World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:12, No:2, 2018

# Three-Dimensional, Non-Linear Finite Element Analysis of Bullet Penetration through Thin AISI 4340 Steel Target Plate

Abhishek Soni, A. Kumaraswamy, M. S. Mahesh



***Abstract*—**Bullet penetration in steel plate is investigated with the help of three-dimensional, non-linear, transient, dynamic, finite elements analysis using explicit time integration code LSDYNA. The effect of large strain, strain-rate and temperature at very high velocity regime was studied from number of simulations of semi-spherical nose shape bullet penetration through single layered circular plate with 2 mm thickness at impact velocities of 500, 1000, and 1500 m/s with the help of Johnson Cook material model. Mie-Gruneisen equation of state is used in conjunction with Johnson Cook material model to determine pressure-volume relationship at various points of interests. Two material models viz. Plastic-Kinematic and Johnson-Cook resulted in different deformation patterns in steel plate. It is observed from the simulation results that the velocity drop and loss of kinetic energy occurred very quickly up to perforation of plate, after that the change in velocity and changes in kinetic energy are negligibly small. The physics behind this kind of behaviour is presented in the paper.

***Keywords*—**AISI 4340 steel, ballistic impact simulation, bullet penetration, non-linear FEM.

## I. Introduction

IMPACT is defined as the collision between two or more solids, where the interaction between the bodies can be elastic, plastic, or any combination of these. Ballistics is the science or art of designing and accelerating objects so as to achieve a desired optimum performance. In modern science, ballistics deals with the motion, forces and impact of projectiles, especially those discharged from firearms and guns. The ballistic trajectory curve is often referred to as the path actually travelled by projectile, as distinguished from its theoretical parabolic path if gravity was the only force acting on it. The science of ballistics is usually sub-divided into three main research areas. Interior ballistics is the study of the motion and forces acting on an object when it is still within the launcher. Exterior ballistics is the study of the motion and forces acting on the object during free flight, while terminal ballistics describes the interaction between the object and target during impact. Here, most effort is used on the field of terminal ballistics. This is the area of greatest interest with respect to fortification, which may be defined as structures used for additional strength or strengthening, especially in defence applications. Penetration is defined as the entry of the projectile into any region of a target. During the impact, the projectile may penetrate the target in several ways. Backman and Goldsmith [1] suggested the following definitions:

1) Perforation if the projectile passes through the target with a constant residual velocity.
2) Embedment if the projectile is stopped during contact with the target.
3) Ricochet or rebound if the projectile is deflected from the target without being stopped.

Dikshit et al. [2] stated that for the ballistic penetration of metallic plates at ordnance velocities, literature work can be grouped into two by assuming thin plates which have a $T/D < 1$($T$ =plate thickness; $D$ = projectile diameter) and thick plates which have $T/D>1$. It is observed that the plate perforation velocity and the plate plugging velocity decrease with increasing plate hardness. Borvik et al. [3] conducted a numerical simulation study of plugging failure in LSDYNA. Blunt projectiles were impacted on Weldox 460 E steel plates. They found that the choice of element size is crucial for adiabatic shear band localization. Agreement with experimental results could be achieved with smaller element sizes. Furthermore, strain rate, temperature and stress state were found to be important parameters for the model. It was further stated that adaptive meshing may become necessary in case of ductile crater hole enlargement using cone projectiles.

Kaufmann et al. [4] conducted a numerical simulation study for the projectile impact on aluminium target using LSDYNA. The influence of mesh intensity on depth of penetration (DOP) results was discussed. It was stated that, there exists an optimum mesh density for which further refinement did not significantly improve the predicted DOP. Moreover, the effect of the erosion strain of target was examined and it was found that optimum values lie in the range 1.2 to 1.4 for more accurate DOP predictions. Borvik et al. [5] studied the nose shape effect of the projectile on ballistic perforation of steel plates by conducting numerical simulation in LSDYNA. Hemispherical and conical nose shapes were studied. Ballistic limit and the residual velocity curve of blunt and hemispherical projectiles from numerical simulations were in agreement with the experimental results. It was stated that severe hydrostatic compression in the vicinity of the nose tip delayed the element erosion process and caused errors that

Abhishek Soni is Mtech student at Department of Mechanical Engineering, Defence Institute of Advanced Technology (DU), Pune- 411025, Maharashtra, India (phone:+917507745367, e-mail: aaabhisheksoni2@gmail.com).

