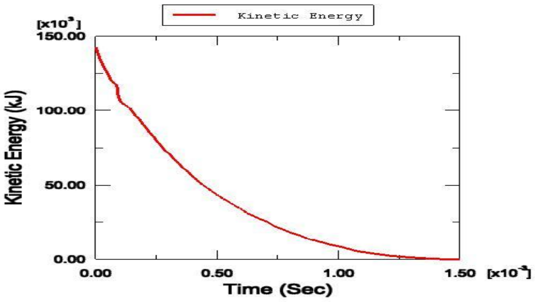

Fig. 8. Shows kinetic energy of Missile with respect to the time.

The results of the impact analyses with a hard missile on concrete slab by using Concrete Damage Plasticity Model of ABAQUS/Explicit reveal that the general obstacle of this constitutive model is that, it contains no failure criteria. Finite elements with high tension stresses or shear stresses cannot be removed throughout the analysis. This means that spalling, scabbing, and perforation cannot be modelled with the Concrete Damage Plasticity Model.

Furthermore the penetration depth results obtained from simulation are presented here which shows the deeper penetration requires higher critical impact kinetic energies, and compared with experimental data, Semi analytical formula, Hughes formula, ACE, UKAEA, and Modified NDRC formulae in terms of kinetic energy. From fig. (9), and (10) in both the cases (CRH = 2.0, and 6.0) it is clearly can be judged that simulation results are closer to the experimental results as compared with all other formulae. It is also can be judged that ACE and UKAEA formulae predict almost same results. It has been shown that Modified NDRC formula gives under prediction results, and the Hughes formula predicts fair results among all empirical formulae.

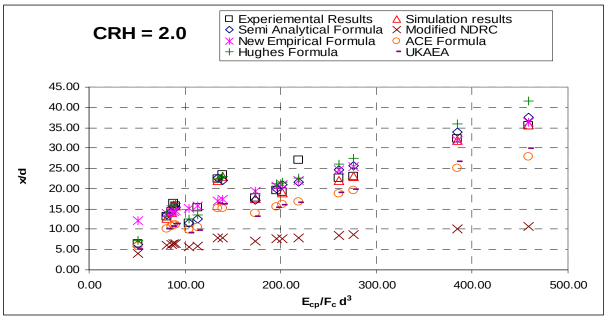

Fig.9. shows the results of simulation and comparison with experimental results of CRH = 2.0.

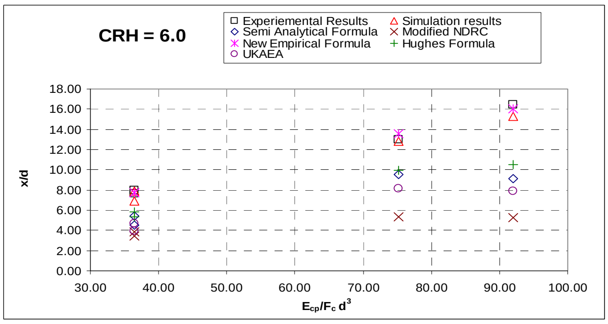

Fig.10. shows the results of simulation and comparison with experimental results of CRH = 6.0.

VI. CONCLUSIONS

Numerical missile impact analyses on a concrete slab were performed with the FE solver ABAQUS/Explicit. Traditional Lagrangian formulations for both the missile and concrete slabs were used, i.e. the missile and the reinforced concrete slab where modelled with solid 2D ax-symmetircal meshes (ABAQUS elements). The constitutive model for concrete in ABAQUS/Explicit, the Concrete Damaged Plasticity Model, is used and its suitability and limitations for missile impact analyses were explored. A hard and a soft missile were used for both constitutive models and sensitivity studies related to the initial missile velocity were performed.

The results show that Strains/stresses are induced in the concrete slab and they propagate in waves through the concrete slab. The lack of failure criterion in concrete damaged plasticity model does not allow the removal of elements during the analyses. This makes it difficult to model missile impact phenomena where spalling, scabbing and perforation of the missile through the concrete slab. This is indeed a problem for the hard missile especially with high initial velocities, for cases, where a deep penetration of the missile into the concrete slab is unlikely straight from the beginning.

Penetration of high velocity objects into the concrete targets is one of the most challenging tribulations for designers in civil defence engineering. Numerical simulation studies have been carried out on the dynamic response of concrete slabs impacted by ogive-nose missile. The penetration depth results also have been carried out for CRH = 2.0, and 6.0 and compared with experimental results, Semi analytical formula, and other empirical formulae. The results compared based on kinetic energy of missile shows that the deeper penetration requires higher critical impact kinetic energies and comparison shows the simulation results are more accurate than other formulae predicted results.

NOMENCLATURE

d	(cylindrical) projectile shank diameter.
E	Modulus of elasticity.
E_k	Impact kinetic energy of the projectile.
E_c	Critical impact energy of projectile.
E_{cp}	Critical impact energy of the projectile for penetration.
σ_c	Uni-axial compressive strength of concrete target.
σ_t	Uni-axial tensile strength of concrete target.
M	Mass of the projectile.
V_o	Impact velocity of projectile.
x	Penetration Depth.
ρ	Density of concrete target.
ε_c^{pl}	Compressive plastic strain
ε_c^{in}	Compressive inelastic strain
ε_t^{pl}	Tensile plastic strain
ε_t^{ck}	Tensile cracking strain
d_c	Compressive damage parameter
d_t.	Tensile damage parameter
δ_c	Compressive stiffness recovery stress state function
δ_t	Tensile stiffness recovery stress state function
E_o	Initial (Undamaged) modulus of elasticity.
ε_c	Total compressive strain
ε_t	Total tensile strain

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