Defence Science Journal, Vol. 75, No. 5, September 2025, pp. 645-654, DOI: 10.14429/dsj.20270

Effectiveness of Reinforcement and Lining in Concrete Target Impact Resistance

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ABSTRACT

This study aims to understand whether introducing a steel liner at the rear face of concrete is beneficial compared to reinforced concrete in improving impact resistance when subjected to flat and hemisphere nose-shaped hard missiles. The paper presents the numerical results of penetration, perforation, and ballistic limit of plain and reinforced concrete targets (1200 mm x 1200 mm x 180 mm) with and without steel liner. Numerical simulations are done using LS Dyna. The thickness of the steel liner varied from 2.25 mm to 4.5 mm according to the percentage of flexural reinforcement for 30, 40 & 50MPa unconfined concrete strengths. 12 mm diameter bars are used as flexural reinforcement spaced at a distance of 100 mm c/c. The geometric dimensions of the missile are 300 mm in length and 80 mm in diameter, and the missile's mass is 11.75 kg. The findings revealed that because of its higher tensile strength, steel reinforcement was shown to decrease penetration depth, whereas steel liners greatly enhance ballistic limits. Plain Concrete with Rear Face Liner PCL2.25 had a 27.7 % higher penetration depth than Single Mat Reinforced Concrete (SMRC) at 100 m/s for 1.75 % reinforcement, while PCL4.5 demonstrated a 22 % higher penetration than Double Mat Reinforced Concrete (DMRC) for 3.5 % reinforcement. PCL4.5 demonstrated a 50 % greater ballistic limit compared to SMRC for a flat nose and a 9 % higher ballistic limit for a hemisphere nose. These results show that steel liners are an alternative for RC in increasing the impact resistance of concrete structures in crucial applications like nuclear and military facilities because of their improved ballistic limits and perforation resistance.

Keywords: Concrete; Steel liner; Missile impact; Compressive strength; Flat and hemisphere nose-shaped missiles

1. INTRODUCTION

Minimizing concrete barrier thickness, spalling, and scabbing phenomena at the wall faces is a crucial part of the design of concrete barriers against missiles. Steel liners or protective plates could be used at the faces to address this issue. Steel liner is one of the essential components of nuclear power plant single-wall prestressed concrete containments. It guarantees that the containment is leak-proof in a serious accident, prevents radioactive material from escaping into the environment, and lessens the accident effects. Depending on the placement of the steel plate, its contribution to missile resistance varies. A rear steel plate stiffens the wall by acting as an additional tension membrane and offers some resistance. The front steel plate functions as an extra compression membrane on the front face, effectively preventing spalling fragments and limiting front face damage[1-2]. It has been demonstrated through perforation experiments on concrete barriers lined with steel plates that the rear steel liner effectively mitigates damage to the composite target's back face[3-6]. Wu*, et al.* studied five configurations of monolithic and segmented RC panels with a rear steel liner, and 25 reduce-scaled projectile perforation tests were carried out. He concluded that the stacked segmented targets have superior impact resistance[7] compared to the spaced segmented targets. Borvit*, et al.* conducted tests on a total of 21 concrete slabs. He concluded that although the unconfined compressive strength of concrete increased approximately by a factor of three, the rise in ballistic limit velocity was only around 20 %. Sanghee et.al. conducted experiments to assess the impact behavior of relatively hard projectiles with conical and hemispherical nose shapes on normal to high strength and ultrahigh performance concrete (UHPC). Experimental results showed that in terms of projectiles, the conical nose shape obtained greater penetration depth in normal-strength concrete, and the difference in the performance of high-strength concrete and UHPC was negligible[9]. Husain*, et al.* studied the effect of reinforcement spacing on the behavior of concrete slabs under hemisphere projectile impact. Both single and doubly reinforced slabs were constructed using two rebar spacing, i.e., 25 and 100 mm, with constant reinforcement ratio and adequate depth. Results revealed that 25 mm spaced rebars effectively decreased the local damage and overall penetration depth and improved the ballistic limit[10]. Mohamed and Ahmed examined the effect of reinforcing ratio and type on concrete performance under impact load. The location of the reinforcement mesh (panel front, middle, and rear) and steel lining (front and rear face) were considered variants. According to experimental findings, lining the front face of a concrete target with steel plates prevented spalling. Still, it had a substantially lower ballistic limit than the placement of steel liner at the rear face, and results revealed no significant effect of reinforcement mesh on ballistic performance[11].

Received : 23 June 2024, Revised : 10 November 2024
Accepted : 24 January 2025, Online published : 01 September 2025

Anas*, et al.* investigated the influence of the thickness of the slab and concrete strength on the impact resistance. The concrete damage plasticity (CDP) material model simulates the concrete behavior under impact loading. Numerical simulations revealed that as slab thickness increases and the dominant mode of rupture switches from punching shear to flexure, the perforation and peak vertical displacement of the slab diminishes, resulting in severe cracking. A higher strength of concrete in the slab slightly reduces the punching but increases flexural damage[12]. Tai evaluated the resistance of ultra-high strength concrete (about 200 MPa) subjected to high velocity. Numerical and experimental findings show that plates with a greater compressive strength are more fragile, and the addition of a small number of steel fibers substantially enhanced the impact resistance of the target plates[13]. Mohamed calibrated the Riedel-Hiermaier-Thoma material model in ANSYS Autodyn to predict the concrete behavior under impact loading[14-15].

1.1 Research Significance and Objectives

During the service life, reinforced concrete (RC) structural members might be subjected to impact loads from accidents or natural disasters. When concrete members collide with vehicles, falling rocks, ships, or airplanes, and when natural calamities like tornados, tsunami drift, or slope failure occur, an external impact force may be generated. To reduce the detrimental effects of debris generated due to impact, steel lining may be considered an alternative to reinforcing the concrete member. There haven't been many studies done to examine how RC slabs respond to impact loading with steel liners. The innovative approach of determining the thickness of steel liners based on the reinforcement ratio and evaluating the behavior of concrete targets under subsonic missile impacts is the unique feature of this research.