A. Kumaraswamy is Professor at Department of Mechanical Engineering, Defence Institute of Advanced Technology (DU), Pune-411025, Maharashtra, India (phone: +918308223526, e-mail: adepu_kswamy@yahoo.com).

M.S. Mahesh is Assistant Professor at Department of Aerospace & Mechanical Engineering, Indian Institute of Technology, Hyderabad, Telangana, India (phone:+919403088478, e-mail: maheshms7@gmail.com).

terminated the simulation. Reducing the material properties of those elements enabled a solution. These results were quantitatively in agreement with the test results despite of some qualitative differences. Borvik et al. [6] investigated the ballistic performance of five different steel plates against 7.62 mm soft core and armour piercing projectiles. The steel plates were represented with the Johnson-Cook strength model combined with the Cockcroft-Latham failure model. It was stated that using the 2-D Lagrangian processor of LSDYNA was difficult to represent soft core projectile impact. From the impact tests, it was found a linear dependence of the ballistic performance between the target yield strength. The importance of ductility with regard to material strength was found to be very low. Moreover, the effects of the brass jacket and the lead cap of the armour piercing projectile were stressed. It was found that only using the core part of the projectile decreases the ballistic limit by 3-5%. Nsiampa et al. [7] presented a numerical and an experimental study regarding the impact of 7.62 mm AP projectile into aluminium 5083 plates. The numerical simulations were found in good agreement with the experimental results. The influences of the jacket and the lead core material in the penetration and perforation mechanisms have been stressed. It was decided that the contribution of the lead core to the DOP results is greater than the contribution of the brass jacket even though the initial kinetic energy of the brass jacket is twice of the one of the lead core.

Kurtaran et al. [8] investigated the ballistic impact simulation of GT model vehicle door using finite element method. In the paper, a bullet with semi-spherical nose shape is simulated at the impact velocities of 500, 1000 and 1500 m/s using Plastic-Kinematic and Johnson-Cook material models. But, in the graphs of finite element analysis for kinetic energy variation with respect to time for both types of material models, there is a mistake regarding units of kinetic energy. In the graph, the unit mentioned is kJ (multiplied by $10^6$). This could be resulted in huge amount of kinetic energy which is not possible for the cases considered. From the graph, one can invoke that at velocity V = 1500 m/s, the kinetic energy (at t = 0 second) is approximately $5\times 10^6$ kJ. From the geometry of bullet, one can calculate its volume as 571.8700609 $m^3$ and density for bullet material (AISI 4340 steel) is 7850 kg/ $m^3$. If velocity is taken as 1500 m/s, then after calculation, the kinetic energy is coming as 5050.327 J (approximately 5.05 kJ), which suggests that the multiplication by $10^6$ is incorrect and there is no need for multiplication.

## II. Geometrical Modeling and Meshing of Parts

The models for bullet and plate are created with the help of ABAQUS software. Bullet having 7.62 mm diameter and semi-spherical nose shape is created in part module with the help of geometrical tools like extrude, revolve. Now module is switched to assembly mode and bullet part instance is created. After that, user can proceed on meshing of bullet. The geometry of bullet is further divided into various regions to facilitate better meshing. Now, one can seed part instance created for bullet to define the number of elements and their shape. After that, with the help of 'mesh part instance' tool, the whole bullet geometry is meshed into various small elements. In this analysis, bullet has 133120 elements and 138694 nodes. The aspect ratio for bullet is 4.57 which is less than safe limit of 5. Now mesh element type assignment is done with explicit 8-noded hexagonal elements. Now 'bullet.ip' job is created with the help of 'job-create' and 'write-input-file' tools. This file could easily be imported in LSDYNA software. The same procedure is adopted to create model of plate, then it's meshing and followed to creation of 'plate.ip' job-file. The plate has divided into three regions and a great care has been taken during plate division and its meshing for the best possible optimization. The meshed plate has 33120 elements and 37773 nodes with the aspect ratio of 4.48. Hence, the overall aspect ratio is within permissible limit and is required for better simulation results.

