International Journal of Civil & Structural Engineering – IJCSE
Volume 1 : Issue 1 *[ISSN 2372 – 3971]*
Publication Date : 09 January 2014

Critical Impact Energy of Ogive Nose Hard Projectile for Penetration and Perforation of Concrete Slab

Simulation Study

Qadir Bux alias Imran Lateef, Department of Civil Engineering, Faculty of Engineering, University of Buraimi, P. O. Box 890, P. C. 512, Al Buraimi, Oman. E-mail: imranqazi37@gmail.com

Ismail Abdul Rahman, Faculty of Civil and Environmental Engineering, University Tun Hussein Onn Malaysia (UTHM), 86400, Parit Raja, Johor, Malaysia, ismailar@uthm.edu.my

Ahmad Mujahid Ahmad Zaidi, Department of Mechanical Engineering, Faculty of Engineering, National Defence University Malaysia (UPNM), 57000, Kem Sungai Besi, Kuala Lumpur, Malaysia, mujahid@upnm.edu.my

Sasitharan Nagapan, Faculty of Civil and Environmental Engineering, University Tun Hussein Onn Malaysia (UTHM), 86400, Parit Raja, Johor, Malaysia, sasi81@yahoo.com

Kamran Lateef, University Tun Hussein Onn Malaysia (UTHM), 86400, Parit Raja, Johor, Malaysia, engr.kamranqureshi@gmail.com

***Abstract* — In this paper two dimension (2D) asymmetrical numerical simulation analyses has been conducted on ABAQUS using dynamic Explicit analysis and Concrete damaged plasticity constitutive model. The simulation study was conducted for critical impact energy on thick concrete slabs impacted with ogive nose hard projectile diameter of 26.9mm and 76.2mm having CRH ratio 2.0 and 6.0. The limitations of concrete damaged plasticity model also have been analyzed. Furthermore, the simulation modeling was extending to achieve critical impact energy and residual impact energy for perforation of same thick concrete slab. In case of penetration, it was found that the simulation results are in close relation with experimental data. The limitation of Concrete damaged plasticity model found as that, during the impact analyses model does not allow the removal of elements. The extended simulation modeling for perforation shows encouraging results for critical impact energy and residual impact energy.**

***Keywords* — Simulation, Impact energy, penetration, perforation, CRH, ogive nose projectile.**

I. Introduction

In civilian and military applications, over the years concrete is used as a construction material for construction of protective structures. Great demand exists for designing of nuclear plants, power plants, military structures, water retaining structures, highway barriers etc., to resist the penetration and perforation of concrete structure against kinetic projectile, generated both accidentally or deliberately, in various impact and blast scenarios (e.g. failure of a pressurized vessel, failure of a turbine blade or other high speed rotating machines, aircraft crashes, fragments generated by accidental explosions, etc.), terrorist attack, and natural disasters like tsunami and etc. Critical impact energy is the dominant cause of damage in dynamic of local impact phenomena [4-7], [22], [23]. When a hard projectile impacts with concrete target, critical impact energy of the projectile is a main reason, that makes concrete target deforms. Therefore, critical impact energy which can cause penetration and perforation in concrete structures is also noteworthy in determining the dynamic response of concrete structures against the penetration and perforation of hard projectile [4-7], [22], [23].

In general, the required critical impact energy of hard missile for penetration and perforation of concrete structures can be studied in three ways, (i) Empirical Studies, (ii) Analytical Studies, and (iii) Numerical Simulation [4-7], [22], [23]. The Numerical Simulation studies are evenly imperative in this field because of complexity of the phenomena.

In this paper a numerical simulation study is conducted to overcome the shortcomings of other modes of studies, to determine the required critical impact energy for maximum penetration, and perforation of hard projectile of 26.9mm and 76.2mm diameter with CRH ratio 2.0 and 6.0, into thick concrete slabs respectively.

II. Literature Review

Joosef Leppanen (2006) modelled the plain concrete by using Rankine–Hugoniot equations (RHT) in AUTODYN together with the Equation of state (EOS) with the introducing bi–linear cracking softening law and a strain rate-dependent law in hydro-code. The results were found having a good agreement with experimental for spalling, cracking and scabbing of plain concrete subjected to fragment and projectile impact [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 and evaluated with the material Type 78 (Matt Soil Concrete) and Type 111 (Matt Johnson Holmquist Concrete) model. 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 [3].

