Defence Science Journal, Vol. 64, No. 1, January 2014, pp. 55-61, DOI:10.14429/dsj.64.4521

Numerical Simulation of Ballistic Impact on Armour Plate with a Simple Plasticity Model

V. Narayanamurthy[*], C. Lakshmana Rao, and B.N. Rao

[*]Research Centre Imarat, Hyderabad-500 069, India
Indian Institute of Technology Madras-600 036, India
[*]E-mail: v.narayanamurthy@rcilab.in

ABSTRACT

Ballistic impact of a steel projectile on armour steel plate is examined by numerical simulations using 3-D nonlinear dynamic explicit finite element code ANSYS LS-DYNA. Simulations are attempted using a simple strain rate dependent plasticity model that can capture large strain, strain rate hardening and fracture encountered at high velocity ballistic impacts. Initial simulations are carried out for a cylindrical bullet with a semi-spherical nose shape impacting a military vehicle door at two different velocities as a test problem. This is then extended to simulate a real problem of armour piercing shot impact on a thick armour steel plate at ordnance velocity regime. The former is compared with results reported in published literature while the latter is assessed with the experimental findings. The deformation pattern generated in the deformed armour plate, residual projectile velocity and displacement of the projectile are taken as the necessary parameters for evaluating the results of simulation. The study presented in this paper demonstrates the effectiveness of the adopted simple plasticity model to simulate a highly nonlinear phenomenon to reasonably predict the physically measurable impact parameters.

Keywords: Numerical simulation, ballistic impact, projectile, armour plate, plasticity model, experimental results, failure

1. INTRODUCTION

The ballistic impact is a highly non linear dynamic phenomenon characterized by large deformation (strain), large strain rate, thermal softening and fracture in addition to constantly changing boundary conditions[1]. Numerous experimental investigations[2-4] have so far been conducted for a normal or an oblique projectile impact on homogeneous or sandwiched metallic or composite plate. But the cost and time involved in ballistic experiments restrict the researchers' dependency on experiments for all impact related studies. The complexity of the ballistic impact and penetration events often limits the general use of closed form analytical solutions[5-7]. So a numerical simulation study is often preferred and resorted as a supplement to ballistic experiments. Simulations help in developing new projectiles and armours in shorter period and permit easy design modifications and improvements. They reduce the experimental needs to a minimum to the extent of limiting to an acceptance or a qualification test. However, only few numerical studies at ordnance velocities are available because it is largely dependent on numerical inputs (material and fracture models) and numerical formulations[8-15].

Recent developments in commercial finite element codes are capable of simulating the complex ballistic impact events. The numerical simulation using finite element (FE) codes requires a sophisticated constitutive model, equation of state and an in-built failure criteria as numerical inputs either individually or in combination to appropriately capture the complete behavior of ballistic events. A number of constitutive models are available in literature with varying capabilities in characterizing the material behavior during impact[16]. Many of them are material dependent and developed empirically or semi-empirically based on plasticity approach. They offer different levels of difficulty in finding a number of material constants presented in material models from different physical tests that are mostly and completely not available in public domain.

A simple rate dependent plastic kinematic hardening material model that can characterize strain and strain rate hardening effects and fracture at high velocity impacts is adopted in this simulation study using the nonlinear dynamic explicit FE software ANSYS LS-DYNA[17]. In this study, the penetration performance of a military vehicle door subjected to the ballistic impact of a cylindrical steel bullet with a semi-spherical nose shape is simulated initially at two different bullet impact velocities as a test problem in Case-1 analysis. This is then extended to simulate a real problem in Case-2 analysis where an armor piercing (AP) shot having a cylindrical body with a triple conical profiled nose shape towards the leading edge, impact on a thick armour steel target plate at ordnance striking velocities. The former is compared with results reported in Kurtaran[9], *et al.* while the latter is assessed with the experimental test results in Narayanamurthy[13].

The pattern of hole generated in the deformed armour plate, residual projectile velocity and displacement of the bullet are taken as the necessary parameters for evaluating the results of simulation. The studies presented in this paper demonstrate

Received 28 April 2013, revised 21 August 2013, online published 23 January 2014

the effectiveness of the adopted simple plasticity model to simulate a highly nonlinear phenomenon to reasonably predict the physically measurable impact parameters. FE modeling is presented first for the Case-1 and Case-2. A detailed discussion on material model and failure criteria is provided followed by analysis of the plate-bullet impact. Finally the results observed in simulations and ballistic experiments are presented and discussed.