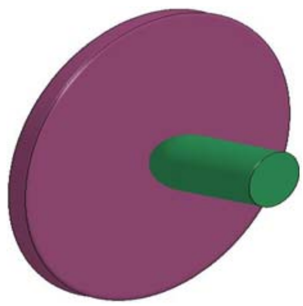


Fig. 1 Modeling of bullet and plate (in ABAQUS)

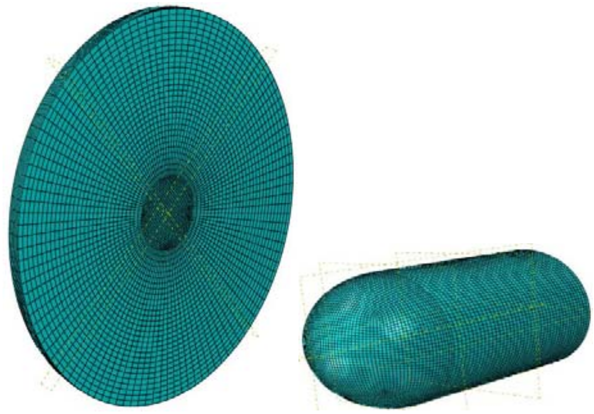


Fig. 2 Meshing of bullet and plate (in ABAQUS)

## III. Constitutive Models

Plastic-kinematic and Johnson-Cook material models are commonly used in ballistic impact simulations. These models are basically different in considering the various effects like large strain, resulting strain rate hardening, material thermal softening and damage of materials. These models require different number of material constants to satisfy the boundary conditions and complete the requirements of the concerned models. Both material models are accompanied with different material damage models. To analyze the effect of the material models on bullet penetration phenomena, finite elements analysis of the plate is repeatedly performed with both material models and compared with each other. Both the material models are now introduced to highlight the importance and usefulness of the material models concerned.

### A. Plastic-kinematic Hardening Material Model (Cowper-Symonds)

Plastic-Kinematic Hardening material model [9]-[11] is a very simple material model. It is a strain rate dependent elastic–plastic material model. It is very useful to study isotropic and kinematic hardening plasticity. This material model accounts strain rate by scaling the yield stress by the strain rate dependent factor as shown below:

$$\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\left(\frac{1}{P}\right)}\right]\sigma_0 \quad (1)$$

where $\sigma_y$ is dynamic yield stress, $\sigma_0$ is the yield stress at starting, $\dot{\varepsilon}$ is strain rate, P and C are the Cowper & Symonds strain rate parameters in (1). Generally, numerical values of C and P are taken as 40 and 5 respectively for AISI 4340 steel. The Plastic- Kinematic Hardening model became very popular in ballistic simulations to characterize the effect of strain rate on material properties. This model was formulated by gathering test data of the dynamic lower yield stress of various materials at different strain rates. This is the simplest material model and is sufficient enough to reasonably predict most of impact parameters such as depth of penetration, residual projectile velocity, and deformation pattern. It incorporates the effect of crack propagation and fracture during penetration of plate with the help of eroding node to surface contact algorithm that removes the damaged elements after certain time duration. Plastic kinematic model constants for AISI 4340 steel are given in Table I [12].

TABLE I
PLASTIC-KINEMATIC MATERIAL MODEL CONSTANTS FOR AISI 4340 STEEL

| Modulus of elasticity, E (MPa) | Density, ρ ($kg/m^3$) | Poisson ratio, $\upsilon$ | Yield stress, $\sigma_y$ (MPa) | Tangent modulus, $E_T$ (MPa) |
|---|---|---|---|---|
| 210000 | 7850 | 0.3 | 792 | 21000 |
| Strain-rate parameter, C | Strain-rate parameter, P | Failure strain, $\varepsilon_f$ | | |
| 40 | 5 | 0.15 | | |

### B. Johnson-Cook Material Model

The Johnson-Cook material model was introduced in 1983 and was popularly used as a computational tool. This model was formulated by gathering test data at different strain rates and temperatures for a wide range of test procedures. Johnson-Cook material model is an empirical constitutive model for metals. It is a strain rate and temperature-dependent (adiabatic assumption) visco-plastic material model. The suitability of this model can be accounted for strain rates vary over a very large range and change in temperature causes material softening effect. For each phenomenon (strain hardening, strain rate hardening and thermal softening), an independent term is created. By multiplying these terms, a flow stress is obtained as a function of the effective plastic strain, effective plastic strain rate and temperature. The constitutive model is relatively easy to calibrate since it allows isolation of the various effects. Due to this property, the model is frequently used in the ballistic society.

