Numerical Modeling of Ballistic Penetration of Long Rods into Ceramic/Metal Armors

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Abstract

Penetration into ceramic/armor targets are of prime importance in research as well as industry and military applications. The recent advances in this field shows considerable improvements in the design of armor and civilian technology. Due to complexity of the problem and interdisciplinary of the subject, most of the works in this respect are experimental in nature. The cost of experimentation is high and the results obtained cannot be extrapolated to a large number of cases. However due to the advances of computer simulation, the field of numerical analysis is becoming highly attractive for application and research.

Numerical modeling of ballistic impact of long rod penetrators into ceramic armor with semi-infinite backing targets is considered in this paper. An explicit, three-dimensional finite element code LS-DYNA is used in the analysis of the problem. The behavior of ceramic and backing materials are modeled as Elastic-Plastic Hydrodynamic with pressure cutoff and failure strain. The projectile is modeled as Johnson-Cook. Mie-Gruneisen and linear polynomial equation of state are used for materials. The impact velocity range is from 750 to 1350 m/s. The results of investigation are in a very good agreement with experimental data.
Keywords: *Ballistic impact; Ceramic armor; Finite element model; Long rod; Penetration depth*

Introduction

Ceramics have main properties, which make them very attractive for armor application. The main characteristics of ceramics are low density, high compressive strength, high bulk and shear modulus. These qualities make ceramic materials a very good candidate to use in ballistic systems as protective armor. In practice, a baking plate usually supports ceramics. The backing plate absorbs the remaining kinetic energy of the projectile after fracturing of the ceramic and supports the ceramic during the penetration process. If the backing plate is thick, it may be treated as a semi-infinite target. Thick backing plate prevents the early fracture of ceramic by deformation of backing plate. After impact, a conical fracture develops at the ceramic material and propagating toward ceramic-backing interface. When the compressive wave reaches ceramic-backing interface, it reflects as a tensile wave, which contributes to ceramic fractures and conoid formation. This conoid spreads the projectile load into larger area of backing over conoid base.

There are three methods for studying and investigating of the penetration mechanism into ceramic armors: 1) numerical methods, 2) empirical and semi-empirical methods, 3) analytical modeling. Up to now several methods have been presented concerning penetration into ceramic armors which include numerical, experimental and analytical methods.
In numerical method, a full solution of penetration process is achieved by solving the whole set of equations. There are different technique for solving the computational continuum dynamics

problems such as finite difference (FD), finite element (FE) and smoothed particle hydrodynamic (SPH). Numerical simulations are useful methods in the analysis of complex problems.

Nomenclature

α	Volume correction factor
A, B, n, c, m	Constant factors of Johnson-Cook model
C_w	Tensile wave speed
C	Intercept of the U_s - U_P curve
$c_0,...,c_6$	Constant factors of linear polynomial equation of state
d	Distance across the smallest finite element
$D_1,...,D_5$	Failure parameters
D	Damage parameter
E	Young's modulus
E_0	Internal energy
E_t	Tangent modulus
E_H	Plastic hardening modulus
P	Pressure
S_1, S_2, S_3	Coefficients of the slope of the U_s - U_P curve
TSSF	Time step scale factor
T_{ROOM}, T_{melt}	Room and melt temperature
T^*	Homologous temperature
U_s	Shock velocity
U_P	Particle velocity
γ	Gruneisen factor
ε	Effective plastic strain
$\Delta\varepsilon$	Incremental effective plastic strain
σ	Von Mises Effective stress
σ_0	Initial yield stress
μ	Compression $\mu=\rho/\rho_0-1$
ρ/ρ_0	Ratio of current density per initial density

The first notable numerical analysis on ceramic armor was implemented by Wilkins and his colleagues [1,2]. They presented a finite difference code (HEMP) to simulate normal impact. Wilkins recognized that in order to optimize a two-component ceramic armor system it is necessary to understand the interaction between target and projectile. Cortes and his colleagues [3] presented another numerical modeling. Their work presented a full two-dimensional numerical modeling of the normal impact of blunt cylindrical projectile on ceramic armors. The behavior of finely comminuted ceramic ahead of the penetrator was modeled by means of a constitutive model, taking into account internal friction and volumetric expansion. Lee and his colleagues [4] studied the ballistic efficiency of ceramic/metal armor by combined numerical and experimental approach. The significant phenomena such as, projectile eroding, crack propagation, formation of ceramic conoid and failure of backing plate were investigated by using smoothed particle hydrodynamic technique. Hari Manoj Simha and his co-workers [5] also presented a computational model for penetration response of high purity ceramic such as AD-99.5 alumina. The model was incorporated into finite element code and the phenomenon of interface defeat was also studied.