2. FINITE ELEMENT MODELING

In Case-1 simulation, the military vehicle door is a single layer thin plate structure of isotropic material. The bullet moving towards the door can hit anywhere on it. Only a small portion of the door where the bullet can hit is utilized in this study to simplify the analysis and the simulations are carried out on this isolated small potential region of impact as adopted in Kurtaran[9], *et al.* This region on the door is considered in the form of a circular plate with diameter 40 mm and thickness 2 mm. The bullet and the plate are considered to be made of AISI 4340 steel. Details of FE modeling of the plate and the bullet for the Case-1 analysis are provided in Fig. 1. The plate and the bullet are discretised with explicit 8-noded hexahedral elements of size varying between 0.25 mm and 1 mm with an aspect ratio not exceeding five. The plate-bullet FE model is made of a total 104800 elements: 76000 for the bullet and 28800 for the target door plate.

In Case-2 simulation, the AP shot has a leading nose tip followed by three conical sections with an included angle of 120°, 40° and 170° respectively for the first 30 mm length. It has a cylindrical section for the remaining length with a diameter of 30 mm and a total length of 98 mm. The target armour is a square steel plate of dimensions 1220 mm x 1220 mm x 40 mm. The potential circular region of impact for the target is taken as 150 mm. The bullet and target are discretised by mapped meshing. The element length varies from a minimum of 0.5 mm to a maximum of 1 mm in bullet and a minimum of 0.5 mm to a maximum of 2 mm in target plate. The total number of elements in the FE model is 132720 with 46080 for the bullet and 86640 for the target plate. Due to the sharp leading edge at the nose tip of bullet the element size tends to get reduced. Sufficient care is taken to fix an element size here. This helps in controlling the time step for the explicit time integration which is calculated based on the minimum element length. The FE model of AP shot and target plate for Case-2 is shown in Fig. 2.

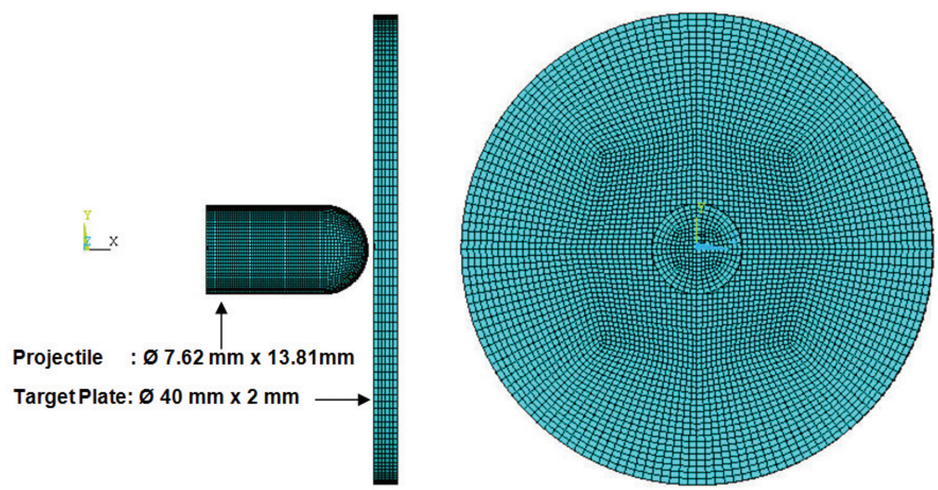


Figure 1. FE model of the bullet and target door plate for Case-1 analysis.