In contrast to previous research, the liner thickness is adjusted by the reinforcement percentage, thereby offering a more optimized design solution for improving the impact resistance of concrete structures. Additionally, this investigation studies the impact of various nose-shaped missiles, including flat and hemispherical, and evaluates their interaction with concrete targets of differing compressive strengths (30, 40, and 50 MPa). 1.75 per cent of reinforcement is considered in the form of single mat reinforced concrete (SMRC), plain concrete with 2.25 mm liner (PCL2.25), and 3.5 per cent of reinforcement is considered in the form of double mat reinforced concrete (DMRC), single mat reinforced concrete with 2.25 mm liner (SMRCL2.25), plain concrete with 4.5 mm thick steel liner (PCL4.5). The thickness of the steel liner is considered to be 2.25 mm and 4.5 mm, respectively, to match the reinforcement percentage of 1.75 % and 3.5 %.

This dual-reinforcement approach allows for the optimization of concrete design, thus ensuring superior protection against high-velocity impacts in critical applications. The exhaustive parametric study, which encompasses variables such as perforation resistance, ballistic limits, and penetration depth, provides valuable information into the performance of reinforced concrete under subsonic missile impacts. By proposing a customized strengthened strategy that considers the shape of missiles, the velocity of impact, and the strength of concrete, this research enhances the structural resilience of critical infrastructure, including military bunkers and nuclear containment structures.

2. VALIDATION OF NUMERICAL APPROACH

To assess the reliability and accuracy of the simulation of reinforced concrete slabs subjected to missile impact, experimental tests conducted by Kojima are considered[16]. Eight node hexahedron elements are used to model a rectangular reinforced concrete slab in the numerical model. Solid element formulation with continuous stress is adopted for modeling the target of dimensions 1200 mm x 1200 mm x 120 mm. For the mesh sensitivity analysis, the uniform mesh sizes of 5 mm, 7.5 mm, 10 mm, and 12.5 mm are adopted, as shown in Table 2. The circular Hughes-Liu beam elements with a diameter of 10 mm bars and two layers separated by 100 mm and a concrete cover of 20 mm from each face were used to represent the steel reinforcement in the slab. They maintained a spacing of 100 mm c/c.

This results in different numbers of elements and nodes for each size. 5mm (Elements – 1382400, Nodes- 1452025), 7.5mm (Elements-409600, Nodes-440657), 10mm (Elements-172800, Nodes- 190333) and 12.5mm (Elements- 92160, Nodes- 103499). The mesh has 3,528 solid elements and 4,035 nodes for a 10mm mesh size to precisely reflect the geometry and behavior of the hemisphere nose-shaped missile during impact events. A mesh with 3,120 beam elements and 6,266 nodes is used for the reinforcement, which enables accurate modeling of the reinforcing bars and how they interact with the concrete matrix. In addition, a mesh criterion consisting of 58,564 nodes and 43,200 solid components is applied for the steel liner part with a thickness of 3.2mm. The steel liner's geometry and structural response under impact loading circumstances are accurately represented. This approach takes into account different mesh sizes that are specific to each part, making it possible to simulate the reinforced concrete target along with the way it interacts with the missile with a hemisphere nose in detail.

The hemisphere nose-shaped missile is modeled with the 8-noded hexahedron elements and the hemispherical missile mass is 2 kg, and its length and diameter are 100 mm and 60 mm, respectively. The missile is striking at the center of the target. The missile's striking velocity is 95 m/s without a steel liner and 212 m/s with the liner at the rear face. LS DYNA is adopted for numerical simulations[17]. The validation of experimental results involves many parameters, including material model selection, replicating the boundary and loading conditions, contact between different elements, and mesh size of the simulation. Many researchers consider the Winfrith material model for concrete a reliable model for predicting concrete behavior in high-strain loading. In Eq (1), a function of the stress and stress deviator tensors analytically describes the yield surface.

$$\frac{AS_2}{\sigma_c^2}+\frac{\lambda\sqrt{S_2}}{\sigma_c}+\frac{BI_1}{\sigma_c}-1=0 \tag{1}$$

Where,

$$\lambda = K_1 \cos\left[-\frac{1}{3}\cos^{-1}(K_2 \cos 3\theta) \right] \quad \cos 3\theta \geq 0$$

$$\lambda = K_1 \cos\left[\frac{\pi}{3} - \frac{1}{3}\cos^{-1}(-K_2 \cos 3\theta) \right] \quad \cos 3\theta < 0$$

$$\cos 3\theta = \frac{3\sqrt{3}}{2S_2^{1.5}} S_3$$

I_1= First stress invariant

S_2, S_3= Second and third deviatoric stress invariants

A, B, K_1 and K_2 are shape parameters

K_1 and K_2 define the shape of shear failure surface in the octahedral plane.

Corresponding material properties used for the validation are presented in Table 1.

The penetration depth and support reaction of concrete targets with and without rear face steel liner agree with Kojima's reported experimental observations. Concrete's maximum penetration depth, with and without a steel liner, obtained from the numerical study is 42 mm (-4.545 %) and 123 mm (1.6 %) in comparison with the experimental results of 44 mm and 125 mm, as shown in Fig. 2 (c) and Fig. 2(d). Maximum Support Reactions are 16.6 T and 18.1 T for concrete with and without steel lining as against 14.5 T and 18.8 T, respectively. The contour plot of penetration depth without steel liner is shown in Fig. 3. Figure 4 and Fig. 5 show the penetration depth of reinforced concrete slab with and without liner at 95 m/s and 212 m/s, respectively. The results indicate that a mesh size of 10 mm predicts the experimental results, i.e., penetration depth and the reaction force with an error of 4.5 % and 14.5 % without steel liner and 1.6 % and 3.72 % with steel liner. Hence, the mesh size of 10 mm is considered for further numerical parametric study.