Analytical modeling or engineering modeling is based on the combined application of the fundamental physical laws. One approach is to simulate penetration process by analytical modeling. Florence [6] developed a model for estimating the ballistic limit, assuming that ceramic only spreads the impact load over a large area onto the backing plate. In Florence's model, with global energy balance, the energy of the projectile and the absorbed energy in the target are equated. This method is used to derive the ballistic limit velocity. Woodward [7] proposed a one-dimensional modeling of perforation and penetration of ceramic armors by using thin and thick backing plates. His approach used lumped mass method. He then investigated projectile and ceramic erosion in a simple way. Reijer [8] presented yet a different model, which considered projectile erosion and mushrooming mode for the backing plate. He derived a constitutive behavior for comminuted ceramic. Zaera [9] developed an analytical model to simulate normal and oblique impact of projectile into lightweight ceramic/metal targets. In his model, the response of the projectile was based on the Tate and Alekseevskii model and behavior of metal backing plate was modeled using the ideas of Woodward and Reijer models. Fellows [10], proposed a model to predict the penetration depth of the projectile into semi-infinite ceramic/metal target. Lumped mass method was used to derive the equations of motion. To analyze the penetration process, Fellows used three different phases i.e. erosion, mushrooming and rigid phases in his approach.

In empirical methods, algebraic equations are extracted using experimental data. The data is then analyzed to predict the influence of the important parameters of the problems. Semi-empirical methods are also developed in order to extrapolate the results of the experimentation for further prediction. Bless and his colleagues [11] and Mayseless and his colleagues [12] presented two empirical models into ceramic armors.

Numerical methods are used extensively in solving penetration problems due to the decrease cost and time. Numerical simulations are used in a variety of problems including oblique impact and multi-layer targets.

This paper is using dynamic, finite element code LS-DYNA, to simulate penetration depth into semi-infinite ceramic/metal target. The materials used are Tantalum, Alumina (AD85) and Aluminum. Tantalum as projectile, Alumina (AD85) as frontal plate and Aluminum for the backing plate are chosen.

Constitutive Equation

The constitutive equations are used to explain the behavior of the materials under environmental variations. Johnson-Cook and Elastic-plastic hydrodynamic models are used to express the material behaviors in this numerical modeling. Johnson-Cook constitutive equation describes the behavior of the materials under very large strains, high strain rates and high temperatures. The basic form of this model is well suited for computational purpose, because this model uses parameters, which are readily available. These parameters are of prime importance in ballistic penetration. The constant parameters for different materials are obtained from experimental data.

The flow stress presented by Johnson and Cook is a follows:

$$\sigma = \left[A + B\varepsilon^n\right]\left[1 + c\ln\dot{\varepsilon}^*\right]\left[1 - T^{*m}\right] \tag{1}$$

where σ is the effective flow stress, ε is effective plastic strain, $\dot{\varepsilon}^* = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_o}$ is dimensionless plastic strain rate for $\dot{\varepsilon}_0 = 1s^{-1}$ and $T^* = \frac{T - T_{Room}}{T_{melt} - T_{Room}}$ is homologous temperature. The five parameters A, B, n, c, m, are experimental constant coefficients. The first bracket in Eq.(1) gives the stress as a function of strain, the second and third brackets give the effects of strain rate and temperature. The constant factor A represents yield stress, B, n show the effect of strain hardening and c is constant of strain rate[13].

The failure model in the Johnson-Cook model is based on strain fracture. The damage parameter is expressed by:

$$D = \sum \frac{\Delta\varepsilon}{\varepsilon^f} \tag{2}$$

Where $\Delta\varepsilon$, the incremental effective plastic, is strain and ε^f is strain at fracture. Fracture occurs when the damage parameter reaches the value 1.

The fracture at strain is given by:

$$\varepsilon^f = [D_1 + D_2 \exp D_3\sigma^*][1 + D_4 \ln\dot{\varepsilon}^*][1 + D_5 T^*] \tag{3}$$

This expression is expressed for constant variables $(T^*, \dot{\varepsilon}^*, \sigma^*)$ and $\sigma^* \le 1.5$. $\sigma^* = \frac{\sigma_m}{\bar{\sigma}}$ is the ratio of pressure or hydrostatic stress per effective stress. $D_1, ..., D_5$ are experimental constants. The first bracket in Eq.3 represents effects of hydrostatic stresses, while second bracket represents strain rates and the third bracket is the temperatures [13].

