# Impact Strength of Mild Steel and Armox 500T Steel

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**Abstract**

A study is based on the finite element investigation of the response of Mild Steel (MS) and Armox 500T Steel (AS) target subjected to macro and micro size impactor. The simulations were carried out on target against penetrator with varying masses, sizes, shapes and different in nature (rigid and deformable projectiles) using ABAQUS/Explicit. The material parameters of the Johnson-Cook elasto-viscoplastic model was employed for predicting the behaviour of target. The impact resistance of MS and AS target plates have been studied against flat nose having masses of 4, 8, 13.5, 27, 32 and 64 kg. The influence of temperature has also been studied numerically for particular penetrator of large masses. To study the influence of nature of projectile, the simulation were performed on MS and AS targets against deformable 2024 aluminium flat, hardened steel flat and hardened steel conical impactor at 950 and 150 m/s incidence velocity. The study thus presents a detailed investigation in terms of penetration, perforation and failure mechanism of MS and AS target and leads to some important conclusions pertaining to the force and resistance offered by the target.

**Keywords:** Finite element analysis, Armox 500T steel, Mild steel, Flat and conical nose impactor, Rigid and deformable projectiles

## 1 Introduction

For successful military operations, high strength steel may be widely considered however, the structural steels like low strength steels are used in the building, automobile and industrial applications. For instance, the tallest structures are constructed using structural steel due to its constructability. High strength and low strength steel plates are predominantly used as civil, aerospace and military protective structures. The idea of using these plates is to protect the personnel against accidental loads, terrorist attacks or international peace keeping operations. Bhat [2] discussed some basic principles that underlie design of materials effective for armour. Brian [3] observed that the IRHA performed better than standard RHA against the L/D 5KE penetrators. Buchar et al. [5] concluded that the targets of dual hardness exhibit very good resistance against the impact of AP projectile. Although the increase in

the hardness of the steel improved its ballistic behaviour, the steel specimens having either 50 or 60 HRc were broken in a brittle manner rather than perforation by the projectiles [6]. Hardness levels in steel plates played an important role in the ballistic performance. When the hardness of the steel plates increased, the penetration and the ballistic performance. When the hardness of the steel plates increased, the penetration and propagation ability of the projectile decreased significantly [19]. A detailed literature survey has been carried out on the target and projectiles in the present study have been carefully identified. The selection of suitable armour materials for defence applications is very crucial in order to design military vehicles, structural occupancy and military bunkers. The ideal material should possess the lowest areal density, high ductility and high strength [8, 9, 18, 7]. However, high strength steel still seems to be an ideal material for armour applications due to high strength and superior mechanical properties. Also, the investigations on armour steel plates against normal and oblique impact by different penetrator and fragments with help of computer tool is interesting [4, 12]. Based on the detailed literature survey, it is observed that the ballistic resistance of Armox 500T steel could not be found much studies in the available literature despite the fact that it possesses high strength, high hardness and high ductility which have been identified as the ideal properties for armour. The numerical reproduction of the experimental results is however limited due to the unavailability of strength and fracture parameters required for the Johnson-Cook constitutive modeling. It is observed that the studies on numerical investigations on ballistic resistance of mild steel, Armox steel target with elevated temperature against large mass flat impactor is limited. Also, it is observed that the ballistic resistance of Armox 500T steel against different penetrator with varying shape, size and mass is limited. In the present study, impact resistance of Armox 500T steel and mild steel targets has been studied against flat nose and conical nose at normal obliquity using ABAQUS/Explicit finite element code. The influence of temperature has also been studied numerically considering the fact that target may experience the temperature load from accidently/man made sources. The temperature was varied as 500, 900 and 1300 °K in light of various scenarios like protective structures against vehicle engine, special application in industry and blast waves cause various level of temperature. The Johnson-Cook constitutive model has been employed for predicting the material behavior of the Armox 500T steel (AS) and mild steel (MS) targets.

# 2 Constitutive Modelling

The flow and fracture behavior of projectile and target material was predicted employing the Johnson-Cook [15] elasto-viscoplastic material model available in ABAQUS [1] finite element code. The material model is based on the von Mises yield criterion and associated flow rule. It includes the effect of linear thermo-elasticity, yielding, plastic flow, isotropic strain hardening, strain rate hardening, softening due to adiabatic heating and damage. The Johnson and Cook [15] extended the failure criterion proposed by Hancock and Mackenzie [10] by incorporating the effect of strain path, strain rate and temperature in the fracture strain expression, in addition to stress triaxiality. The fracture criterion is based on the damage evolution wherein