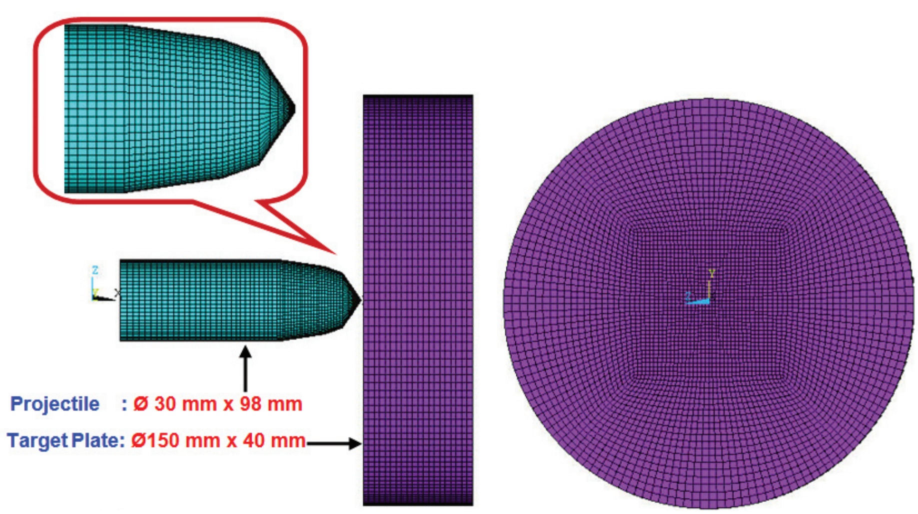


Figure 2. FE model of the AP shot and armour steel target plate for Case-2 analysis.

The element parameters like aspect ratio, parallel deviation, maximum corner angle and Jacobian ratio are maintained within limits prescribed for the explicit 8 node hexahedral element used in ANSYS LS-DYNA[17]. The elements are gradually coarsened from inner to outer part of the target. This facilitates more number of finer elements at the middle portion of the target plate that experiences the actual contact–impact and less number of coarser elements in the remaining portion of the target plate. Mesh transition between regions is good enough to prevent stress wave reflections from the boundary of the regions. The gradual transition also avoids sudden jumps in the stress wave. The boundary of the plate is specifically chosen to be circular instead of other shapes such as rectangle. Because, the symmetry of stress wave propagation and reflection (i.e. stress value) in the circumferential direction of the plate can be preserved in circular shape but not in rectangular shape during the normal impact of the projectile[9]. The translational nodal degrees of freedom along the boundary of the target plate are constrained to prevent any translational motion.

3. A SIMPLE PLASTICITY MODEL

The constitutive model adopted is a simple plastic kinematic hardening material model which is a strain rate dependent elastic–plastic model. In this model, strain rate is accounted for using the Cowper–Symonds model which scales the yield stress by the strain rate dependent factor as

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

where σ_y is the dynamic yield stress; σ_0 is the initial yield stress; $\dot{\varepsilon}$ is the strain rate; and C and P are the Cowper–Symonds strain rate parameters. To allow crack growth and fracture during penetration, the plastic kinematic hardening material model is coupled with an element-kill algorithm available in LS-DYNA that removes the damaged elements from the mesh when the damage variable reaches the predetermined critical value. Failure or complete fracture of finite elements is assumed to occur when equivalent plastic strain (erosion strain) reaches a critical value (failure strain) that is considered here as a failure criteria. Plastic kinematic hardening material model is simplistic in nature in describing strain hardening and strain rate hardening behaviors.

The model constants for AISI 4340 steel[9] used in the simulation for both bullet and the target plate for Case-1are:

Material	=	AISI 4340 Steel	
Density (ρ)	=	7850	kg/m^3
Young's modulus (E_x)	=	2.1 E 5	MPa
Yield stress (σ_y)	=	792	MPa
Tangent modulus (E_t)	=	2.1 E 4	MPa
Hardening parameter (β)	=	0	
Strain rate parameter (C) (Cowper-Simonds)	=	40	
Strain rate parameter (P) (Cowper-Simonds)	=	5	
Failure strain (ε_f)	=	0.15	

The AP shot and the target plate for the Case-2 analysis are made of two different alloy steels[13] and the model constants adopted are:

Material	=	Armour steel
Density (ρ)	=	7850 kg/m^3
Young's modulus (E_x)	=	2.1 E 5 MPa
Yield stress (σ_y)	=	800 MPa for AP shot & 900 MPa for target plate
Tangent modulus (E_t)	=	2.1 E 4 MPa
Hardening parameter (β)	=	0
Strain rate parameter (C) (Cowper-Simonds)	=	40
Strain rate parameter (P) (Cowper-Simonds)	=	5
Failure strain (ε_f)	=	0.15 for AP shot & 0.21 for target