The Johnson-Cook material model represents the flow stress with an equation of the form [9]-[11]:

$$\sigma_y = (A + B\,\varepsilon^n)(1 + C\ln\dot{\varepsilon}^*)(1 - T^{*m}) \quad (2)$$

where A, B, C, and m are Johnson-Cook Material constants, ε is the effective plastic strain for material, $\dot{\varepsilon}^*$ is the normalized effective plastic strain rate, n is the work hardening exponent in (2), and $\sigma_y$ is the effective stress of material. Normally $\dot{\varepsilon}^*$ is normalized to a strain rate of 1.0 $s^{-1}$. The quantity $T^*$ is mathematically defined in the following form:

$$T^* = \frac{T - T_{room}}{T_{melt} - T_{room}} \quad (3)$$

where $T_{melt}$ is the melting point temperature and is typically taken as the solidus temperature for an alloy and $T_{room}$ is the working room temperature. Fracture of elements in the Johnson-Cook material model occurs according to the following cumulative damage law:

$$D = \sum \frac{\Delta\varepsilon}{\varepsilon_f} \quad (4)$$

in which $\varepsilon_f$ took the following mathematical form:

$$\varepsilon_f = [D_1 + D_2\exp(D_3\sigma^*)][1 + D_4\ln\dot{\varepsilon}^*][1 + D_5T^*] \quad (5)$$

where Δε is the increment of effective plastic strain during an increment in loading and $\sigma^*$ is the mean stress normalized by the effective stress. The parameters $D_1$, $D_2$, $D_3$, $D_4$ and $D_5$ are fracture constants. Failure of elements is assumed to occur when D = 1. The failure strain $\varepsilon_f$ and thus the accumulation of damage is a function of mean stress, strain rate, and temperature. Failed elements are removed from the finite element mesh in the progress of the impact analysis because eroding node to surface type of contact is used in defining the constants of this model.

### C. Mie-Gruneisen Equation of State

In material characterization at high strain rates, the pressure is calculated from the equation of state (EOS). The high strain rate deformations involve the generation of high temperatures under shock wave conditions which necessitates the consideration of the temperature or energy in the formulation of an EOS. The equation of states can be determined from the knowledge of the thermodynamic properties of the materials and ideally should not require dynamic data to build the relationship. During a bullet impact, significant high pressures ($p$ > 10 GPa) can arise in the loaded materials. The Mie-Gruneisen equation of state is related to shock Hugoniot curve via the Rankine-Hugoniot relations and is therefore able to model the shock and its residual temperature more properly. Mie-Gruneisen equation of state model in this study is used in conjunction with Johnson-Cook material model. It defines the pressure volume relationship in one of two ways, depending on whether the material is compressed or expanded. The Mie-Gruneisen equation of state with cubic shock velocity-particle velocity defines pressure for compressed materials as [9]:

$$p = \frac{\rho_0 C_{sp}^2 \mu\left[1+\left(1-\frac{\gamma_0}{2}\right)\mu-\frac{a}{2}\mu^2\right]}{\left[1-(S_1-1)\mu-S_2\frac{\mu^2}{\mu+1}-S_3\frac{\mu^3}{(\mu+1)^2}\right]} + (\gamma_0 + a\mu)E_{in} \qquad (6)$$

And for expanded materials

$$p = \rho_0 C_{sp}^2 \mu + (\gamma_0 + a\mu)E_{int} \qquad (7)$$

where $E_{int}$ is internal energy, $S_1 - S_3$ are the coefficients of the slope of the $v_s - v_p$ curve, $\gamma_0$ is the Gruneisen gamma, $C_{sp}$ is the intercept of the $v_s - v_p$ curve, a is the first order volume correction to $\gamma_0$ , and μ is mathematically defined as:

$$\mu = \frac{\rho}{\rho_0} - 1 \qquad (8)$$

Johnson-Cook and Mie-Gruneisen equation of state models constants for AISI 4340 steel are given in Table II [10], [13].