the damage of the material is assumed to occur when the damage parameter, exceeds unity: The strain at failure is assumed to be dependent on a non-dimensional plastic strain rate, a dimensionless pressure-deviatoric stress ratio, (between the mean stress and the equivalent von-Mises stress) and the non-dimensional temperature, $\hat{T}$ defined earlier in the Johnson-Cook hardening model. When material damage occurs, the stress-strain relationship no longer accurately represents the material behavior [1]. The use of stress-strain relationship beyond ultimate stress introduces a strong mesh dependency based on strain localization i.e., the energy dissipated decreases with a decrease in element size. Hillerborg's [11] fracture energy criterion has been employed in the present study to reduce mesh dependency by considering stress-displacement response after the initiation of damage.

# 3 Finite Element Modelling

The finite element simulation of the problem was carried out using ABAQUS/-Explicit finite element code. The explicit algorithm of the code was employed for predicting the perforation phenomenon. The AS and MS target of thickness 3.18 and 4.7 mm was modelled in ABAQUS/CAE as three dimensional deformable continuum. The targets were restrained at periphery with respect to all degree of freedom. The calibrated JC model discussed in Iqbal et al. [12, 13] was employed to assign the flow and fracture behaviour of the target material. The geometry of flat and conical nose impactor was also created in accordance with its actual dimensions of Goldsmith and Finnegan [8] as a three dimensional deformable body. The geometry of large mass flat nose impactor was also created in accordance with its actual dimensions of Jones and Kim [16], as a three dimensional deformable body. As discussed above the steel core of the projectile has been modelled for all the finite element simulations assuming that the brass jacket has stripped off and had no influence the perforation process. The flow and fracture behaviour of target [12, 13] as well as projectile [17] was modelled employing the JC model. The target was meshed with eight node linear hexahedral elements with hourglass control. The finite element model of of a typical target with impactor are shown in Fig. 1. The element size in the impact zone of the targets for all the simulations of MS and AS were considered 0.2 and 0.35 $mm^3$ respectively and the aspect ratio close to unity. Away from the impact region, however, the size of element was slightly increased keeping the aspect ratio unity. The hexahedral elements of 0.9 $mm^3$ was used to discretize the conical and flat 2024 aluminium deformable projectile throughout its body. The contact between the projectile and target was modelled by employing the Kinematic contact algorithm, ABAQUS. The projectile was considered as master and the through thickness contact region of the target as node based slave surface. In the present study, a coefficient of friction of 0.02 was assumed between the projectiles and target.

# 4 Results and Discussion

The simulations were performed on various target and impactor configuration and classified into six phases. First phase, the simulations were performed on 4 mm

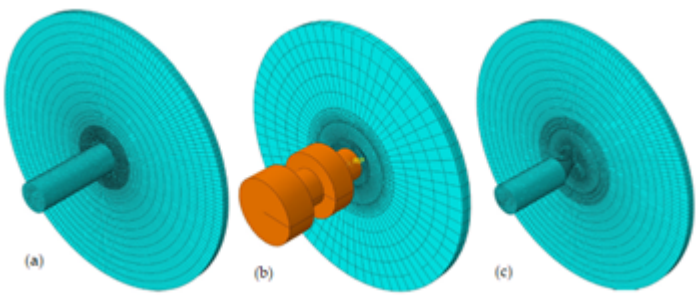


Figure 1: Target with (a) flat (b) double nose flat (c) conical (d) 12.7 mm and (e) 7.62 mm impactor

thick targets against 4, 8, 13.5, 27 and 64 Kg mass by 8.1 m/s incidence velocity (considering the drop of mass from 3.2 m height). Also, the influence of temperature on both the target against varying temperature was studied. Second phase, the simulation was performed on 3.18 mm thick targets against solid deformable 2024 aluminium flat impactor at 0° obliquity against 150 and 950 m/s incidence velocity. Third phase, the simulation was performed on 3.18 mm thick targets against solid deformable hardened steel flat impactor against 150 and 950 m/s incidence velocity. Fourth phase, the simulation was performed on 3.18 mm thick targets against solid deformable hardened steel conical impactor at 0° obliquity against 150 and 950 m/s incidence velocity. The ballistic resistance for all chosen target thicknesses has been studied numerically at given incidence velocities. The resistance of monolithic and layered targets studied in terms of forces and acceleration has been compared and discussed.

## 4.1 Response of target by varying mass of flat nose impactor

The impact resistance of 4 mm thick MS plates have been studied against blunt nose cylindrical object having masses of 4, 8, 13.5, 27, 32 and 64 kg at 8.1 m/s incidence velocity through numerical simulations using ABAQUS/Explicit. The numerical results pertaining to the resistance of 101 mm span target has been compared in our previous studies and validated with experiments conducted by Jones and Kim [16], see Figs. 2-4.