The elastic-plastic hydrodynamic constitutive equation is used for modeling materials undergoing large amount of strain, where the plastic behavior can either be defined from a set of data points or from the yield stress and plastic hardening modulus. If the effective true stress and effective plastic true strain data are not specified, the yield strength is calculated as:

$$\sigma = \sigma_0 + E_h\varepsilon \tag{4}$$

Where σ_0 is the initial yield stress, ε is the effective plastic strain and E_H is the plastic hardening modulus which is defined in term of Young's modulus, E and the tangent modulus, E_t by the following expression[14]:

$$E_h = \frac{E_t E}{E - E_t} \tag{5}$$

Equations of State (EOS)

The relation between pressure, volume and internal energy of a material is defined as the equation of state. In this numerical modeling, Mie-Gruneisen and linear polynomial equations of state are used.
The Mie-Gruneisen equation of state is expressed as follows:

$$P = \frac{\rho_0 C^2 \mu (1 + (1 - \gamma/2)\mu - (\alpha/2)\mu^2)}{[1 - (S_1 - 1)\mu - S_2\mu^2/(\mu+1) - S_3\mu^3/(1+\mu)^2} + (\gamma + \alpha\mu)E_0$$

(6)

where P is pressure, S_1, S_2, S_3 are coefficients of the slope of the $U_s - U_p$ curve, U_s and U_P are Shock velocity and Particle velocity respectively. γ is the Gruneisen factor (gamma), C intercept of the $U_s - U_p$ curve, E_0 is internal energy, α is volume correction factor and $\mu = \rho/\rho_0 - 1$ is compression factor ρ/ρ_0 is the ratio of current density per initial density.
Table 1 shows the Mie-Gruneisen EOS data for Tantalum and Alumina AD-85 that were extracted from reference [15] using $U_s - U_p$ curve.

Table 1
Mie-Gruneisen EOS data

Materials	C(m/s)	S_1	S_2	S_3	γ
Tantalum	3400	1.17	0.074	-0.038	1.6
AD-85	9003	-3.026	2.350	-0.383	1

The linear polynomial EOS that is used for Aluminum is defined as follows:

$$P = c_0 + c_1\mu + c_2\mu^2 + c_3\mu^3 + (c_4 + c_5\mu + c_6\mu^2)E_0 \quad (7)$$

where, $c_0, ..., c_6$ are the constant parameters of linear polynomial EOS and μ, E_0 were defined previously.
The constant coefficients of linear polynomial EOS for Aluminum are presented in Table 2.

Table 2
Linear polynomial EOS data

Material	c_0(Mbar)	c_1(Mbar)	c_2(Mbar)	c_3 (Mbar)	c_4	c_5	c_6
Aluminum 6061	0	0.742	0.605	0.365	1.97	0	0

Numerical Simulation

Two-dimensional axisymmetric numerical analysis with LS-DYNA is used to analyze the normal impact of long rod projectile into ceramic armor.

LS-DYNA is an explicit finite element code for analyzing the large deformation dynamic response of structures. This code is suitable for solving impact and penetration problems where, high velocity and impulsive loadings are encountered. The solution method in LS-DYNA code is based on explicit time integration.

Finite element modeling

The proposed finite element model is shown in Fig.1. This model consists of three distinct parts. These three parts are: long rod projectile (Tantalum), ceramic (AD-85) and thick backing plate (Aluminum). The diameter of projectile is 4.9 mm and its aspect ratio (L/D) is 5. The ceramic dimension is $50\,\mathrm{mm}\times 9.3\,\mathrm{mm}$ and backing plate dimension is $50\mathrm{mm}\times 100\mathrm{mm}$. Therefore, the backing plate can be considered a semi-infinite target in this respect.

Since Four-noded quadrilateral shell elements are used, then element formulation 14 is considered. Since axisymmetric geometry is used, a one-point quadrature rule is considered for explicit time integration pattern.

As for AD-85, the frontal face of armor, was used with the following properties:
Density $3420\,\mathrm{kg/m^3}$, shear modulus of 108 GPa, Poisson ratio of 0.22, compressive yield stress $1.95\,\mathrm{GPa}$ and static tensile yield stress of 0.155 GPa [16]. Alumina is one of the materials which is readily available and has a very good ballistic performance.
Aluminum 6061-T6 is used as the backing material. A density of $2750\,\mathrm{kg/m^3}$, a shear modulus of $25\,\mathrm{GPa}$, a Poisson ratio of 0.28, a yield stress of $298\,\mathrm{MPa}$ and an effective plastic strain at failure of 0.88, are considered [15].
Tantalum with a density of $16650\,\mathrm{kg/m^3}$, a shear modulus of $69\,\mathrm{GPa}$, Young's modulus of 179 GPa and a Poisson ratio of 0.3 are employed. The failure parameters are $D_1 = 0.7, D_2 = 0.32, D_3 = -1.5, D_4 = D_5 = 0$ [15].