TABLE II
JOHNSON-COOK AND MIE-GRUNEISEN EQUATION OF STATE MODELS CONSTANTS FOR AISI 4340 STEEL

| Density, ρ ($kg/m^3$) | Poisson ratio, $\upsilon$ | Modulus of Elasticity, E (MPa) | Strength constants | | | | |
|---|---|---|---|---|---|---|---|
| | | | A (MPa) | B (MPa) | N | C | M |
| 7850 | 0.3 | 210000 | 910 | 586 | 0.26 | 0.014 | 1.03 |
| Fracture constants: $D_1 = -0.8, D_2 = 2.1, D_3 = -0.5, D_4 = 0.002, D_5 = 0.61$ | | | | | | | |
| Mie- Gruneisen EOS constants: $S_1 = 164, S_2 = 294, S_3 = 500, \gamma_0 = 1.16$ | | | | | | | |

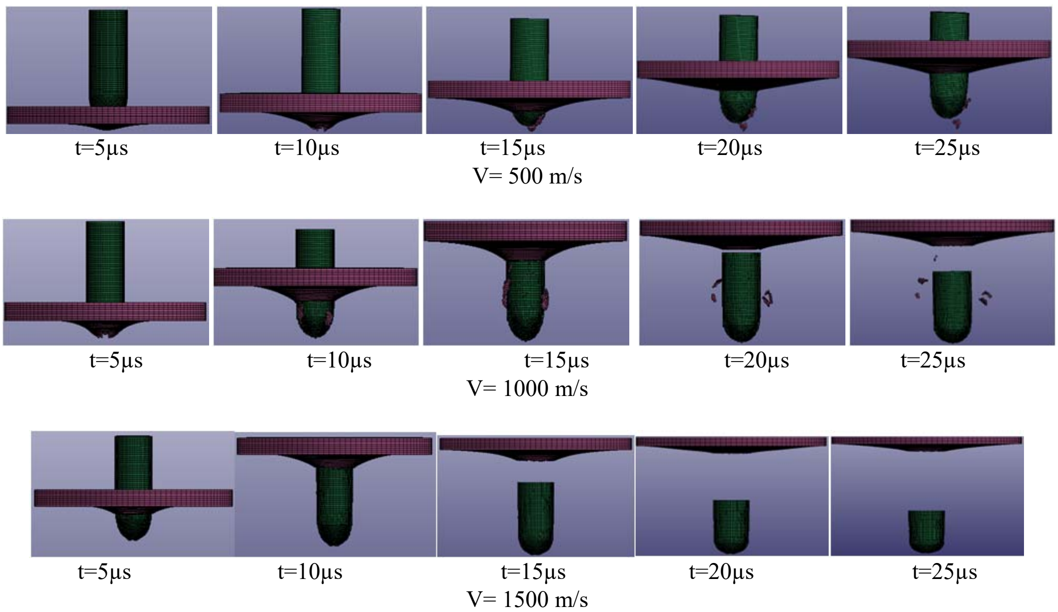



Fig. 3 Assembly condition of bullet and plate with Plastic-Kinematic material model at different time frames

## IV. SIMULATION OF BULLET PENETRATION

The developed three-dimensional finite element model is to be simulated using two different material models viz. Plastic-Kinematic and Johnson-Cook material models. The created part files of bullet and plates are imported in LSDYNA Pre-post, and a proper assembly condition is ensured with the help of transformation tools such as translation and rotation. In conjunction with Johnson-Cook material model, the coefficients of Mie-Gruneisen equation of state are defined. Once the assembly is met, then material properties are assigned according to material models. In both models, the boundary of the plate is kept fixed by arresting its all degrees of freedom. Velocity of bullet is assigned with the help of 'initial-velocity-generation' tool. One has to define the contact type as 'eroding node to surface' and end time for simulation is 50 μs. One should be careful for assigning different scale factors suitably because low value of scale factor will be unable to detect bullet impact and bullet will just pass the plate without detecting contact and we have to save changes made each time in the defining constants and boundary conditions; otherwise; it will give absurd results or failed to simulate sometimes and generate error warnings.