The forces offered by the target has been simulated within 10% deviation from the experimental results, Fig. 2(a). However, the predicted as well as measured maximum force offered by the target was found to be same 35.8 kN at 1.8 milli seconds. The penetration and perforation of target by striker at various time step has been shown in Fig. 2(b)-(d). It is observed that the predicted force was found to be overestimated upto 2 milli seconds whereas it is found under estimated after 2 milli seconds. The residual velocity of penetrator has been simulated within 15% deviation from the experimental results, Fig. 3(a). The simulated and measured residual velocity was found to be 0 and 1.68 m/s respectively, at 1.9 milli seconds. It is observed that the predicted residual velocity was found to be under predicted near about to 2 milli seconds whereas it is found in close agreement to their actual results upto 1.5 milli seconds. The penetration event of target by striker at 1, 2 and

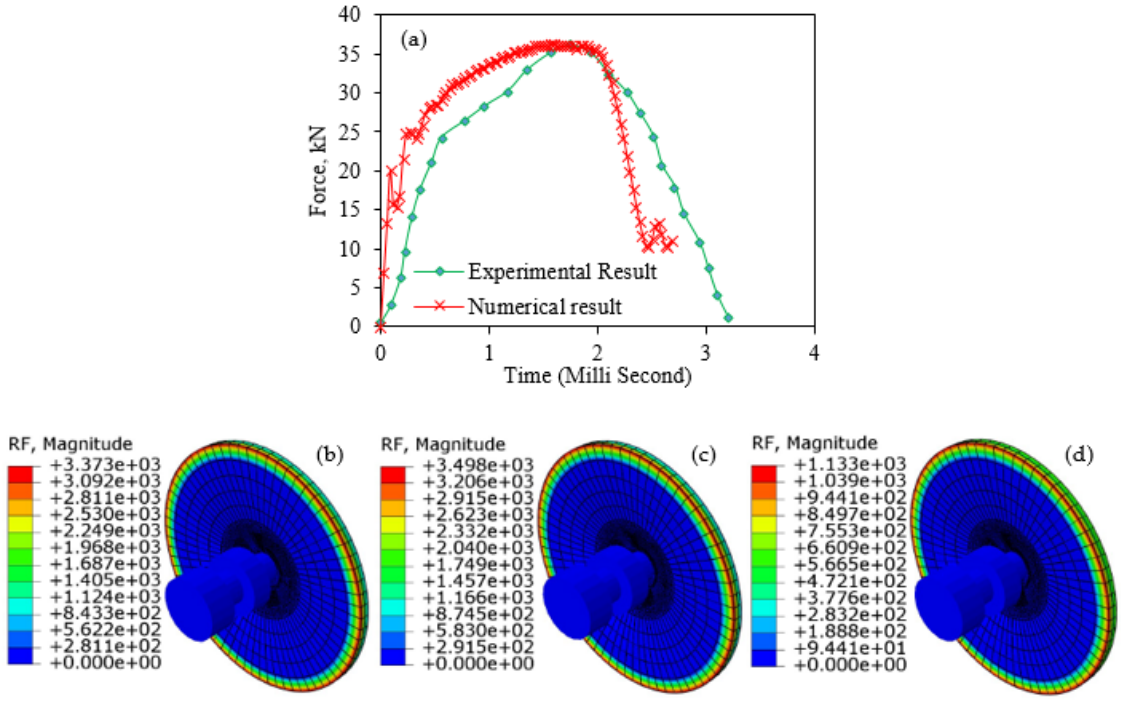


Figure 2: Comparison of (a) actual and simulated results of force by 8 Kg penetrator at (b) 1.0 (c) 2.0 and (d) 2.5 milli second and enlarged view at (e) 1.0 (f) 2.0 and (g) 2.5 milli second

2.5 milli seconds time step has been shown in Fig. 3(b)-(d).

The deflection of target has been predicted maximum 17% deviation from the experimental results, Fig. 4(a). The simulated as well as measured deflection of the target was found to be same, till 1.6 milli seconds. After 1.6 milli seconds, the predicted deflection was found to be lesser than measured deflection. It is also observed that the simulated residual velocity was found to be underestimated near about to 2 milli seconds whereas it is found in close agreement to their actual results upto 1.6 milli seconds. The deflection of target at 1, 2 and 2.5 milli second time step has been shown in Fig. 4(b)-(d). Therefore, it is concluded that the deflection of target and residual velocity of penetrator were in close agreement to their actual results upto 1.6 milli seconds, whereas the force offered by the target found deviated maximum of 10%. After 1.6 milli seconds, the force offered by the target was found in good agreement to their experimental results, whereas the deflection and residual velocity of projectile was found deviated to maximum of 16%.