The Winfrith Concrete Model is appropriate for additional investigation in scenarios involving projectile impact on concrete targets because of its strong prediction ability, especially when it comes to modeling scabbing occurrences. The near alignment of the numerical simulation results for the scabbing area in reinforced concrete targets with the experimental data shows the accuracy of the numerical model. The numerical simulation calculated the scabbing area to be 150 x 160 mm, whereas the experimental scabbing area was measured to be 162 x 146 mm as shown in Fig. 1(a). The close agreement between the experimental and numerical data validates the model's ability to accurately predict the scabbing behavior of the specimen under ballistic impact. Damage plots

Table 1. Material properties

Material	Model	Properties	Unit	
		Density	2500	Kg/m^3
		Initial tangent modulus	32.68	GPa
		Poisson's ratio	0.19	
Concrete	Winfrith model	Compressive strength	28	MPa
		tensile strength	2.67	MPa
		Fracture energy	60.04999	$N\text{-}m/m^2$
		Aggregate size	0.008	m
		Density	7850	kg/m^3
		Young's modulus	210	MPa
Reinforcement and steel liner	Plastic kinematic model	Poison ratio	0.3	
		Yield stress	428	MPa
		Failure strain	0.2	
		Density	7850	kg/m^3
Missile	Rigid model	Young's modulus	210	GPa
		Poisson's ratio	0.3	

Table 2. Mesh sensitivity analysis

Mesh size 'mm'	Exp. penetration depth 'mm'	Num. penetration Depth 'mm'	Error %	Exp. reaction force 'tonne'	Num. reaction force 'tonne'	Error %	Computational time 'hr'
Without liner @ 95 m/s	**44**			**14.5**			
5		50	-13.6		12.2	15.86	12 hr 34 min
7.5		47	-6.81		12	17.24	4 hr 11 min
10		42	-4.545		16.6	-14.48	2 hr 5 min
12.5		26	40.91		18	-24.14	0 hr 59 min
With lliner @ 212 m/s	**125**			**18.8**			
5		Perforated	-----		-----	-------	18 hr 51 min
7.5		152	-21.6		19.2	-2.13	6 hr 17 min
10		123	1.6		18.1	3.72	4 hr 50 min
12.5		92	26.4		22.3	-18.61	1 hr 45 min

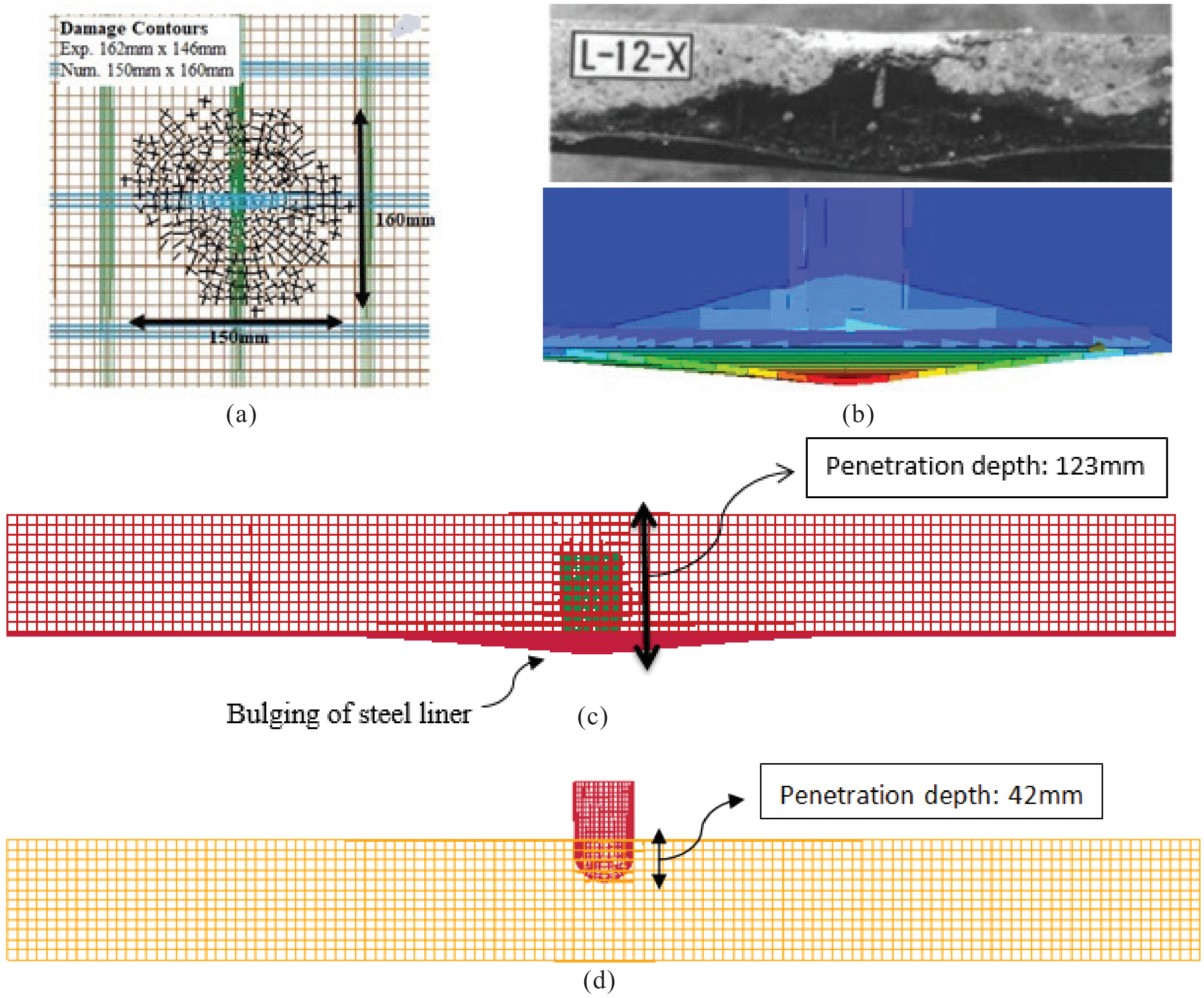

Figure 1. (a) Damage contour of the reinforced concrete (RC) slab under missile impact without a steel liner; (b) Damage contour of the RC slab with a steel liner; (c) Penetration depth of the RC slab at an impact velocity of 95 m/s; and (d) Penetration depth of the RC slab at an impact velocity of 215 m/s.