## V. RESULTS AND DISCUSSION

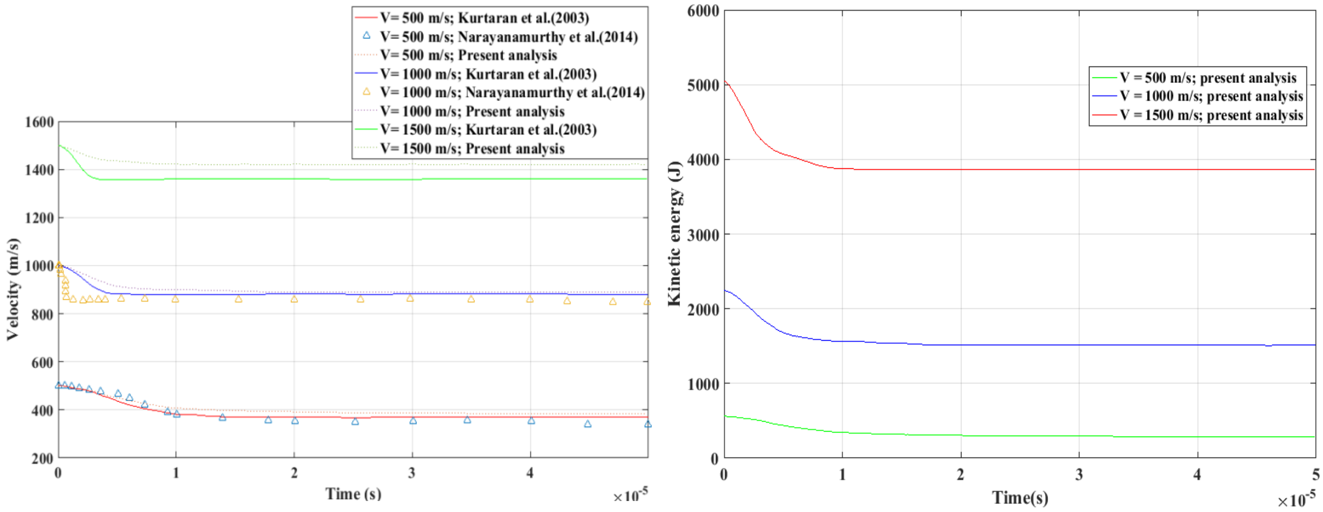
Simulation running time for Plastic-Kinematic and Johnson-Cook models, are generally 2-6 hours (depends on processing speed of computer). This simulation is performed for the duration of 50 μs in HP-Z420 workstation with Intel Xeon E5-1603, 2.8 GHz, 4 core processor, 8GB DDR3-1600ECC RAM, NVIDIA Quadro 2 GB Graphics and Windows 7 Professional 64-bit operating system. Once the simulation is completed successfully without error warnings; then user can access the results of simulation with the help of post-processing module in LSDYNA.

### *A. Results with Plastic-Kinematic Material Model*

The results of bullet penetration using Plastic-Kinematic model is demonstrated in Figs. 3 and 4 for the bullet impact velocities of 500, 1000, and 1500 m/s. The time duration for the simulation is sufficient to observe the perforation of plate. Captured simulation photos are presented at the interval of 5 µs, while the results are plotted for time duration of 50 µs.

### *B. Results with Johnson-Cook Material Model*

The results of bullet penetration using Johnson-Cook material model is demonstrated in Figs. 5 and 6 for the bullet impact velocities of 500, 1000 and 1500 m/s. With the help of Figs. 3 and 5, it could be easily predicted that the simulation results are different for different material models. The one of the possible reasons may be that the models are based on different assumptions and their limitations to accept different natural phenomenon. It can also be derived that the Johnson-Cook material model comparatively gives better results due to its sophisticated nature and its capability to assume the effect of large strain and strain rate with thermal softening. The results obtained from simulation with Plastic-Kinematic model are compared with the literature in which comparison for velocity has done with results presented by Narayanamurthy et al. [14], while results obtained from simulation with Johnson-Cook model are compared with the results presented by Kurtaran et al. [8] for bullet velocities of 500, 1000, and 1500 m/s. Results are in good match in the case of Plastic-Kinematic model, while the deviation of results is in permissible limit for simulation with Johnson-Cook material model.