The influence of temperature on MS and AS target has been studied by varying the temperature. Fig. 5 shows the effect of temperature at 230, 500, 900 and 1300 °K on both the target impacted by 8 Kg mass at 8.1 m/s incidence velocity. The maximum forces offered by the MS target was 37, 37, 24 and 15 kN against 230, 500, 900 and 1300 °K temperature, respectively. The maximum resistance offered by AS target was 93, 86, 66 and 42 kN against 230, 500, 900 and 1300 °K temperature, respectively. It is observed that the resistance of target was found to decrease almost 50% when the target temperature increased from ambient temperature to 1300 °K.

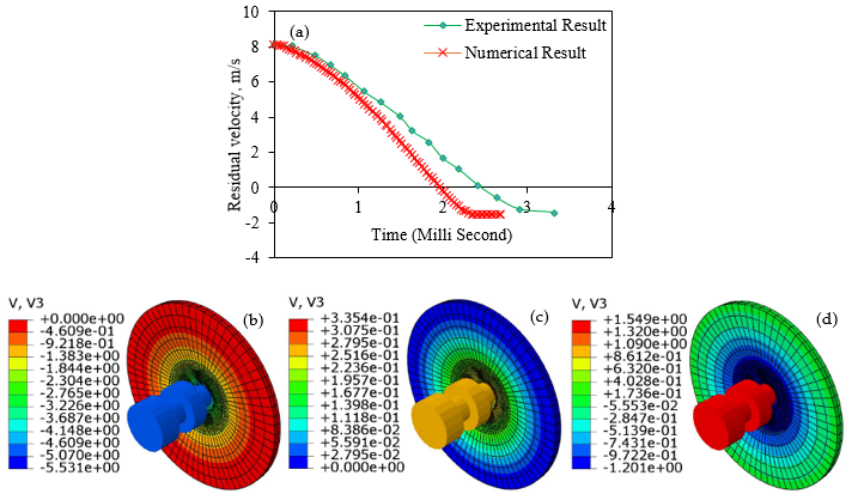


Figure 3: Comparison of (a) actual and simulated results of residual velocity by 8 Kg penetrator at (b) 1.0 (c) 2.0 and (d) 2.5 milli second and enlarged view at (e) 1.0 (f) 2.0 and (g) 2.5 milli second

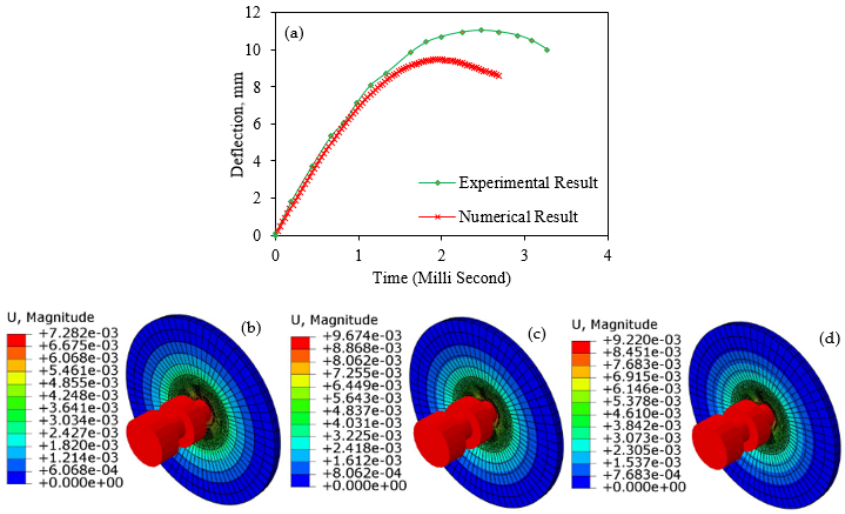


Figure 4: Comparison of (a) actual and simulated results of deflections of target by 8 Kg penetrator at (b) 1.0 (c) 2.0 and (d) 2.5 milli second and enlarged view at (e) 1.0 (f) 2.0 and (g) 2.5 milli second

The MS target has experienced penetration when the temperature of target was 1300 °K whereas AS target offered resistance significantly and doesnвΓЄt experience perforation under high temperature, i.e. upto 1300 °K.