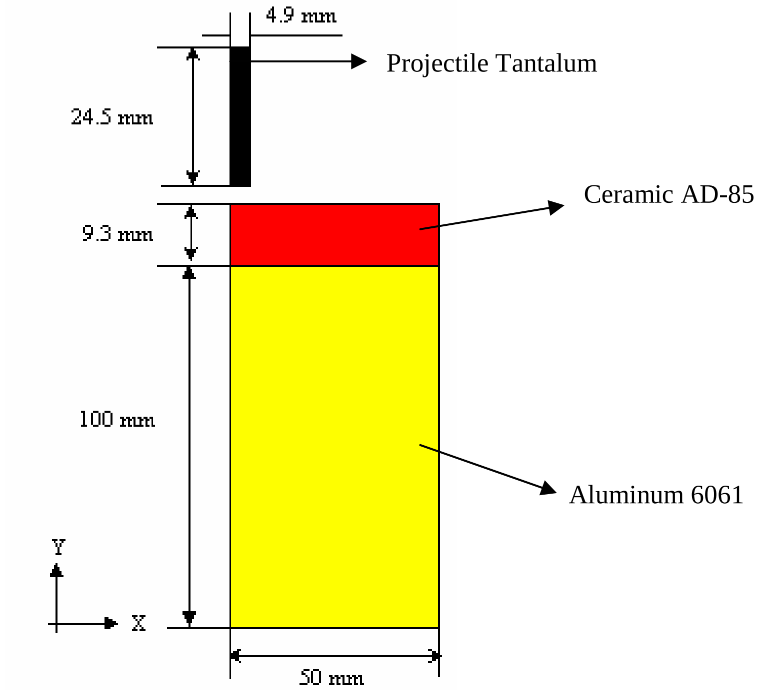

Fig. 1. Finite element model

Contact Surface

The treatment sliding and penetrating along interface is described by contact surface. In this analysis, automatic contact surface to surface has been used between projectile – ceramic and projectile – backing interface. At first interface, projectile part is selected for slave and ceramic for master. In hypervelocity impact and thick backing, all of the ceramic is eroded and this is due to the second interface which is used by choosing, projectile part as the slave and backing part as the master. The coefficients of friction are ignored during the impact because of early fracture of ceramic and hypervelocity of impact.

Initial and Boundary Conditions

The axis of symmetry is the Y axis and the fixed conditions are imposed at the boundaries at a distance of 50mm from the axis of symmetry. The only initial condition is the impact velocity. This condition is imposed by choosing a box around the whole nodes of projectile. The impact velocity at each run of the program is changed. The change intervals are from 750 to 1350 m/s.

Control Parameters

Control parameters are used to control the output, hourglass, termination of solution, time step size, contact and degree of the accuracy of the calculations.

One of the most important control parameters in impact problems, is time step scale factor (TSSF). TSSF is used to provide an optimum time step to confirm stability. In high velocity impact phenomena, due to the occurrence of the large deformation, value of the time step size varied throughout the simulation process. For stability during the process, value of Δt (time step size) must be smaller than the time for a stress wave to pass through the smallest element. In two dimensions, this relationship is expressed by:

$$d = \frac{1}{TSSF} C_w \Delta t \tag{8}$$

where d is the distance across the smallest element, C_w is the tensile wave speed of the material $(\sqrt{E/\rho})$, E is the Young's modulus, ρ is the density and $TSSF$ is the time step scale factor. LS-DYNA has a default value of 0.9, but in this analysis, TSSf of 0.24 is chosen [17].
One of the biggest disadvantages of one-point integration is the requirement to control the zero energy modes, so called hour-glassing modes. Hourglass parameters are used to prevent the occurrence of zero energy deformation modes. Therefore, in this analysis, hourglass parameters are used to stabilize the method. In order to do so the following values are used:

Hourglass viscosity coefficient = 0.10, quadratic bulk viscosity = 1.5 and linear viscosity coefficient = 0.06. The termination time and time interval are assumed to be $85\mu s$ and $1\mu s$ respectively. Other control parameters are chosen by default.

Results and Discussion

The numerical method presented in this article provides valuable information concerning kinetics and kinematics of the penetration process. At each time increment, values for projectile velocity, interface pressure, penetration depth, position and other relevant physical parameters are provided and simulated. The main objective of this simulation is to obtain penetration depth into backing material. The impact velocity range considered is from 750 to 1350 m/s.

Fig.2 depicts the deformation of the projectile and the target with velocity of 1350 m/s. Projectile penetrates into ceramic target until stops or reaches to termination time.