(a) (b)

Fig. 4 (a) and (b), Variations of velocity and kinetic energy vs. time during bullet penetration respectively

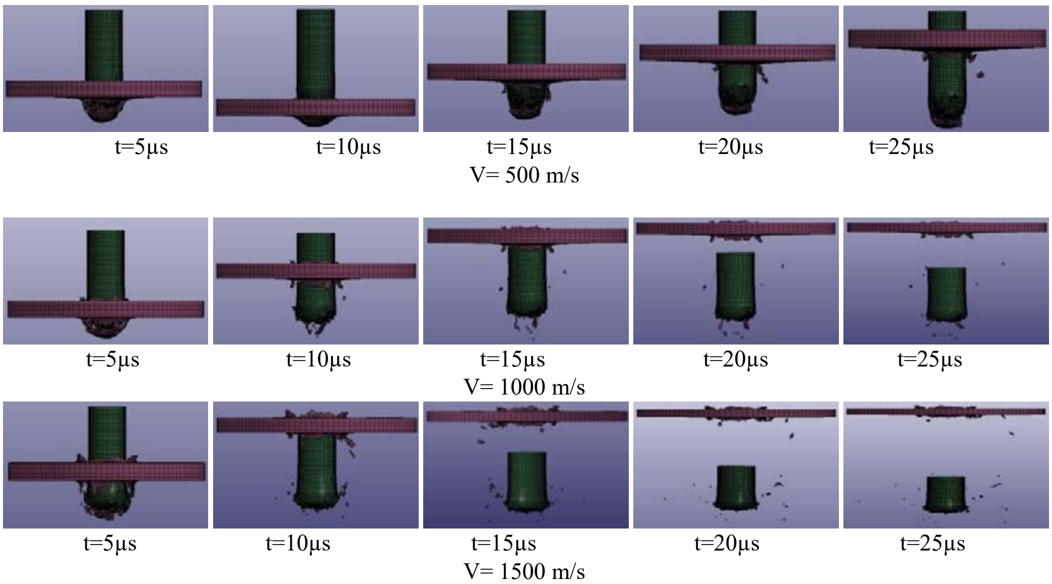
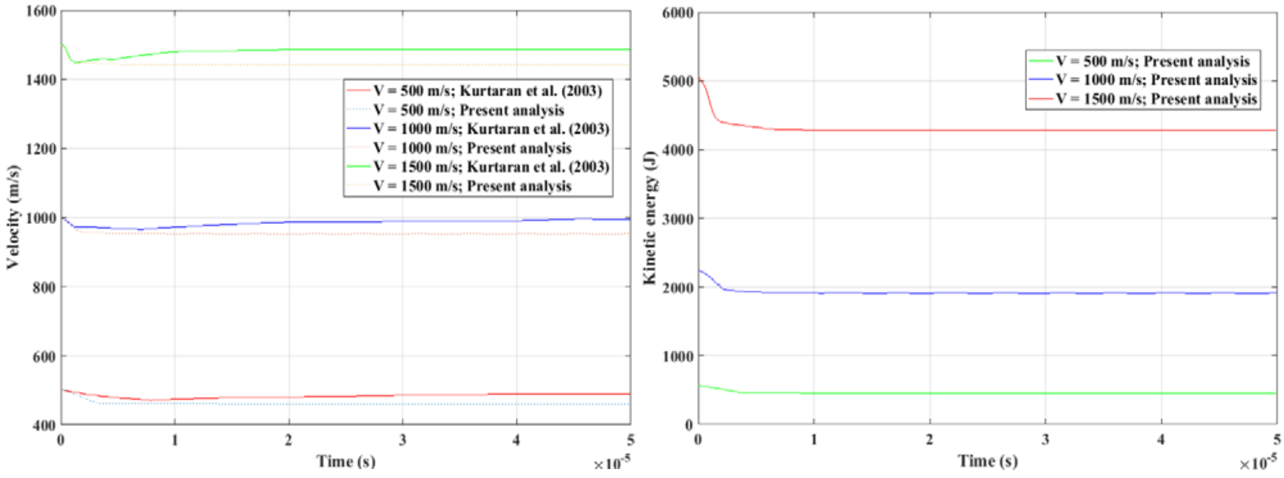



Fig. 5 Assembly condition of bullet and plate with Johnson-Cook material model at different time frames




(a) (b)

Fig. 6 (a) and (b), Variations of velocity and kinetic energy vs. time during bullet penetration respectively

## VI. Conclusion

This research paper focuses on non-linear, dynamic and explicit analysis of bullet penetration, and its simulation is performed with the help of LSDYNA impact analysis software package. Due to use of steel in various defense vehicles, it is imperative to analyse what-if scenario of bullet impacts at ordinance velocity regime. Data for bullet residual velocity and kinetic energy are plotted in the graphs with respect to time, and they are very helpful to understand the behaviour of bullet impact at very small duration period (generally in micro-seconds).