4. FINITE ELEMENT ANALYSIS

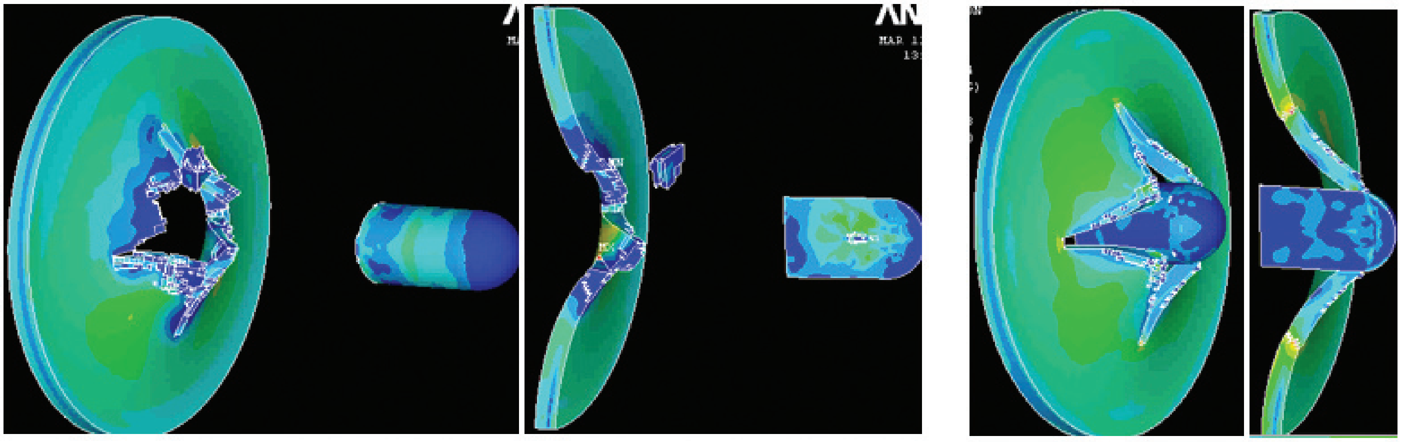
In FE analysis, eroding node-to-surface contact algorithms is employed to simulate the contact behavior between surfaces during penetration. Finite element analysis is conducted for the bullet impact velocities of 500 m/s and 1000 m/s for the Case-1 and 800 m/s and 830 m/s for the Case-2 on a P4-Dell PC with 3.06 GHz processor for a time duration of 50 μs and 100 μs respectively for the two cases. The time scale is chosen to cover a period of time corresponding to complete perforation of the plate. For the FE model in Figs. 1 and 2, analyses were completed between 2 h and 6.5 h of CPU time for the Case-1 and 7 h and 10 h for the Case-2.

5. RESULTS AND DISCUSSION

5.1 Case-1 Analysis

The FE simulation results for the bullet striking velocities V of 1000 m/s and 500 m/s for the Case-1 are shown in Fig. 3. The bullet at V = 1000 m/s as well as 500 m/s is able to penetrate through the plate within a duration of time t of 30 μs and beyond 50 μs respectively. Deformed plate shown in Fig. 3 illustrates that the plate undergoes initial bending at the centre soon after impact. When tensile strain at the rear side exceeds the failure limit, the crack is initiated and propagated in all four opposite orthogonal directions. This leads to a tearing type of deformation and failure at centre of the plate in this Case-1 analysis. The pattern of deformation in bullet and target; and depth of penetration u_x of the bullet at various instant of time from present Case-1 analysis[13] agreed well with that in Kurtaran[9], *et al.* for both V = 1000 m/s and 500 m/s.

The initial kinetic energy of the bullet is the total energy due to its mass and initial velocity. It is utilized in deforming the plate centrally. The kinetic energy and the initial velocity in the bullet gradually decrease during the process of penetration and it remains almost constant after the penetration is completed[13]. The kinetic energy lost in the above process is responsible for the rise in the internal energy, plastic deformation and perforation in vehicle door plate. Even the centre of plate experiences a rise in kinetic energy till crack initiation due to the particles in the plate being accelerated by the kinetic energy of the bullet. A part of the kinetic energy of the bullet is then spent in perforating the plate. The plate offers an initial



(a) (b)

Figure 3. Deformed bullet and target plate at t =50 μs: (a) V = 1000 m/s and (b) V = 500 m/s.

resistance for bending and this imparts a rise in the internal energy of the bullet to an extent. The internal energy of the plate rises steadily at a higher rate than that of the bullet till crack is initiated. The rate of rise in the internal energy of the bullet due to its work done is almost negligible after the crack initiation.