P. Forquin, A. Arias, and R. Zaera (2008) a numerical simulation have been done to check the influence of porosity on the impact behaviour of two fine cementious mortars – one with silica fume and another without silica fume, by suing Krieg Swenson and Taylor material model together with ABAQUS/Explicit FE code in ABAQUS. The simulation results explain the better ballistic performance (lower depth of penetration) in mortar without siliceous additives [10].

M. Polanco - Loria et. al. (2008) 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 [11].

G. Shiqiao et al. (2008) proposed a fuzzy model for describing characteristic of penetration resistance of semi–infinite concrete targets against rigid missile from low to high strike velocities. The results of deceleration show good agreement with experimental data [12].

Review of previous work reveals that only limited numerical simulation works have been done by researchers on the penetration and perforation of hard missile on concrete targets with the vision of critical impact energy [4-7], [22], [23]. Therefore, a numerical simulation study has been carried out to explore and further improve the prognostic simulation models for penetration and perforation of hard missile on concrete targets footed on critical impact energies.

III. Numerical Simulation

This simulation study was conducted for required critical impact energy for maximum penetration of concrete slab on the experiments data of Forrestal et al., [17], [18], [20], and Frew et al., [19], [21]. Furthermore, the simulation study has been extended to achieve perforation in thick concrete slab. The description of simulation modelling of concrete slabs and projectile are explained below:

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 26.9mm 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 76.2mm. For Penetration mechanical properties of concrete slabs and projectile are given in table (1).

For perforation, the above mentioned penetration simulation models are extended up to such a level where complete perforation can be achieved. Table 2 shows the mechanical properties of both concrete slabs and projectile for the case of perforation.

TABLE I. TABLE 1. MECHANICAL PROPERTIES OF CONCRETE AND PROJECTILE FOR PENETRATION.

Concrete		**Projectile**			
Density (kg/m^3)	***fc (Mpa)***	***CRH Ratio***	***Dia. of Projectile (mm)***	***Mass of Projectile M (kg)***	***Vs (m/s)***
2340-2370	32.4-108.3	2	26.9	0.898-0.912	277-800
2040-2250	23-39	6	76.9	12.873-13.064	238.4-448.5

TABLE II. TABLE 2. MECHANICAL PROPERTIES OF CONCRETE AND PROJECTILE FOR PERFORATION.

Concrete		**Projectile**			
Density (kg/m^3)	***fc (Mpa)***	***CRH Ratio***	***Dia. of Projectile (mm)***	***Mass of Projectile M (kg)***	***Vs (m/s)***
2340-2370	32.4-108.3	2	26.9	8.35-35.2	499-1022
2040-2250	23-39	6	76.9	12.909-15.873	478.6-1048.5

The 2d-asymmetric FE models are developed for concrete slabs and ogive nose hard projectile. Concrete slabs are modelled in both quadrilateral (Type CAX4R) linear solid elements, and tri-angular (Type CAX3) linear solid elements with Lagrangian formulation, for making the mesh of the concrete slab reasonable to produce stable time for simulation. The ogive nose hard missile of 26.9mm and 76.2mm in diameter with CRH ratio 2.0, and 6.0 are modelled as a discrete rigid body with linear line elements (Type RAX2) in order to avoid excessive simulation times caused by heavy distortion of the elements at the projectile nose.

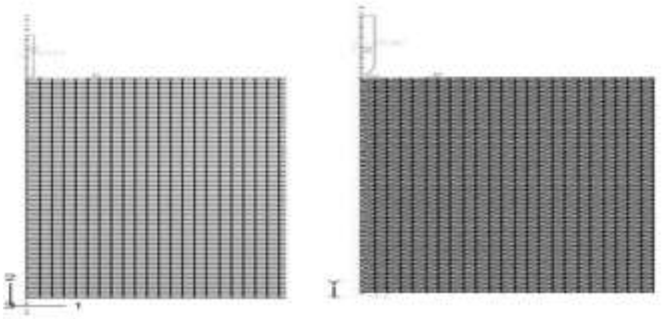

Figure 1. Finite element quadrilateral (Type CAX4R) explicit linear solid elements and triangular (Type CAX3) explicit linear solid elements mesh for ax-symmetric concrete model and discrete rigid body linear line elements (Type RAX2) for projectile, in case of penetration and perforation.