Fig.3 presents the velocity contour of the system. In the figure it is shown that when projectile stops or its velocity becomes zero, penetration time can be calculated by using Fig.4. As it is shown in the Fig.1, it is noted that the coordinate system has been chosen at the bottom of this contour. Therefore, crater depth can be obtained in this coordinate system if the dimensions of projectile, ceramic and the backing plate are known. As it is seen in Fig.4 the penetration is continued until the projectile deriving force is ended or the termination time is reached. In this figure it is shown that all the ceramic has been eroded and projectile has entered into the backing plate. Since backing plate is considered a semi-infinite plate, projectile will ultimately stop and crater depth can be calculated.

Fig.5 shows the velocity of the projectile nodes verses time. As it is seen in this figure, the initial velocity of the projectile is 1350 m/s and the velocity direction is assumed towards the bottom of the system. So the sign of velocity is considered negative. In this figure velocity history of the two nodes of the projectile are shown. It is observed that projectile velocity decreases during impact process, until becomes a constant value at zero velocity.

Fig.6 shows the position of the two nodes of the projectile versus time. It is observed that the position of the projectile decreases with respect to selected coordinate system. This figure shows that the residual length and residual mass of the projectile can be calculated. Crater depth, the main parameter, may be obtained from this diagram, but has not been done in this paper.

Fig.7 depicts the penetration depth of Tantalum projectile versus initial impact velocity. As it is shown in this figure the accuracy of results at low velocity are lower than high velocity. This may be due to constitutive equations employed in this paper. Some of the equations of state used in this article may not be suitable at low velocity. This figure also shows that the results of the simulation are in good agreement with experimental data [11].

It is recommended that in modeling the penetration process for ceramic materials instead of using an elastic-plastic hydrodynamic constitutive equation, that a constitutive equation be used which is merely for brittle materials. This may be accomplished if all the data concerning the required parameters are readily available.

Conclusions

This work presented a numerical modeling of the normal impact of a long rod projectile into ceramic armor with thick backing plate at velocities ranging from 750 to 1350 m/s. The penetration depth into backing material was the main objective. Johnson-Cook and elastic-plastic hydrodynamic were assumed to govern the behavior of the impacting materials. The equations of state used were Mie-Gruneisen and linear polynomial. The numerical results were found to be in good agreement with experimental data.

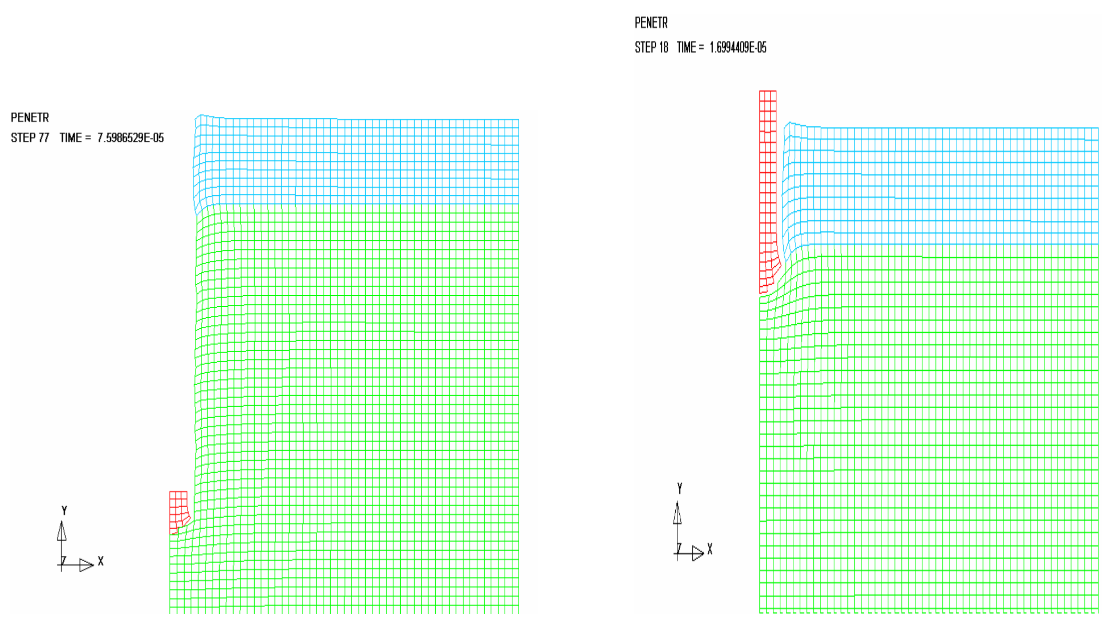

Fig.2. Deformation of projectile, Alumina and Aluminum at two time step at impact velocity=1350 m/s