of simulated specimens are compared with the reported results of Kojima's experiments, as shown in Fig. 1(b).

3. NUMERICAL SIMULATION

A concrete target of 1200 mm × 1200 mm × 180 mm was modeled. The concrete target is reinforced with 10 mm dia. reinforcing bars at a spacing of 100 mm c/c in both longitudinal and transverse directions. Concrete compressive strength of 30 MPa, 40 MPa, and 50 MPa is considered for the study. Input properties for the Winfrith concrete model have been tabulated in Table 3 and calculated based on the CEB-FIP code[18]. The plastic Kinematic model (MAT_003) is used to model the reinforcing bars, considering the strain rate effect. Properties used for modeling the steel are density 7850 kg/m^3, Young's modulus 210 MPa, Poison's ratio 0.3, Yield stress 428 MPa, and failure strain 0.2. Strain rate parameters used to define by Cowper- Symonds model C & P are 40.4 and 5. The eroding contact surface between the reinforced concrete, missile, and steel liners has been defined. 80 mm diameter, 300 mm long, and 11.75 kg mass complex missile of flat and hemisphere nose shape is considered for the impact. A rigid model (MAT 020) is chosen to represent non-deformable solid or hard missiles. Missile model parameters are density 8245 kg/m^3, Young's modulus 210 MPa, and poisons ratio 0.3. Six different cases considered for the analysis are shown in Fig. 2. Flat and hemisphere nose-shaped missiles are considered for the numerical study. Striking velocity has been varied between 100 m/s and 150 m/s at 10 m/s intervals.

Table 3. Properties of concrete material model

Compressive strength 'MPa'	Density Kg/m^3	Tangent modulus of concrete 'Pa'	Poisson's ratio	Compressive strength of concrete 'Pa'	Tensile strength of concrete 'Pa'	Fracture energy Nm/m^2	Aggregate size 'm'
30	2500	$3.4*10^{10}$	0.17	$3*10^{7}$	$2.9*10^{6}$	65	0.008
40	2500	$3.6*10^{10}$	0.17	$4*10^{7}$	$3.5*10^{6}$	70	0.008
50	2500	$3.9*10^{10}$	0.17	$5*10^{7}$	$4.1*10^{6}$	85	0.008

Contact interactions between the missile, concrete, reinforcement, and any additional components, like a steel liner, must also be established. Finally, material properties and failure criteria must be specified in a way that is consistent with experimental data. LS-DYNA simulations can closely replicate the experimental setup by carefully characterizing these boundary conditions and contact settings. This allows for precise prediction of the structural reaction of RC targets to missile impact.

A crucial idea in contact algorithms used in finite element analysis is master and slave. The relationship between two interacting surfaces or simulation parts is indicated by these. The surface or part of it is regarded as the primary or reference geometry in the contact interaction and is usually referred to as the master part. The surface or element that communicates with the master part during the contact analysis is referred to as the slave part. This is crucial if parts are slipping, separating, and coming into touch. Table 4 shows advanced contact algorithms to model the interaction between the missile and the concrete surface to explain the impact dynamics.

4. RESULTS & DISCUSSION

4.1 Depth of Penetration (DOP)

When a missile or projectile strikes concrete, the depth to which it can be through the surface is referred to as the penetration depth. The value of the penetration depth is influenced by several variables, including the mass, velocity, shape, and material characteristics of the missile as well as the strength and thickness of the concrete target. Variations of penetration depth with different patterns of reinforcement

Table 4. Contact algorithm

FEM parts	Contact keyword	Master	Slave
Concrete and Rebar’s	CONSTRAINED_LAGRANGE_SOLID	Concrete	Rebar’s
Rebar’s and hard missile	CONTACT_ERODING_NODES_TO_SURFACE	Hard missile	Rebar’s
Concrete and missile	CONTACT_SURFACE_TO_SURFACE	Hard missile	Concrete
Concrete and steel liner	CONTACT_AUTOMATIC_SURFACE_TO_SURFACE	Steel liner	Concrete
Rebar’s and steel liner	CONTACT_ERODING_NODES_TO_SURFACE	Steel liner	Rebar’s
Steel liner and missile	CONTACT_SURFACE_TO_SURFACE	Hard missile	Steel liner