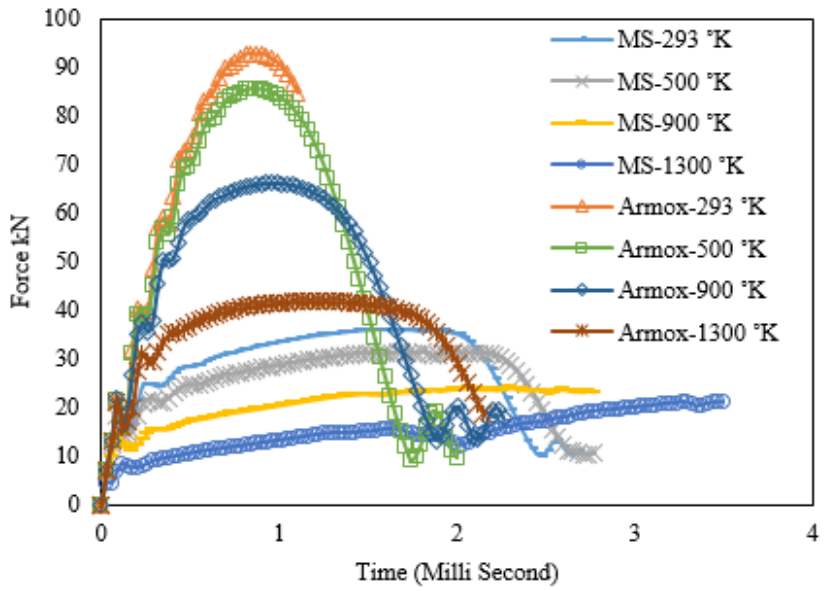


Figure 5: Resistance offered by the target against varying temperature

## 4.2 Response of target by deformable aluminium flat nose impactor

The simulations were performed on 3.18 mm thick targets of 118 mm span against solid deformable 2024 aluminium flat impactor of 37 grams by 150 and 950 m/s incidence velocity. The influence of low and high incidence velocity of impactor on mild steel and Armox 500T steel has been studied. At 150 m/s incidence velocity, both the target offered resistance significantly without any perforation and the impactor was found rebound back into same direction. The maximum forces offered by the MS and AS target at 150 m/s velocity was 17.6 and 26.3 kN respectively corresponding to 100 micro Seconds, see Fig 6(a)-(l). At 950 m/s velocity, Armox target offered resistance significantly without any penetration whereas the mild steel target was found perforated. It is observed that the AS target has experienced global deformation due to deformable impactor found deformed into mushroom shape, see Fig 6(d, h and l). The maximum forces offered by the mild steel and Armox target at 950 m/s velocity was 12.8 and 128 kN respectively. It is observed that the AS target offering resistance was found to be increased almost 30% as compared to MS target for low velocity whereas in case of high velocity, AS target offering resistance was found to be increased almost 90% as compared to MS target. Therefore, it is concluded that at low incidence velocity, the forces of both the target found almost similar whereas at high incidence velocity AS target was found to be superior against flat nose deformable projectiles.