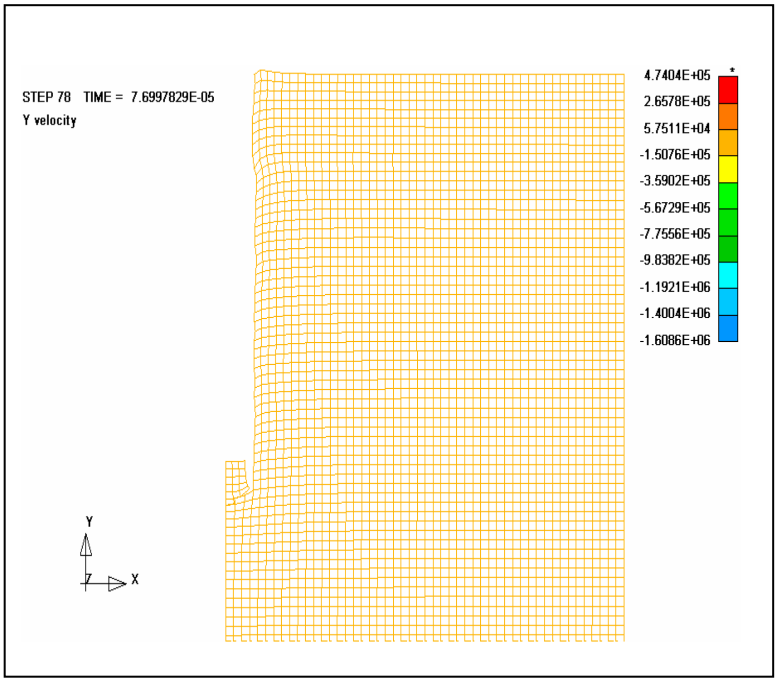

Fig 3. Velocity contour at impact velocity of 1350 m/s

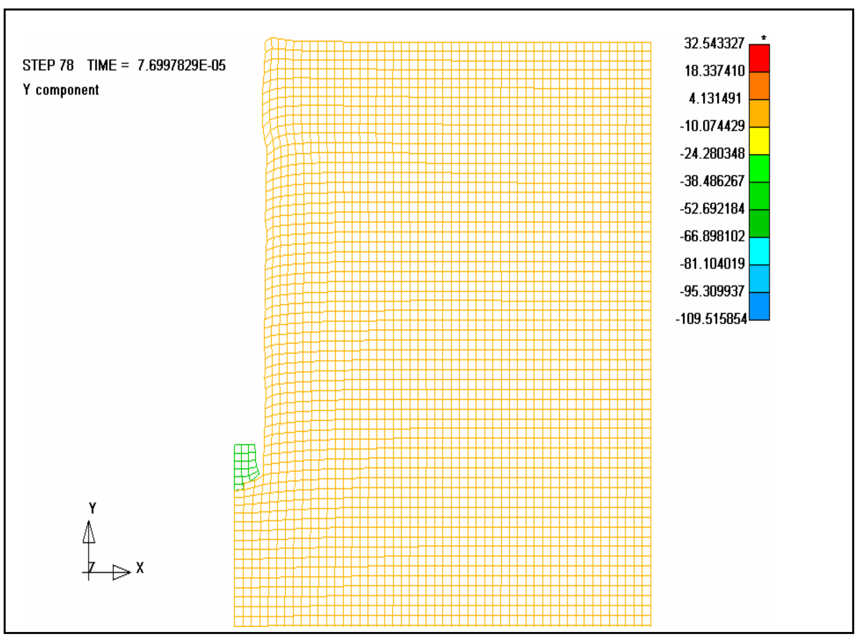

Fig.4. Penetration development at impact velocity=1350 m/s

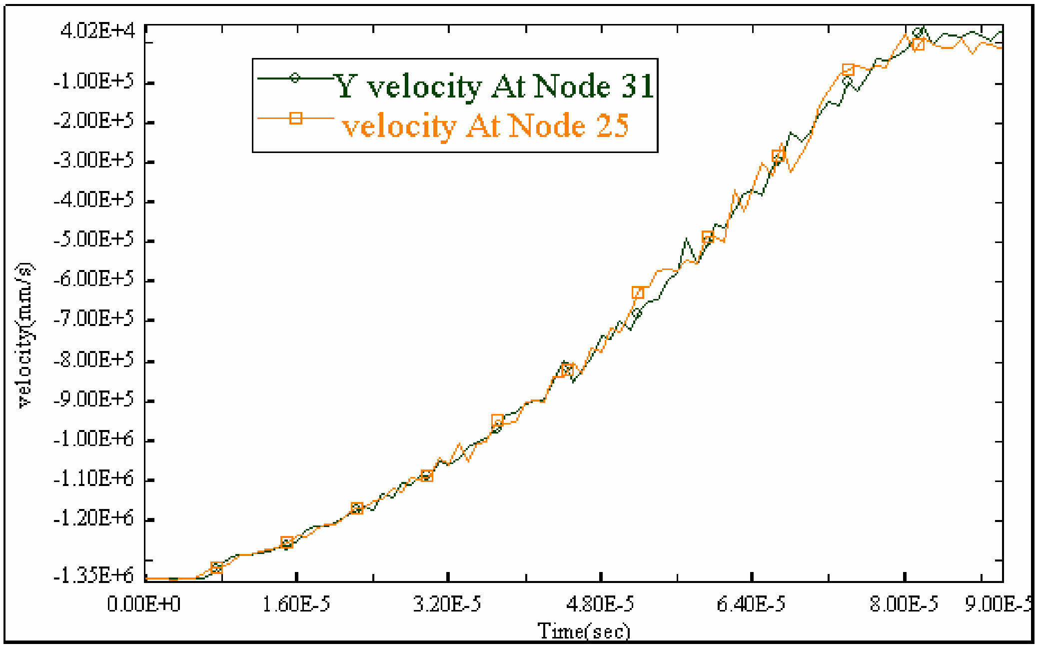