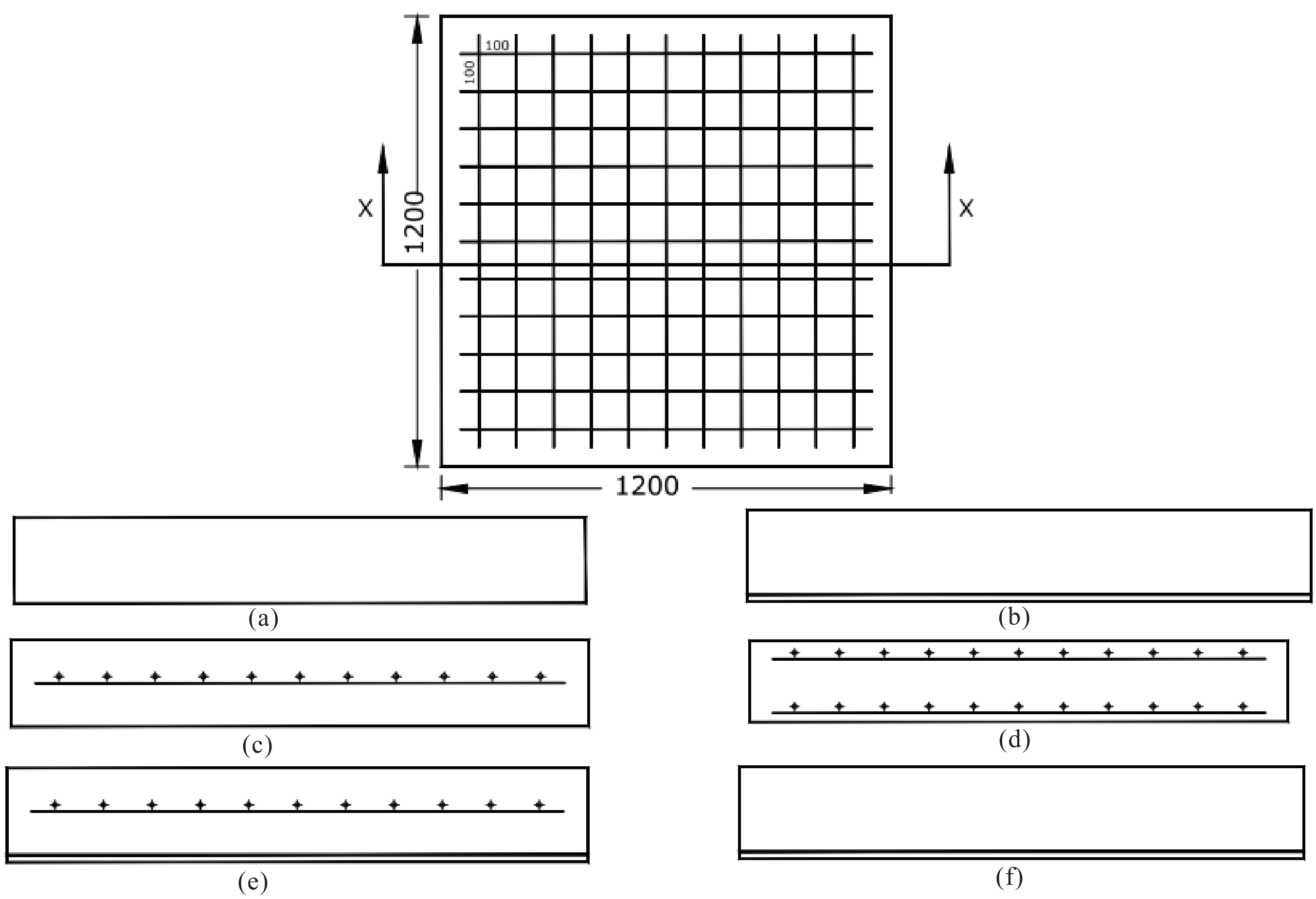

Figure 2. Reinforced concrete targets (a) Plain concrete; (b) Plain concrete Liner-2.25; (c) Single mat RC; (d) Double mat RC; (e) Single mat RC- Liner; and (f) Plain concrete liner-4.5.