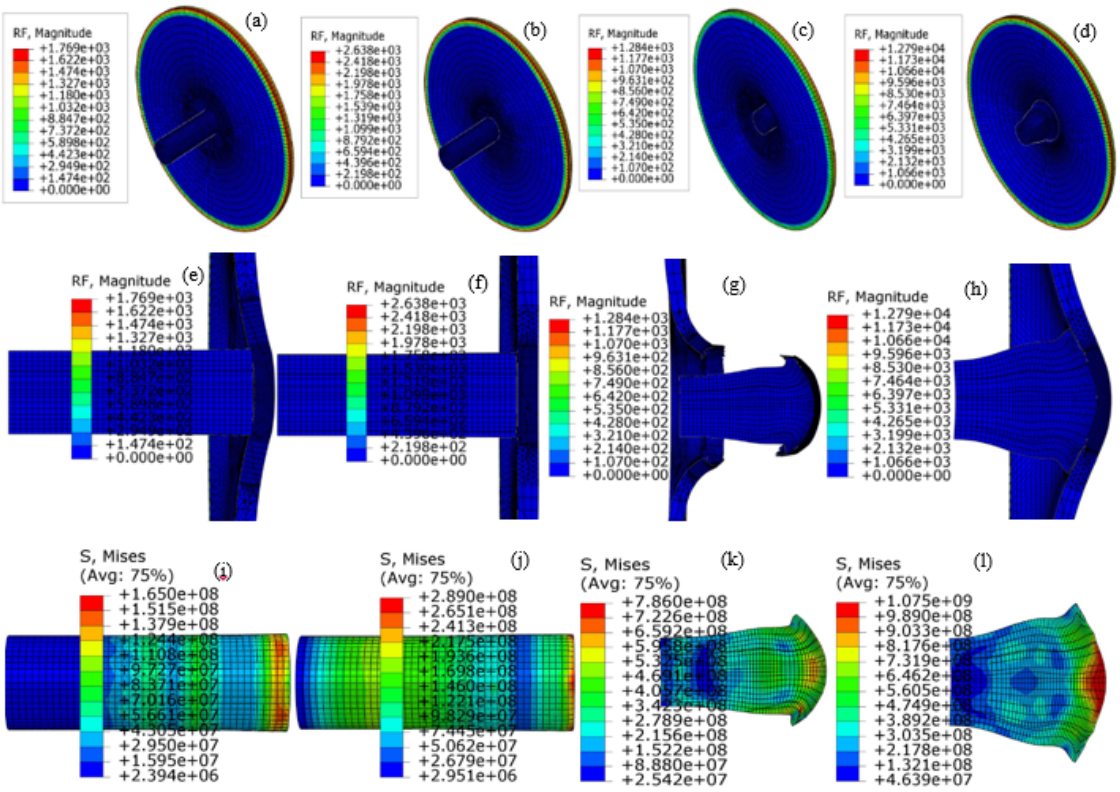


Figure 6: Resistance (Kg) offered by the target against deformable aluminium flat impactor of (a) MS-150 m/s (b) AS-150m/s (c) MS-950 m/s and (d) AS-950 m/s targets at 100 micro second, enlarged view of (e) MS-150 m/s (f) AS-150m/s (g) MS-950 m/s and (h) AS-950 m/s targets and deformation of projectiles by (i) MS-150 m/s (j) AS-150m/s (k) MS-950 m/s and (l) AS-950 m/s target in terms of von-Mises stresses

## 4.3 Response of target by hard steel flat nose impactor

The simulations were performed on 3.18 mm thick targets against solid hardened steel flat impactor by 150 and 950 m/s incidence velocity. Fig. 7(a)-(b) shows the effect of incidence velocity of 150 and 950 m/s on both the target impacted by 37 grams mass flat impactor. At 150 m/s incidence velocity, both the target offered resistance significantly without any perforation and the impactor was found rebound back into same direction, see Fig. 8. The maximum forces offered by the MS and AS target at 150 m/s velocity was 12 and 56 kN respectively corresponding to 100 Bxs, see Fig. 8(a)-(b) and Fig. 8(a). It is observed that the Armox target has experienced global deformation whereas the mild steel target has experienced local deformation. At 950 m/s velocity, both the target was found perforated. The maximum forces offered by the MS and AS target at 950 m/s velocity was 4.7 and 12.3 kN respectively, Fig. 7(b). It is observed that the AS target offering resistance was found to be increased almost 78% as compared to MS target for low velocity whereas in case of high velocity, AS target offering resistance was found to be increased almost 62% as compared to MS target.

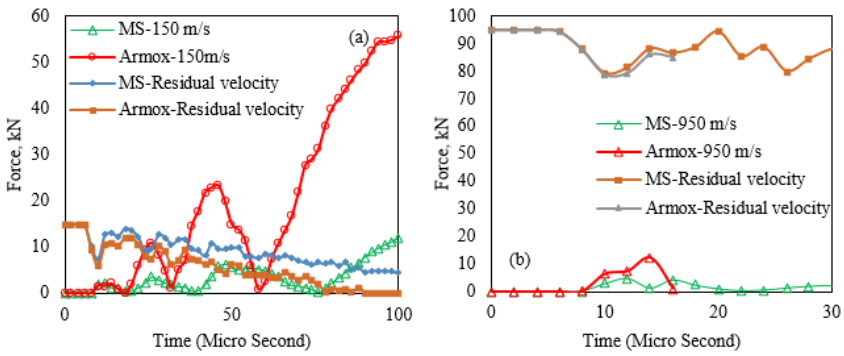


Figure 7: Resistance offered by the target against flat impactor at (a) 150 and (b) 950 m/s incidence velocity