The change in the velocity of the bullet during penetration and residual velocity after penetration for the two striking velocities considered in this simulation are shown in Fig. 4 and are in close agreement with the results available in Kurtaran[9], *et al*.

Stress and strain in the bullet also increase steadily and are higher at a higher bullet velocity during initial stage[13]. The stress levels decrease substantially in bullet during subsequent stages. Due to the plastic deformation the strain levels are on higher side during subsequent stages also. It is observed that both stress and strain increase steadily in the plate during initial stage of impact and remains almost at an increased level in subsequent stages. Initial strain rate is found to be constant in bullet as well as in target plate. The variation in strain rate actually occurs during and aftermath of penetration process.

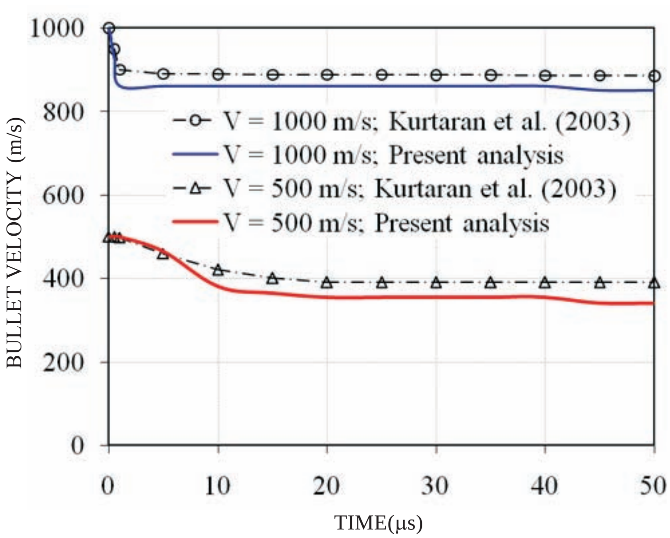


Figure 4. Change in bullet velocity during penetration in Case-1 analysis.

5.2 Case-2 Analysis

The elements located at the middle portion of the target plate starts failing when their strain level exceeds the failure strain limit set by the constitutive model due to the impact. They are seen to get eliminated from the computational domain gradually after penetration of the bullet through the plate. The bullet during penetration induces large strain in the target which is responsible for the hole formation and also experiences similar strain level within itself which subjects a large damage to the frontal portion of bullet during penetration. The high speed photographic snap shot images of the AP shot impact on the armour plate are taken during the experiment[13] at different time intervals during the penetration process at a striking velocity V = 830 m/s. These images are in good agreement and comparable with that extracted from Case-2 simulation.

Figure 5 shows the deformation in target plate for V = 830 m/s at t = 1000 μs in Case-2 analysis. It has been observed in tests[13] that the hole generated due to impact has a bulged appearance at the front side and a normal appearance at the rear side of the target. Due to this effect the diameter of hole is observed higher at the front side than that at the rear. The above effect is also seen in simulation. Though bulging is not seen explicitly in Case-2 simulation, the hole size decreased from the front to the rear side of the target. The measured hole diameters are close to that of the test as illustrated in Fig. 5(a). The target plate deforms globally to a small extent in the frontal direction (i.e. initial projectile direction) due to the effect of stress waves in which the middle portion alone deforms significantly in the rear side due to the impact which is clearly seen in the middle picture of Fig. 5(a). The amount of lateral deformation and its direction at centre and away from centre of target plate are illustrated respectively in Figs. 5(b) and 5(c).

The displacement and residual velocity of AP shot during penetration for a striking velocity V = 830 m/s are shown in Fig. 6. The displacements from simulations have a variation ranging from 0 mm to 20 mm to that of test results (Fig. 6(a)). Both results have a same displacement pattern and increase gradually. The residual velocities from simulations have a difference of around 100 m/s during initial stage of impact up to t = 100 μs as compared to test results. The retardation