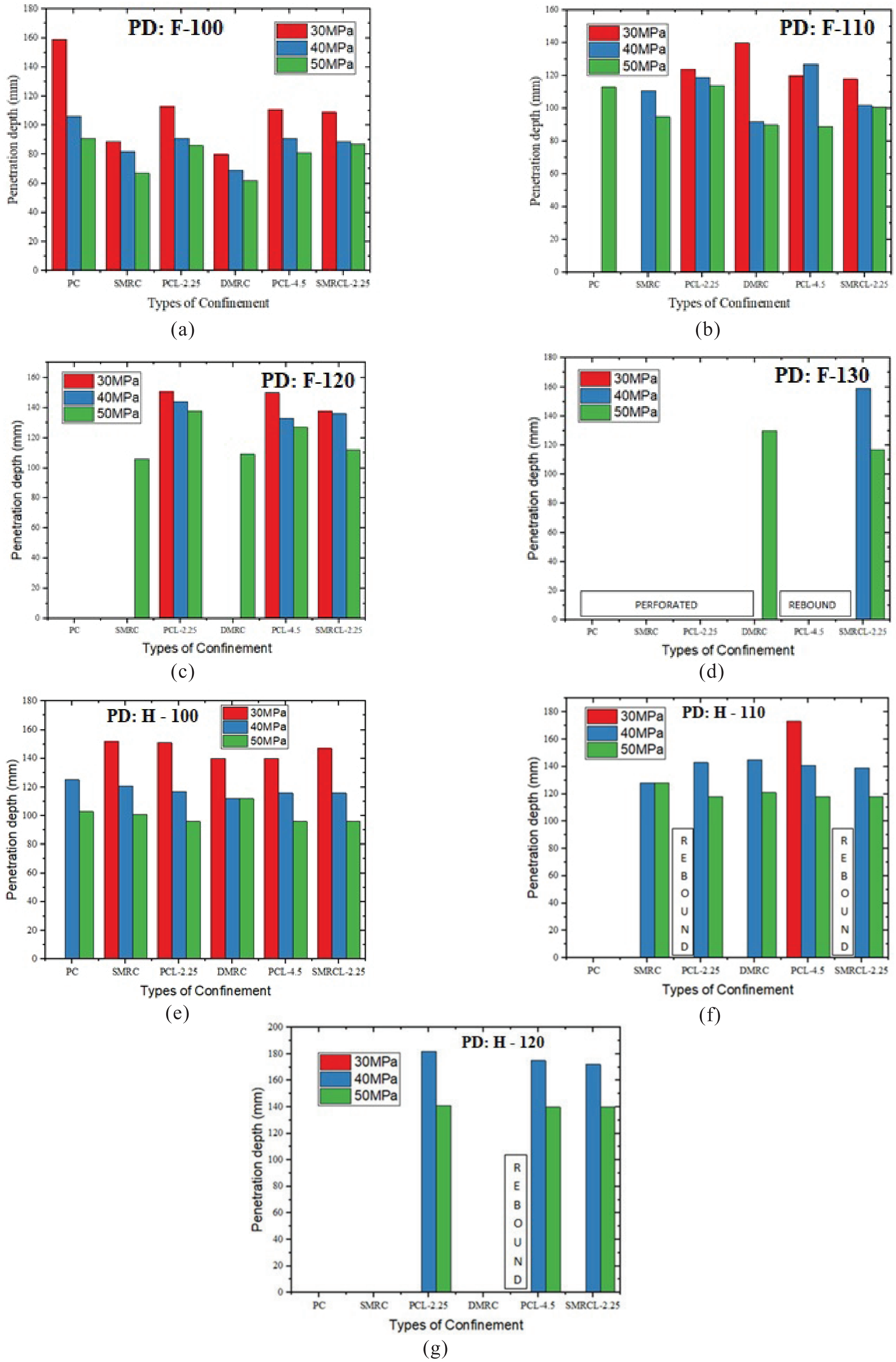

Figure 3. Penetration depth of concrete targets with different types of confinement and compressive strengths under flat nose missiles at (a) 100 m/s; (b) 110 m/s; (c) 120 m/s; (d) 130 m/s, and hemisphere nose missiles at (e) 100 m/s; (f) 110 m/s; and (g) 120 m/s.

when subjected to flat and hemisphere nose missiles are shown in Fig. 3 at various striking velocities. Irrespective of the type of confinement and missile impact concrete resistance to penetration increases with an increase in compressive strength as also observed by Hanchak[19], *et al.* This increase might be because higher compressive strength can better withstand the high stress and pressure generated by a missile impact. The penetration depth of 30 MPa plain concrete is 43 % greater than 50 MPa concrete when subjected to flat nose missiles and perforated when subjected to hemisphere nose missiles at 100 m/s. Steel reinforcement increases the tensile strength of concrete targets, which helps to withstand the forces generated by a missile impact and reduces penetration depth.

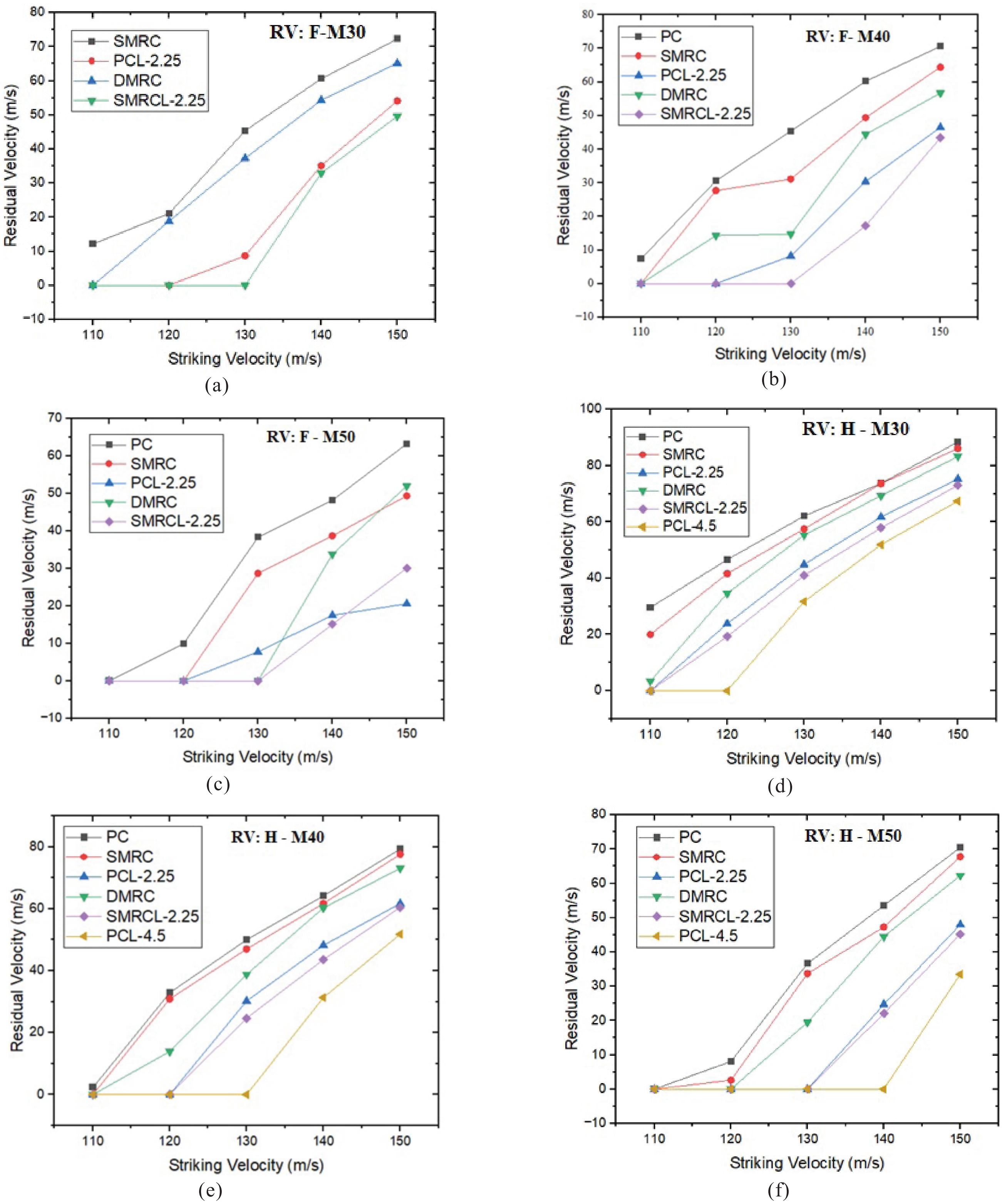

Figure 4. Residual velocity of the missile with different types of confinement and compressive strengths under flat nose missiles at (a) M30; (b) M40; (c) M50; and hemisphere nose missiles at (d) M30; (e) M40; and (f) M50.