For the explanation, the development of one of the above mentioned simulation models are described in detail here. The 2d-asymmetric FE model of concrete slab of (685mm x 1220mm) having density 2340 kg/m3, 90.5Mpa unconfined compressive stress modelled with quadrilateral standard linear solid elements type (C4X4R) having dimension of (27.40mm x 27.11mm) approximately are used with Lagrangian formulation, for making mesh reasonably fine to produce stable time for simulation. The hard missile of 26.9mm in diameter CRH 2.0, having mass of 0.907kg, impacted with 561/m/sec striking velocity is modelled as a rigid body with 20 discrete rigid linear elements type (RAX2), 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^o.

IV. Results and Discussion

A. *Critical Impact Energy for Penetration*

Concrete Damaged Plasticity Model clearly provides loading in the form of strains/stresses in the concrete slab due to the missile impact. Figure (2) shows the very nicely propagation of the stresses and stress distributions in the form of waves inside concrete slab at various moments in time for the impact of hard missile, in case of penetration.

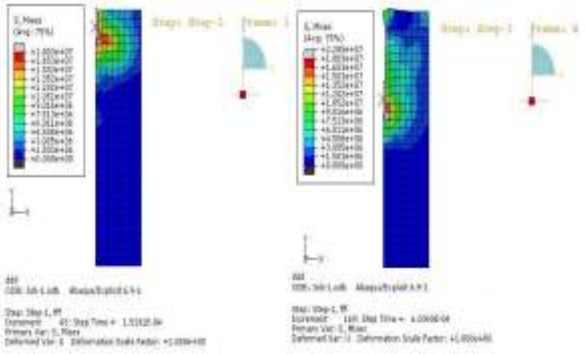

Figure 2. Van mises stress distribution wave propagation during penetration FEA explicit ax-symmetric model simulation using quadrilateral (Type CAX4R) linear solid elements mesh.

The visualized results reveals that the general obstacle of this constitutive model is that, Concrete Damaged Plasticity Model contains no failure criteria. Finite elements with high tension stresses or shear stresses cannot be removed throughout the analysis.

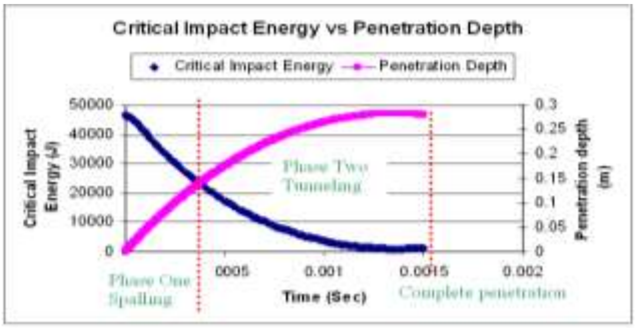

Figure 3. Critical impact energy vs position of missile with respect to the time.

Figure (3) shows the time history of the position of projectile into concrete target and critical impact energy in two phases. In phase one, spalling of concrete slab occurs because of sudden impact of hard projectile. The critical impact energy required to cause spalling can be obtained from phase one. In phase two tunnelling of concrete slab occurs, which is taken as beyond the depth of spall crater. The critical impact energy required to cause tunnelling can be obtained from start point of phase two till end of phase two. Therefore complete penetration takes place, by combining both phases (depth of spalling + depth of tunnelling), and critical impact energy required for complete penetration can be obtained by combining both the critical impact energies of spalling and tunnelling (critical impact energy for spalling + critical impact energy for tunnelling). At complete penetration it is concluded that no further energy left in projectile to make further penetration, scabbing or perforation in to concrete slab. This means that the concrete slab target still has enough strength to resist the further penetration, scabbing, and perforation of hard projectile.