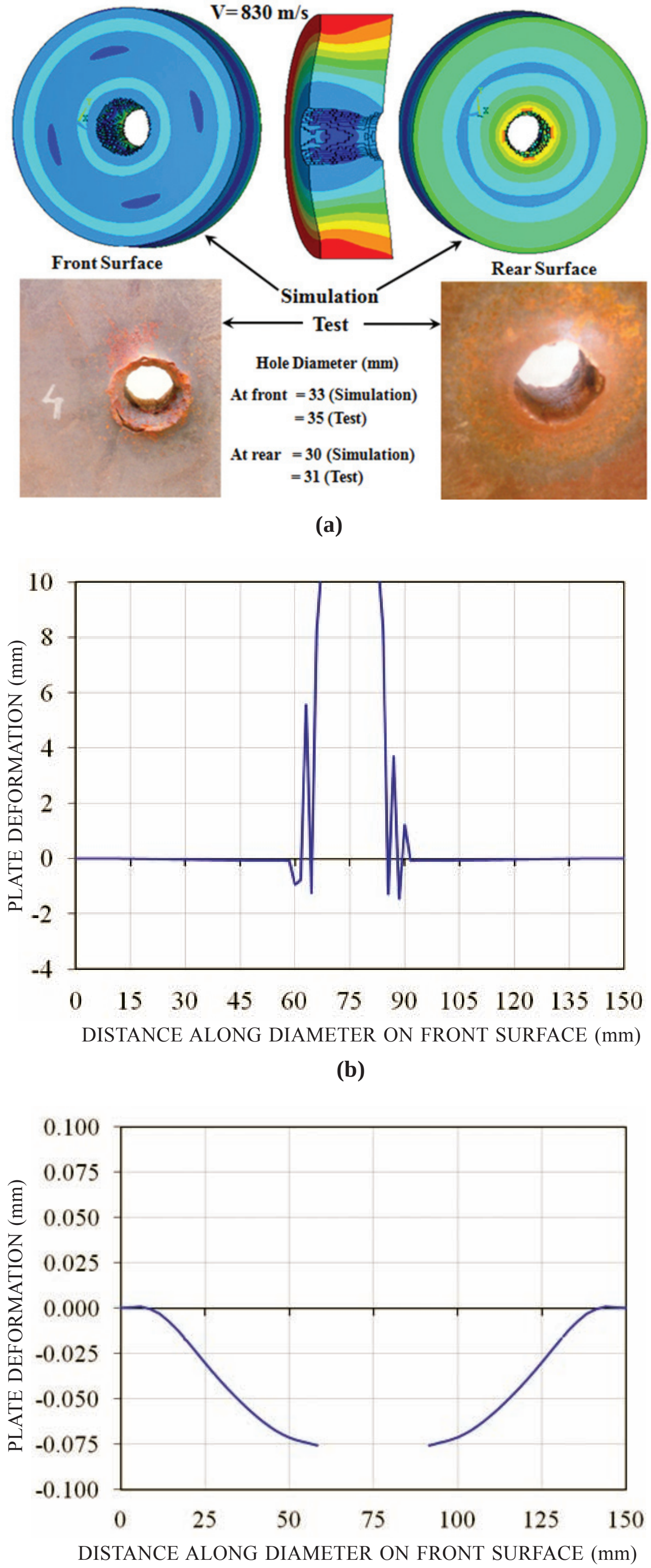


Figure 5. Deformation in target plate in Case-2 analysis for *V* = 830 m/s at *t* = 1000 µs. (a) Deformed armour plate in Case-2 analysis and test[13], (b) Lateral deformation at centre, and (c) Lateral deformation away from centre.

in AP shot at this stage perfectly matches simulation and test (Fig. 6(b)). The residual velocities obtained from simulation gradually decrease by about 80 m/s between t = 200 µs and 1000 µs. The residual shot velocities from test have small oscillations during this stage and have a reasonably good agreement with the simulation.

The material in front of the shot is rapidly accelerated at impact, giving a relative velocity i.e. kinetic energy within the target. This gives rise to a localized deformation under adiabatic conditions in narrow zones at the well defined periphery of the projectile. The kinetic energy in the bullet decreases significantly during the initial stage of impact and gradually during later stages. The internal energy of the bullet increases during initial stage by a very small amount and immediately decreases to a minimum value at the end of this initial stage. The kinetic and internal energies in the target plate increase during initial stage of impact and decrease to a minimum value at the later stages. The magnitude of kinetic and internal energies in the target and the internal energy in the bullet are all less than 30J which is insignificant compared to the kinetic energy in the projectile[13].