At 100 m/s initial velocity, concrete strength of 30 MPA, and 1.75 % of reinforcement, i.e., SMRC (single mat reinforced concrete) and PCL 2.25, the penetration depth of the latter is 27.7 % greater than the former when subjected to flat nose missile. In contrast, the penetration depth achieved is 150 mm for both SMRC and PCL2.25 when subjected to a hemisphere nose missile. For 3.5 % of reinforcement, the penetration depth observed at 100 m/s in DMRC, PCL4.5, and SMRCL2.25 is 80 mm, 111 mm, and 110 mm, respectively, when struck with flat nose missiles, whereas for hemisphere nose missile DMRC and PCL4.5 has a penetration depth of 140 mm while SMRCL2.25 has a penetration depth of 145 mm. A similar trend is observed in other grades of concrete also. At higher striking velocity, targets with liner rebound the missile, whereas others perforated.

Hence, in terms of penetration resistance for the exact % of reinforcement, steel bars are effectively compared to the placement of steel liner at the rear face. When nose shape was considered, hemi-sphere-nosed missiles had a deeper penetration depth than flat-nosed missiles. The reason is that hemi sphere-nosed missiles are made to displace more material when they penetrate, lowering the resistance force and enabling deeper penetration. PC target penetrated for flat-nose missiles, while it got perforated for hemisphere missiles at 30 MPa.

4.2 Residual Velocity

The residual velocity of a missile after impact can be significantly influenced by the strength of the concrete. In general, high-strength concrete can better resist the forces generated by a missile impact, which results in a lower residual velocity of the missile. Fig. 4 shows the variation of residual velocity for different grades of concrete when subjected to flat-nose and hemisphere-nose missiles. Compared to plain concrete for 50 MPa, the residual velocity of plain concrete for 40 MPa is higher by 13.4 % at a striking velocity of 150 m/s. The steel liner and reinforcing mesh offer additional resistance to help mitigate the impact effects of concrete targets. PCL4.5 offers the highest resistance compared to the rest of all cases under flat and hemisphere nose missiles.

When a missile with a flat nose and a hemisphere nose has the same striking velocity, it has been observed that the Hemi sphere nose missile will have a higher residual velocity. This is because the hemisphere-nosed missile experiences less slowdown from friction with the concrete since it is intended to displace more material as it penetrates. On the other hand, the flat-nosed missile has a more significant area of impact, which results in more resistance and accelerates the deceleration. The flat-nose missile has a reduced residual velocity as a result of punching through the thickness of concrete. In comparison to the PC of a flat nose for 30 MPa, the residual velocity of the PC of a hemisphere for 30 MPa at 150 m/s is higher by 17.3 %.

Figure 5 shows the damage contour plots of the RC without and with steel liner at 150 m/s to identify the ruptures and damage area. Because of the immense force created by the missile impact, a steel liner struck by a missile will rupture. The material's tensile strength exceeds severe deformation, and the spread of cracks or fractures are just a few causes of rupture.

4.3 Ballistic Limit

The ballistic limit observed from the numerical simulations is shown in Fig. 6, irrespective of the nose shape of the missile; PCL4.5 offers more penetration resistance compared to the other cases, which means that the ballistic limit can be improved by adding a steel liner rather than reinforcing. The ballistic limit for 1.75 % reinforcement and 30 MPa concrete is 100 m/s for SMRC and 120 m/s for PCL2.25 in case of a flat nose and 110 m/s in case of a hemisphere nose missile. A similar trend is observed for 4 MPa and 50 MPa concrete also. The ballistic limit for 3.5 % reinforcement and 30 MPa concrete is 100 m/s for DMRC, 130 m/s for SMRCL and 150 m/s for PCL4.5 in case of flat nose, and 110 m/s for SMRCL, 120 m/s for PCL4.5