Fig.5. History of velocity for two nodes of the projectile at impact velocity=1350 m/s

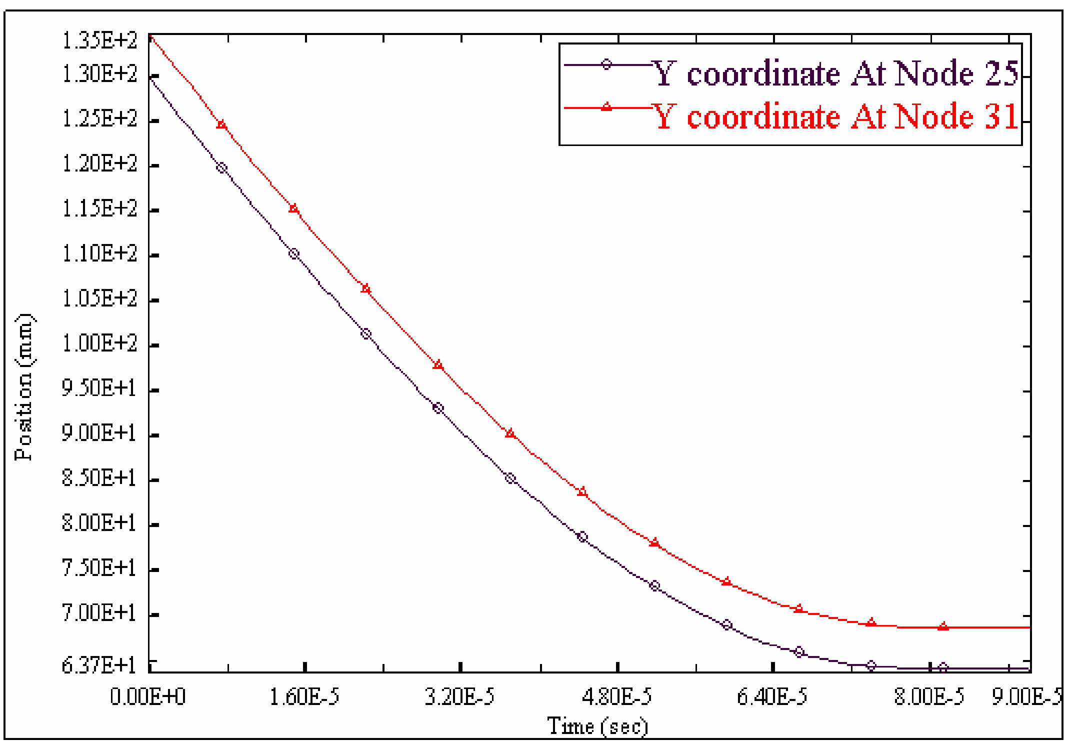

Fig.6. Time history of position variations for two nodes of projectile initial velocity =1350 m/s