The total energy, variation of kinetic energy and internal energy in the system during ballistic impact are provided in Narayanamurthy[13] for two different striking velocities. The

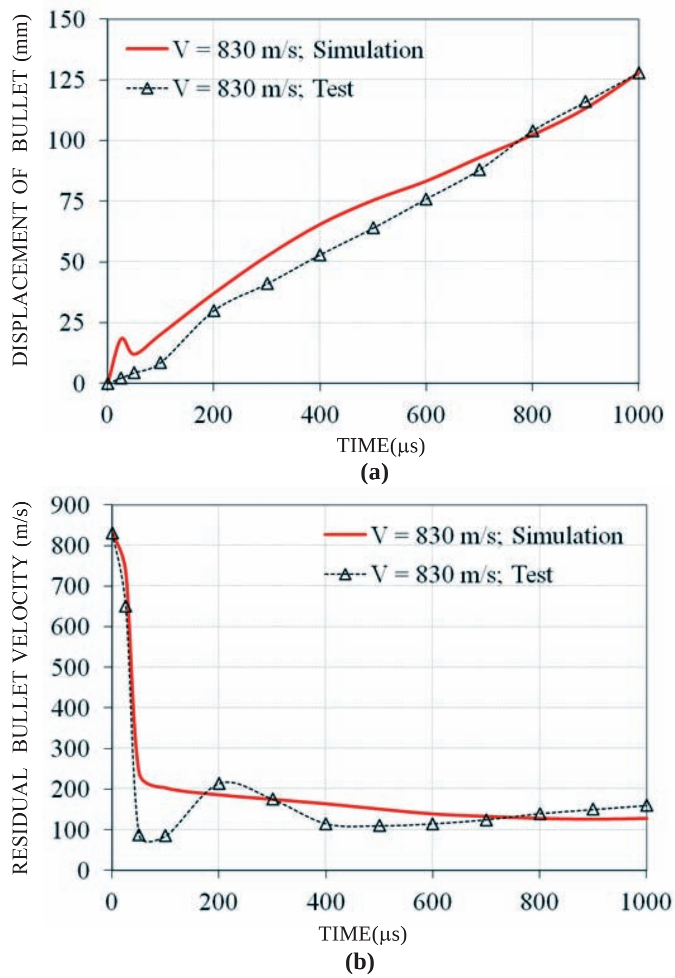


Figure 6. Displacement and residual velocity of AP shot in Case-2 analysis : (a) Displacement and (b) Residual velocity.

loss of energy is the difference between the total energy and the summation of kinetic and internal energies which is responsible for the plastic dissipation in the bullet and the target. Even some amount of energy though comparably very less is spent for hourglass control and artificial viscosity in the numerical simulation. This energy is said to be a percentage of the internal energy which itself is observed to be insignificant in this Case-2 simulation.

In Case-1 and Case-2 simulations discussed above, it is demonstrated that a simple plasticity model is sufficient to obtain information regarding the energy transfer, residual projectile velocity, displacement of bullet and deformation pattern. The results from simulations are found to agree reasonably well with that in literature[9] for the Case-1 and tests for the Case-2 for the parameters of interest. Plug formation observed in tests is not revealed in the simulations.

6. CONCLUSION

This paper is concerned with the numerical simulation of ballistic impact of a cylindrical bullet on a military vehicle door in Case-1 and an armour piercing projectile on an armour plate in Case-2 using a non-linear explicit finite element code ANSYS LS-DYNA. The simulations reveal that even a simplistic material model of plasticity such as kinematic hardening model that accounts the effects due to large strain and strain rate can predict most of the impact parameters such as residual projectile velocity, displacement of projectile and the deformation pattern to a reasonable accuracy besides providing a detailed insight into the understanding of the kind of energy transfer and distribution in projectile and target plate. This model is unable to predict the plug formation at this high velocity that may be attributable to the nature of failure criteria coupled with this material model. Considering the complexity of the highly nonlinear impact problem; the simplicity offered by the material model; and a reasonably good result achieved from simulations, the kinematic hardening plasticity model is demonstrated to be suitable for the ballistic impact simulation at ordnance velocity regimes.

ACKNOWLEDGEMENTS

The authors thank Dr N. Nayak, Joint Director and Mr. Arcadev Banerjee, Scientist at Proof Experimental Establishment, Balasore, India for sharing their rich experimental experiences and some of their test observations.