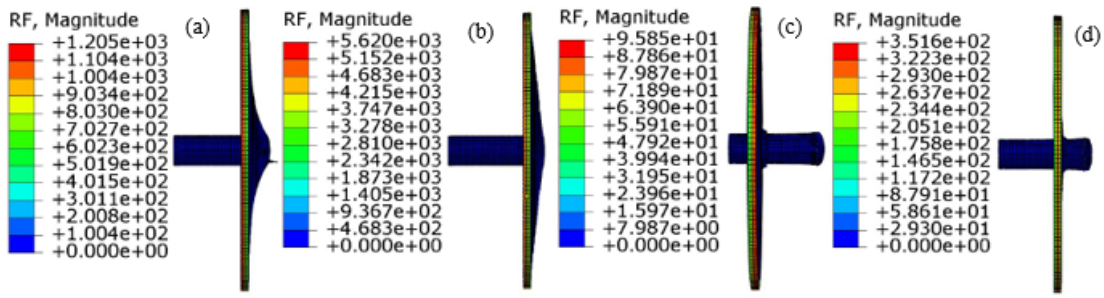


Figure 8: Resistance (Kg) offered by the target against hard steel flat impactor by (a) MS-150 m/s (b) AS-150m/s (c) MS-950 m/s and (d) AS-950 m/s configuration at 100 $\mu$s

## 4.4 Response of target by conical impactor

The simulations were performed on 3.18 mm thick targets against hardened steel conical impactor by 150 and 950 m/s incidence velocity. At 150 m/s incidence velocity, both the target offered resistance significantly without any perforation and the impactor was found struck inside the target, Fig. 9(a)-(b). The maximum forces offered by hard steel conical impactor on MS and AS target at 150 m/s velocity was 36.3 and 50.2 kN respectively corresponding to 250 and 150 Bxs respectively, see Fig. 9(a). It is observed that the AS target has experienced global deformation whereas the MS target has experienced local deformation, see Fig. 10(a)-(b). At 950 m/s velocity, both the target was found perforated. At 950 m/s incidence velocity, the maximum forces offered by hard steel conical impactor on MS and AS target was 4.17 and 46.9 kN respectively, see Fig. 10(c)-(d). It is observed that the forces of AS target found better resistance for both high as well as low incidence velocity, whereas both the target was found to offer resistance better against low incidence velocity. Therefore, it is concluded that when incidence velocity of conical projectiles increases from low to high, the response of AS target is found insignificant whereas MS target is found to decrease by 90%. It may be due to the low stiffness and low strength of MS target and sharp nose of projectiles, the target loses its resistance quickly.

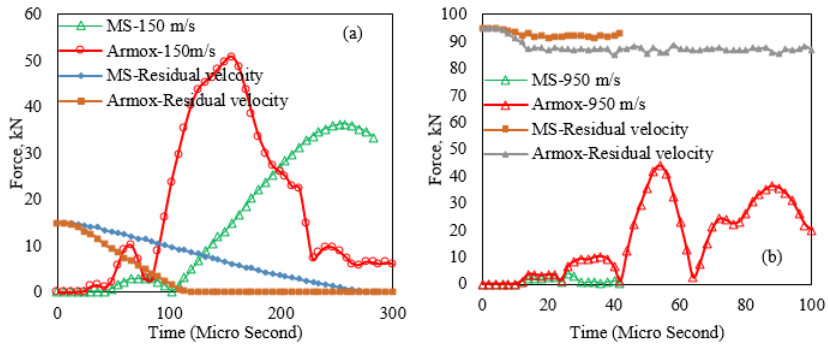


Figure 9: Resistance offered by the target against conical impactor at (a) 150 and (b) 950 m/s incidence velocity

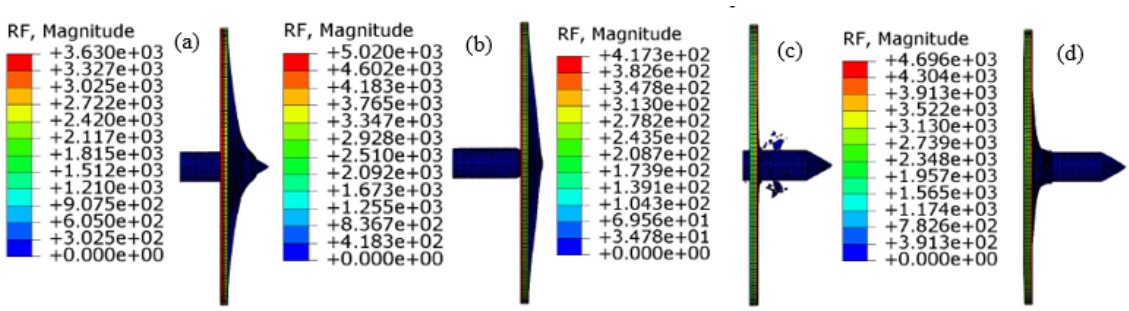


Figure 10: Resistance (Kg) offered by the target against hard steel flat impactor of (a) MS-150 m/s (b) Armox-150m/s (c) MS-950 m/s and (d) Armox-950 m/s configurations

# 5 Conclusions

A detailed numerical investigation has been carried out on Armox 500T steel and mild steel targets against flat, conical and ogival nosed projectiles. The results wherein the induced peak force and damage of target were predicted and compared with each other. The influence of temperature has also been studied numerically for particular penetrator and the following conclusions are drawn.