Both the material models viz. Plastic-Kinematic and Johnson-Cook resulted in different deformation patterns in steel plate and the target plate having thickness of 2 mm is unable to prevent full penetration by bullet moving at velocities of 500, 1000, 1500 m/s. From the Figs. 4 and 6, it can be observed that the velocity drop and loss of kinetic energy of bullet occurred very quickly up to perforation of plate, after that the velocity drop and change in kinetic energy are negligibly small. The one of the possible reasons may be the absence of resistance in its intended path once bullet perforated the plate.

## Acknowledgment

Authors want to thank Dr. Surendra Pal, Vice Chancellor, Defense Institute of Advanced Technology (DU), Pune-411025, Maharashtra, India for his guidance and support with his rich practical experience.

## References

[1] Backman, M. E. and Goldsmith, W., "The mechanics of penetration of projectiles into targets," *International Journal of Engineering Science*, Vol. 16, No. 1, 1978, pp. 1–99.

[2] Dikshit, S., Kutumbarao, V., and Sundararajan, G., "The influence of plate hardness on the ballistic penetration of thick steel plates," *International journal of impact engineering*, Vol. 16, No. 2, 1995, pp. 293–320.

[3] Borvik, T., Hopperstad, O., Berstad, T., and Langseth, M., "Numerical simulation of plugging failure in ballistic penetration," *International Journal of Solids and Structures*, Vol. 38, No. 34, 2001, pp. 6241–6264.

[4] Kaufmann, C. and Williams, K., "Optimization of a numerical simulation involving the impact of an AP-T C44 12.7 mm projectile on a semi-infinite monolithic 6061-T6 aluminium target," Tech. rep., Technical report, Defence Research and Development Canada, 2004.

[5] Borvik, T., Hopperstad, O., Berstad, T., and Langseth, M., "Perforation of 12mm thick steel plates by 20mm diameter projectiles with flat, hemispherical and conical noses: part II: numerical simulations," *International Journal of Impact Engineering*, Vol. 27, No. 1, 2002, pp. 37–64.

[6] Borvik, T., Dey, S., and Clausen, A., "Perforation resistance of five different high-strength steel plates subjected to small-arms projectiles," *International Journal of Impact Engineering*, Vol. 36, No. 7, 2009, pp. 948–964.

[7] Nsiampa, N., Dyckmans, G., and Chabotier, A., "Impact of 7.62 mm AP ammunition into aluminium 5083 plates," *Proc. of the XXIII International Symposium on Ballisitic, Tarragona, Spain*, 2007.

[8] H. Kurtaran, M. Buyuk, A. Eskandarian,''Ballistic impact simulation of GT model vehicle door using finite element method,'' *Theoretical and Appied. Fracture Mechanics,* Vol.40, 2003, pp.113–121.

[9] J. O. Hallquist, LSDYNA Theoretical Manual, Livermore Software Technology Corporation, Livermore, CA, USA, 1997.

[10] J. A. Zukas, High Velocity Impact Dynamics, John Wiley & Sons Inc., NY, 1990.

[11] Michael Dietenberger, Murat Buyuk, Cing Dao (Steve) Kan, ''Development of a High Strain-Rate Dependent Vehicle Model,'' LS-DYNA Anwenderforum, Bamberg 2005.

[12] Borvik, T., Langseth, M., Hopperstad, O., and Malo, K., "Ballistic penetration of steel plates," *International Journal of Impact Engineering*, Vol. 22, No. 9, 1999, pp. 855–886.

[13] T. J. Holmquist, D. W. Templeton, K. D. Bishnoi, ''Constitutive Modeling of aluminium nitride for large strain, high strain rate, and high pressure applications,'' *International Journal of Impact Engineering,* 2001, pp.211–231.

[14] V. Narayanamurthy, C. Lakshmana Rao, and B. N. Rao, ''Numerical Simulation of Ballistic Impact on Armour Plate with a Simple Plasticity Model,'' *Defence Science Journal*, Vol.64, January 2014, pp.55-61.