REFERENCES

1. Zukas, J.A. Impact Dynamics. John Wiley & Sons Inc., NY, 1990.
2. Borvik, T.; Langseth, M.; Hopperstad, O.S. & Malo, K.A. Ballistic penetration of steel plates. *Int. J. Impact Eng.*, 1999, **22**, 855-86.
3. Charles, E.A.; Volker, H.; James, D.W. & Alois, J.S. The influence of projectile hardness on ballistic performance. *Int. J. Impact Eng.*, 1999, **22**, 619-32.
4. Golsdmith, W. Penetration and perforation processes in metal targets at and above ballistic velocities. *Int. J. Mech. Sci.*, 1971, **13**(10), 843-66.
5. Awerifuch, J. & Bodner, S.R. Analysis of the mechanics of perforation of projectiles in metallic plates. *Int. J. Solids Struct.*, 1974, **10**(6), 671-84.
6. Forrestal, M.J.; Tzou, D.Y.; Askari, E. & Longcope, D.B. Penetration into ductile metal targets with rigid spherical-nose rods. *Int. J. Impact Eng.*, 1995, **16**(5-6), 699-710.
7. Woodward, R.L. Modeling geometrical and dimensional aspects of ballistic penetration of thick metal targets. *Int. J. Impact Eng.*, 1996, **18**(4), 369-381.
8. Liang, Y.; McmMeeking, R.M. & Evans, A.G. Designs and simulations of ballistic-resistant metal/ceramic sandwich structures. *In* the Advances in Ceramic Armor: A Collection of Papers Presented at the 29th International Conference on Advanced Ceramics and Composites, Jan 23-28, 2005, Cocoa Beach, Florida, Ceramic Engineering and Science Proceedings (ed J.J. Swab), 2008, **26**(7), John Wiley & Sons, Inc., Hoboken, NJ, USA.
9. Kurtaran, A. H.; Buyuk, M. & Eskandarian, A. Ballistic impact simulation of GT model vehicle door using finite element method. *Theor. Appl. Frac. Mech.*, 2003, **40**(2), 113–21.
10. Chocron, S.; Charles. E.A.; Donald, J.G. & Carl, H.P. Impact of the 7.62-mm APM2 projectile against the edge of a metallic target. *Int. Impact Eng.*, 2001, **25**(5), 423-37.
11. Adams, B. Simulation of ballistic impacts on armored civil vehicles. Department of Mechanical Engineering, Eindhoven University of Technology, Netherlands, 2003. PhD Thesis.
12. Borvik, T.; Hopperstad, O.S.; Berstad, T. & Langseth, M. A computational model of visco-plasticity and ductile damage for impact and penetration. *European J. Mechanics Solids*, 2001, **20**(5), 685–712.
13. Narayanamurthy, V. Simulation of ballistic impact on armour plates. Department of Applied Mechanics, IIT Madras, India, 2007. M.Tech Thesis.
14. Johnson, E.A.F.; Saleh, M. & Edwards, L. Ballistic performance of multi-layered metallic plates impacted by a 7.62 mm APM2 projectile. *Int. J. Impact Eng.*, 2011, **38**(12), 1022-1032.
15. Rajesh, P.N. & Lakshmana Rao, C. Simulation of depth of penetration during ballistic impact on thick targets using a one-dimensional discrete element model. *Sadhana : J. Indian Academy Sci.*, 2012, **37**(2), 261–279.
16. Hallquist, J.O. *LS-DYNA* Theoretical manual. Livermore Software Technology Corporation, Livermore, CA, USA, 1997.
17. ANSYS Release 10.0. *ANSYS LS-DYNA User's Guide*. ANSYS Inc., Canonsburgh, PA 15317, USA, 2005.

CONTRIBUTORS

Dr Vijayabaskar Narayanamurthy is working as a Scientist-D at Research Centre Imarat, Hyderabad. His research interests include structural mechanics modeling in hybrid beams, plates and shells; ballistic impact mechanics; flight interface structures and mechanics of fastenings.

Dr C. Lakshmana Rao is a Professor in the Department of Applied Mechanics at Indian Institute of Technology Madras, Chennai. He teaches courses on continuum mechanics, numerical modeling, fracture mechanics and mechanics of materials. His research interests include modeling of failures in brittle materials, buckling control using smart materials and ballistic impact mechanics.

Dr B.N. Rao is an Associate Professor in the Department of Civil Engineering at Indian Institute of Technology Madras, Chennai. His research interests include developing new methods in the areas of computational solid mechanics, finite element analysis, meshless analysis, computer-aided design, structural reliability, optimization, stochastic mechanics, fuzzy structural analysis, dimension reduction methods, fracture analysis, crack propagation simulation studies, and related fields.