The critical impact energy required for maximum penetration of concrete structures without rear effect results obtained from simulation, and compared with experimental data of Forrestal *et al.* [17], [18], [20], and Frew *et al.*, [19], [21]. Figure (4) undoubtedly shows that simulation results are closer to the experimental data with maximum error of (3%) in case of CRH ratio 2.0. In case of CRH 6.0, the simulation results are closer to the experimental data with maximum error of (10%), as shown in figure (5).

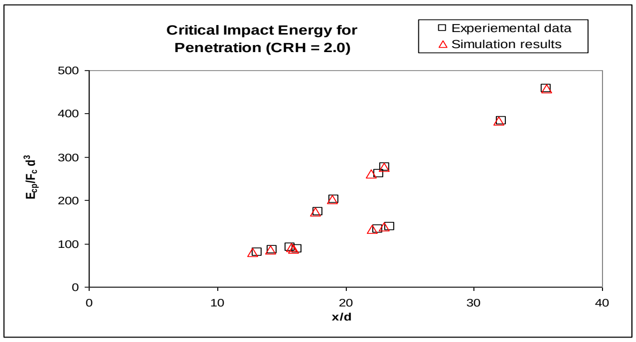

Figure. 4. The required critical impact energy for penetration in case of CRH = 2.0.

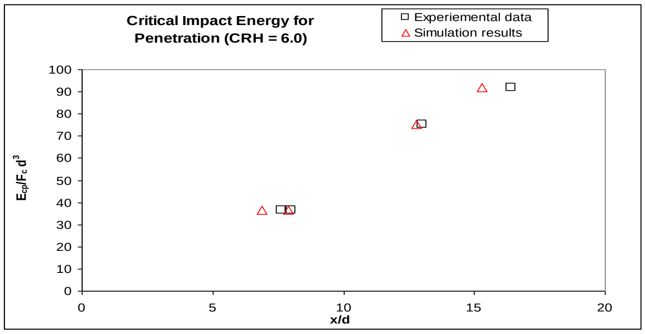

Figure 5. The required critical impact energy for penetration in case of CRH = 6.0.

B. *Critical Impact Energy for Perforation*

In case of perforation, same as case of penetration Concrete Damaged Plasticity Model evidently show the very nicely propagation of the stresses distribution inside the concrete slab in the form of waves. It also found that the general obstacle of this constitutive model is same as in case of penetration.

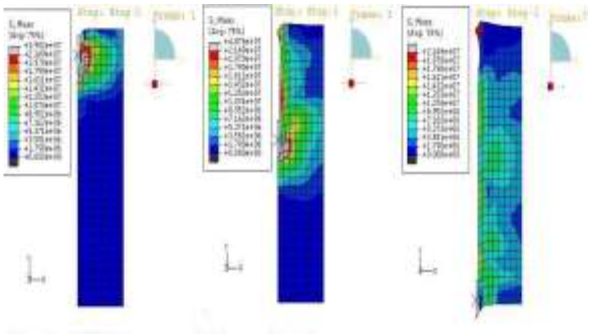

Figure 6. Van mises stress distribution wave propagation during perforation FEA explicit 2d-asymmetric model simulation using quadrilateral (Type CAX4R) linear solid elements mesh.

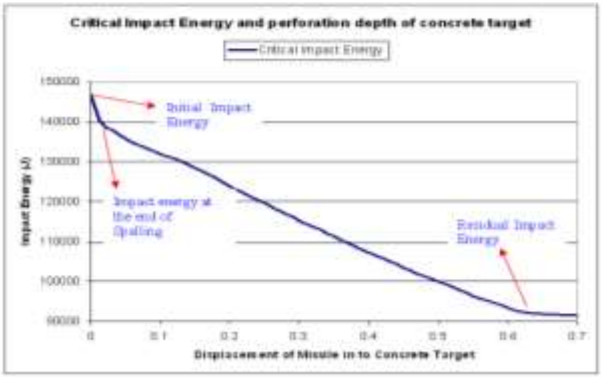

Figure 7. History of Critical impact energy from initial impact energy to residual energy based on perforation depth.

