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Research article

# BALLISTIC RESPONSE AND INDUCED DAMAGE OF PLAIN AND REINFORCED CONCRETE PLATES

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**Abstract.** The present study shows the comparison of ballistic response and induced damages of plain and reinforced concrete plates subjected to the normal impact of ogive-nosed steel projectiles. The evaluation of damage has been described by the presence of cracking and measuring the size of the crater in terms of equivalent diameter, formed at front and rear concrete surfaces. The ballistic limits of plain and reinforced concrete have been obtained through the varied projectile velocities. The Plain concrete experienced the cracking and cratering at the front and rear surfaces while the reinforced concrete plates experienced only cratering that has been found in the region smaller than that of the plain concrete, describing the influence of the reinforcement. The cratering at the rear surface of concrete plates decreased with an increase in the projectile incidence velocity while it remained unaffected at the front surface with respect to the incidence velocities. The penetration depth and scabbing limit of non-perforated plates are also calculated using empirical equations and compared with the actual results. The ballistic limit of the reinforced concrete plate has been found to be 13% higher than the plain concrete plate.
**Keywords:** ballistic limit, concrete plates, residual velocities, induced damage

## 1. Introduction

The study of the ballistic response of reinforced concrete is very vital in order to design the defensive and protective structures which are subjected to direct impact and explosive loads. Many researchers have already carried out the perforation experiment in past [1-5]. Hanchak et al. [1] conducted perforation experiments with the concrete of 48MPa and 140MPa unconfined compressive strengths and concluded that the residual velocities for the 140MPa concrete were found to be 20% lower than that for the 48MPa concrete, nearly threefold increment in the strength of the concrete shows the minor changes in the residual velocities. Frew et al. [2] carried out sets of experiments with a varying diameter of concrete targets and found negligible changes in penetration depth. Zineddina et al. [3] performed experiments and addressed dynamic response with varying reinforcements in concrete slabs. Jinzhu et al. [4] conducted several perforation experiments on plain concrete with varying thickness against 400m/s striking velocity of the projectile. It was found that the kinetic energy consumed has increased with an increase in the target thickness, and the kinetic energy consumed per meter of the target thickness decreased with an increase in target thickness. Rajput et al. [5] studied the ballistic response of plain and reinforced concrete targets with varying thickness against 1kg projectile of diameter 19mm and length of 450mm and found that the ballistic limit increased with an increase in target thickness. Backman and Goldsmith [6] described the concept to find the ballistic limit for the concrete plates through the averaging of the highest projectile velocity for partial penetration and the lowest projectile velocity for complete perforation.

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Many researchers have also been carrying out empirical studies, and proposed, various empirical equations for penetration depth, and scabbing and perforation limit for the concrete material based on the experimental results. The modified Petry formula, the oldest empirical equation [7-9], was developed for calculating the penetration depth, and the scabbing and perforation limits in 1910. Similarly, the Ballistic Research Laboratory (BRL) had also formulated empirical expressions in 1941 to calculate the penetration depth and scabbing and perforation limit of the concrete, and these empirical equations are known as the BRL formulae [7,10-12]. Based on the experimental results prior to1943 from the Ordnance Department of the US army and the BRL, the army corps of engineers (ACE) formulated the empirical equations for penetration depth and scabbing and perforation limit for the concrete material [7,13,14].

The present study shows the comparison of ballistic response and induced damage of plain and reinforced concrete plates. The concrete plates of 48 MPa unconfined compressive cylindrical strength were subjected to the normal impact of hardened steel ogive nosed projectiles of diameter 19 mm, mass 0.4 kg and length 200mm. The concrete plates of edge lengths 600 mm × 600 mm and thickness 100 mm with and without (8 mm @ 90 mm c/c) reinforcement were tested. The incidence velocities of the projectiles were varied between 130 to 220 m/s. The evaluation of the damage of plain concrete plates had been described by the presence of cracking and the size of the crater formed at front and rear concrete surfaces. The damage evaluation of reinforced concrete plates has been carried out by measuring the size of the crater formed at front and rear concrete surfaces. The size of the crater was measured in terms of the equivalent diameter of the crater at the front and rear concrete surfaces. The ballistic limit of plain and reinforced concrete was obtained through the varied projectile velocities. The experimental results of both the concretes (plain and reinforced) have been compared and discussed. Some non-perforated plates of plain and reinforced concrete have also been found and their scabbing limit and penetration depth has been calculated using the empirical equation formulated by the ACE formulae [14], and the calculated results were compared with the experimental results. The forthcoming sections show the detailed descriptions of the present study.