The maximum forces offered by AS and MS target was 121 and 41 kN and corresponding mass 27 and 13.5 Kg mass respectively. It is concluded that this behavior describes that the ballistic performance of target has improved significantly with increase in strength and hardness of target. It is observed that the resistance of both the target found to decrease almost 50% when the target temperature increased from ambient temperature to 1300 °K.

It is observed that at low incidence velocity of deformable flat nose projectiles, the forces of both the target found almost similar whereas at high incidence velocity AS target was found to be superior due to the high resistance capacity and high stiffness. In case of hard flat nose projectiles, the trend is reverse that at high incidence velocity, the acceleration of both the target found almost similar whereas in case of low incidence velocity, AS target was found superior.

It is concluded that the AS target offered better resistance against high as well as low incidence velocity of conical nose projectiles, whereas both the target was found to be better against low incidence velocity. It is also concluded that the acceleration of AS target was found to be increased by only 16% as compared to MS target for both the incidence velocity.

# References

[1] ABAQUS (2010) Explicit User's Manual Version 6.14.

[2] Bhat TB (1985) Science of armour materials. Defence Science Journal 35: 219-223.

[3] Brian LR (1996) Improved rolled homogeneous armor. Army Research Laboratory. ARL-CR-285: 1-28.

[4] Borvik T, Dey S and Clausen AH (2009) Perforation resistance of five different high-strength steel plates subjected to small-arms projectiles. International Journal of Impact Engineering 36: 948-964.

[5] Buchar J, Voldrich J, Rolc S and Lisy J (2002) Ballistic performance of dual hardness armour. In. Proc: 20th international symposium of ballistics. 23-27 September; Orlando; p. 1-8.

[6] Demir T, Ubeyli M and Yildirim RO (2008) Investigation on the ballistic impact behavior of various alloys against 7.62 mm armor piercing projectile. Materials and Design 29: 2009-2016.

[7] Dikshit SN (1998) Ballistic Behaviour of thick steel armor plate under oblique impact: Experimental investigation. Defence Science Journal 48: 271-276.

[8] Goldsmith W and Finnegan SA (1986) Normal and oblique impact of cylindro-conical and cylindrical projectiles on metallic plates. International Journal of Impact Engineering 4: 83-105.

[9] Gupta NK and Madhu V (1997) An experimental study of normal and oblique impact of hard-core projectile on single and layered plates. International Journal of Impact Engineering 19: 395-414.

[10] Hancock JW and Mackenzie AC (1976) On the mechanisms of ductile failure in high-strength steels subjected to multi-axial stress-states. Journal of the Mechanics and Physics of solids 24: 147-169.

[11] Hillerborg A, Modeer M and Petersson PE (1976) Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. Cement and Concrete Research 6: 773-782.

[12] Iqbal MA, Senthil K, Bhargava P, et al. (2015) The characterization and ballistic evaluation of mild steel. International Journal of Impact Engineering 78: 98-113.

[13] Iqbal MA, Senthil K, Sharma P, et al. (2016) An investigation of constitutive behavior of Armox 500T steel and armour piercing incendiary projectile material. International Journal of Impact Engineering 96: 146-164.

[14] Iqbal MA, Senthil K, Madhu V, et al. (2017) Oblique impact on single, layered and spaced mild steel targets by 7.62 AP projectiles. International Journal of Impact Engineering 110: 26-38.

[15] Johnson GR and Cook WH (1985) Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressure. Engineering Fracture Mechanics 21: 31-48.

[16] Jones N and Kim SB (1997) A study on the large ductile deformations and perforation of mild steel plates struck by a mass - Part I: Experimental results. Transactions of the ASME 119: 178-184.

[17] Kay G (2003) Failure modeling of titanium 6Al-4V and aluminum 2024-T3 with the JohnsonвЃ“Cook material model. Rep. No. DOT/FAA/AR-03/57, Federal Aviation Administration, Washington, D.C.

[18] Pritti J, Castro M, Squillacioti R, et al. (1997) Improved rolled homogeneous armour (IRHA) steel through higher hardness, ARL-TR-1347, 1-49.

[19] Ubeyli M, YДçldДçrДçm RO and Ogel B (2007) On the comparison of the ballistic performance of steel and laminated composite armors. Materials and Design 27: 1257-1262.

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