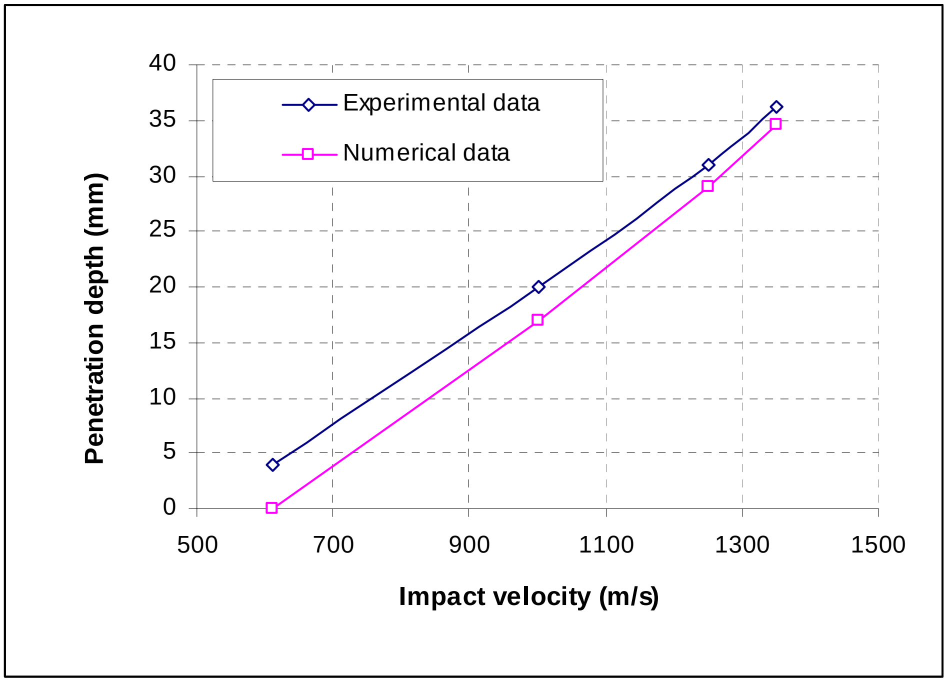

Fig.7. Comparison of numerical penetration depth with experimental results [11]

Reference

[1] Wilkins ML. "Mechanics of penetration and perforation", Int J Engng Sci.Vol 16, pp.793-807,(1978).
[2] Wilkins ML, Landigham RL, Honodel CA. " Fifth progress report of light armor program" Lawernce Radiation Laboratory, Livermore, UCRL-50980,Junuray (1971).
[3] Cortes R, Navarro C, Martinez MA, Rodriguez J, Sanchez-Galvez V," Numerical modeling of normal impact on ceramic composite armours ", Int J Impact Engng .12, pp.639-651,(1992).
[4] Lee M, Yoo YH. "Analysis of ceramic/metal armour systems". Int J Impact Eng;25:819-829, (2001).
[5] Hari Manoj Simha C, Bless SJ, Bedford A."Computational modeling of penetration response of a high-purity ceramic". Int J Impact Engng. 27, 65-86, (2002).
[6] Florence AL, "Interaction of projectile and composite armour part 11" Stanford Research Institute .Menlo Park, California, USA.,AMMRG-CR-69-15,(1969).
[7] Woodward RL. "A simple one-dimensional approach to modeling ceramic composite defeat". Int J Impact Eng ;9(4):455-74, (1990).
[8] Reijer. P.C," Impact on ceramic faceed armours". Ph.D. Thesis, Delft University Of Technology,(1991).
[9] Zaera R, Sanchez-Galvez V. "Analytical modeling of normal and oblique ballistic impact on ceramic/metal lightweight armours". Int J Impact Eng;21(3):133-48, (1998).
[10] Fellows NA, Barton PC, " Devlopment of impact model for ceramic-faced semi-infinite armour". Int J Impact Eng; 22,.pp.793-811, (1999).
[11] Bless SJ, Rozenberg Z, Yoon B, "Hypervelocity penetration of ceramics". Int .J Impact Eng vol(5).pp.165-171, (1987).
[12] Mayseless M, Goldsmith W, Virosterk SP, Finnegan SA, "Impact on ceramic targets". J Appl Mech, 54,373-378, (1987).
[13] Johnson GR, Cook WH, "Fracture charactristics of three metal subjected to various strain, strain rates, temperature and pressure". Eng Fracture Mech, 21(1).pp.31-48, (1985).
[14] LS-DYNA Manual Reference, Livermore Software Technology Corporation, (2001).
[15] Marsh PS. "LASL shock hugoniot data" University Of California Press, Berkeley.pp.136, 181, 373.(1980).
[16] Rajendran AM. "Modeling the impact behavior of AD85 ceramic under multiaxial loading". Int J Impact Engng, 57, 5087, (1994).
[17] Lim CT, Shim VPW, Ng YH, " Finite-element modeling of the ballistic impact on fabric armor". Int .J Impact Eng vol(28).pp.13-31, (2003).