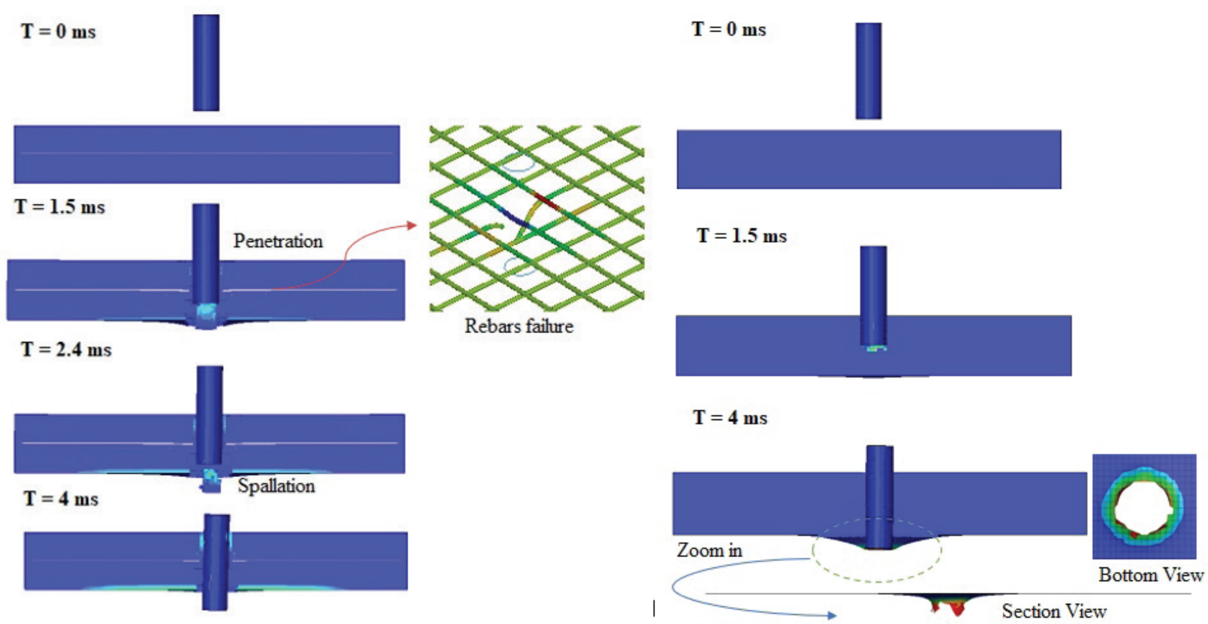

Figure 5. Contour plots of (a) SMRC; and (b) PCL- 2.25 under missile impact at various time intervals.

in case of hemisphere nose missile. The results show clearly that the ballistic limit of the concrete targets can be improved by placing steel liners instead of reinforcing them.

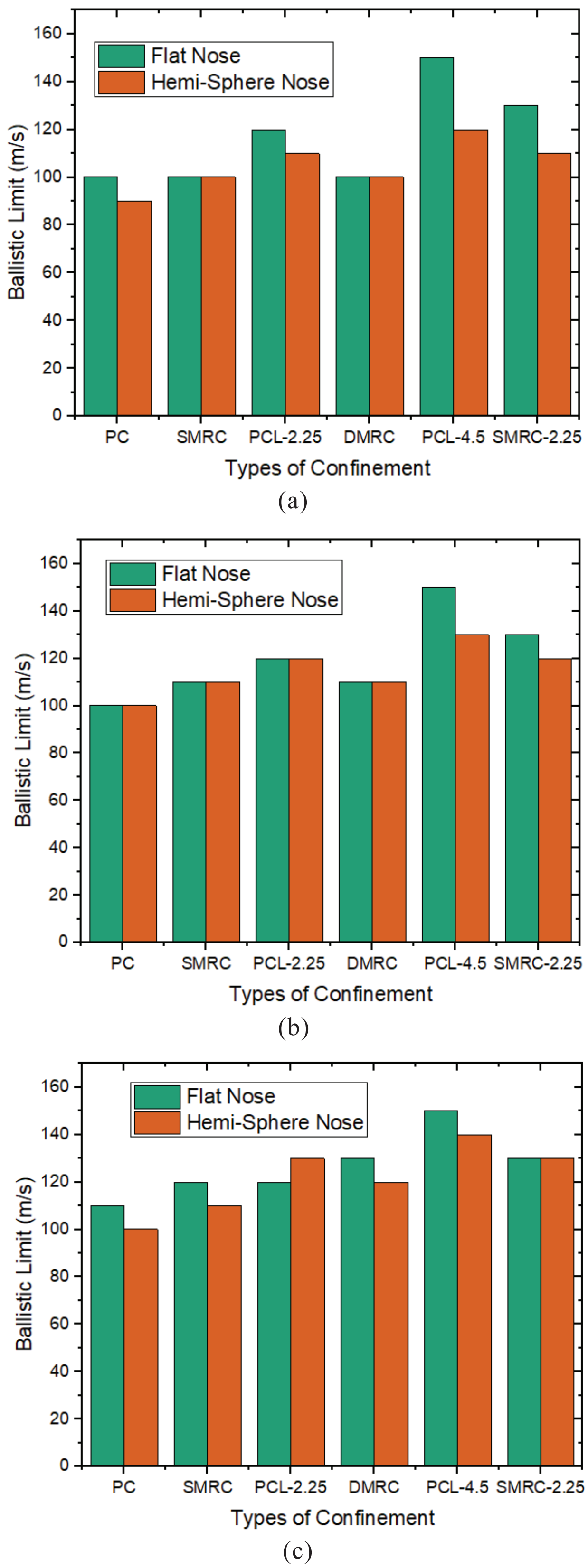

Figure 6. Types of confinement vs Ballistic limit of compressive strengths (a) 30; (b) 40; and (c) 50 MPa for flat and hemi sphere nose-shaped missiles.

5. CONCLUSIONS

A parametric study is done to evaluate the effect of reinforcement and steel liner on missile impact resistance. Three concrete strengths of 30, 40, and 50 MPa with two reinforcement percentages, 1.75 and 3.5, are considered. For 1.75 % reinforcement SMRC, PCL2.25 is compared, and for 3.5 % reinforcement DMRC, PCL4.5 and SMRCL are considered. All the targets were subjected to flat-nose and hemisphere-nose missiles. Conclusions from the numerical study are as follows:

- Steel liners placed at the rear face of concrete targets do not improve penetration resistance for both flat and hemisphere nose missiles. However, reinforcement can offer resistance and improve penetration resistance
- When the targets are subjected to flat nose missiles with 1.75 % reinforcement, the penetration depth of PCL2.25 is 21 % at 30 MPa, 10 % at 40 MPa, and 22 % at 50 MPa, more significant than SMRCL. Even with 3.5 % reinforcement DMRC and SMRCL had lesser penetration depth compared to PCL4.5
- No significant deviation is observed between reinforcement and lining when the targets are subjected to a hemisphere nose missile
- Compared to hemi sphere nose missiles, flat nose missiles exhibited less penetrating depth, less residual velocity, and more ballistic limit
- Steel liners offer more perforation resistance compared to the reinforcement mesh, so the ballistic limit also can be improved
- Higher compressive strength shows significant variation in depth of penetration and residual velocity but not much variation in ballistic limit.

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