Figure (7) shows the time history of the position of projectile into concrete target and critical impact energy for perforation in division of three phases of spalling, tunnelling, and perforation. In phase one spalling occurs which start from point 1 and ends at point 2. Phase two the tunnelling phase, starts from point 2 and ends at point 3. Phase 3 shows the completer perforation of hard projectile through concrete slab target. The critical impact energy for occurrence of spalling can be obtained between point 1 to point 2, the critical impact energy for tunnelling can be obtained between point 2 to point 3, and in 3rd phase residual impact energy of projectile can be obtained at point 3. Therefore critical impact energy required to achieve complete perforation of concrete target impacted with hard projectile can be obtained between point 1 and point 3, by subtracting the residual impact energy from initial impact energy.

The critical impact energy required for complete perforation of deep concrete structures are predicted in case of CRH ratio 2.0, and CRH 6.0, by extending penetration modeling are shown in figure (8) and (9) respectively. The result are encouraging.

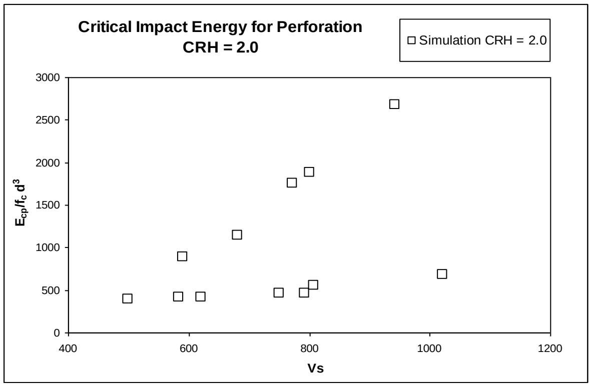

Figure 8. The simulated results of required critical impact energy for perforation in case of CRH ratio 2.0.

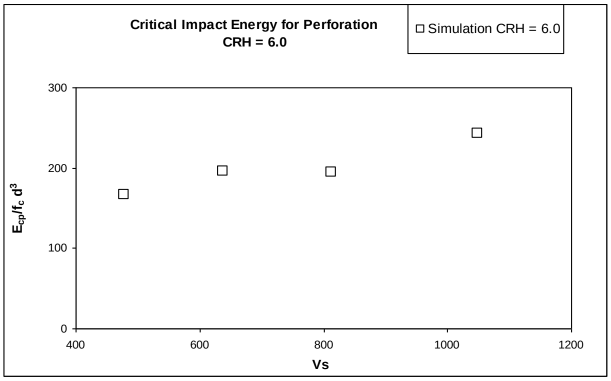

Figure 9. The simulated results of required critical impact energy for perforation in case of CRH ratio 6.0.

C. *Residual Impact Energy*

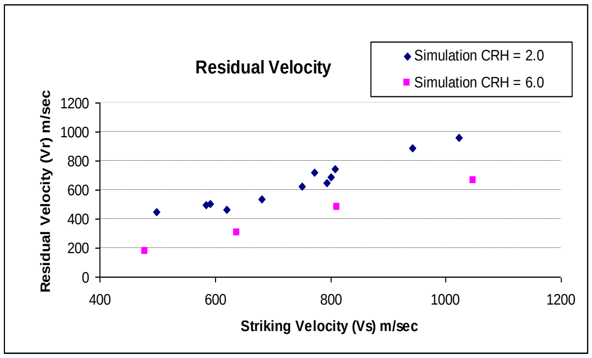

Figure 10. The simulated results of residual impact energy after perforation in case of CRH ratio 2.0, and 6.0.

The residual impact energy after complete perforation of deep concrete structures are also have been analyzed in case of CRH ratio 2.0, and CRH 6.0. Figure (10) shows that the residual impact energy after complete perforation of deep concrete target are higher in case of CRH 2.0, as compared to the CRH 6.0.

The shear plugging has significant effects on critical impact energy and residual impact energy in case of perforation. This this simulation the effect of shear plugging is not included because of limitation of Concrete damaged plasticity model.

Acknowledgment

The Authors would like to thank University Tun Hussein Onn Malaysia (UTHM) for supporting this research, and University of Buraimi (uob).

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