## 2. Concrete Mix Design

A concrete mix was designed in accordance with IS-10262 [15]. The ordinary Portland cement, tap water, fine river sand, and basalt coarse aggregate of maximum size 10 mm were used for the preparation of concrete. The proportion by volume of the constituents used in the mix design of concrete is presented in Table 1. The 0.6% of concrete proportion by volume superplasticizers was also used for achieving the desired workability in accordance with IS-456 [16]. The concrete specimens prepared for material characterization were water cured up to 28 days before testing. A set of three cylinders were tested under uniaxial compression testing machine with a 0.02 mm/s loading rate and the average strength of concrete was found to be 48 MPa.

Table 1. Constituents of Concrete for 48 MPa average cylindrical strength

| Concrete Constituents | Cement ($kg/m^3$) | Sand ($kg/m^3$) | Aggregate ($kg/m^3$) | Water ($kg/m^3$) | W/C ratio | Size of coarse Aggregate (mm) | Size of fine aggregate (sand) (mm) |
|---|---|---|---|---|---|---|---|
| Proportion by volume | 450 | 975 | 904 | 171 | 0.38 | 10 or smaller | 4.75 or smaller |

## 3. Preparation of target specimens and projectile

The plain and reinforced concrete plates of 600 mm × 600 mm edge lengths and 100 mm thicknesses were casted for the projectile impact experiments. The high yield strength deformed (HYSD) steel reinforcement (500MPa) was provided in reinforced concrete plates, in the orthogonal directions with respect to 8 mm dia. @ 90 mm c/c with a nominal cover of 10 mm, see Fig.1. The reinforcing bars were provided in such a manner that they could not cross the centre of the plate span. Thus, the projectile could not strike the reinforcing bars during the perforation of concrete plates.

The steel projectiles (320MPa) were machined to obtain their mass 0.4kg, length 200mm, shaft diameter 19 mm, and 3 caliber radius head (CRH) nose, see Fig. 2. Also, the projectiles had been heated up to 800°C temperature, and then oil quenched and tempered. Due to this, the rigidity of the projectile had been enhanced so that it could be considered as non-deformable.

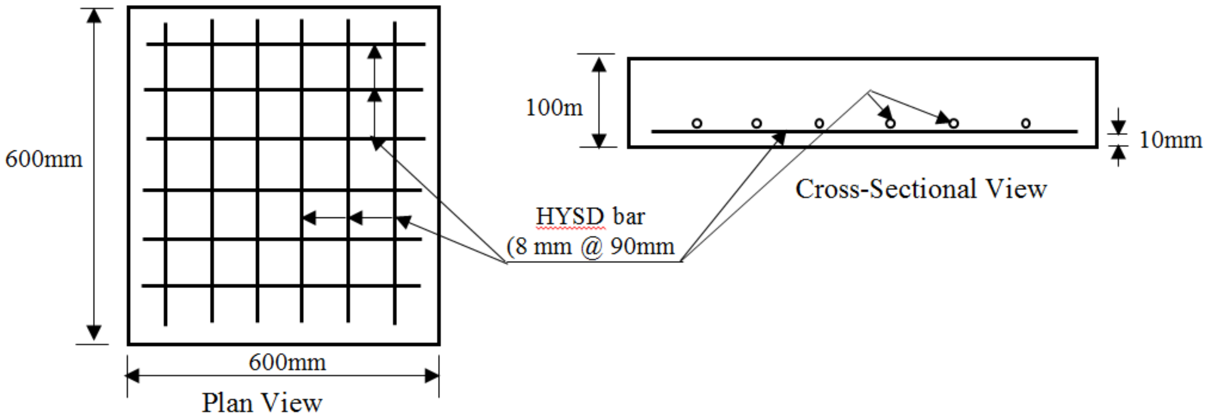



**Fig.1.** Geometry of Reinforced Concrete plate

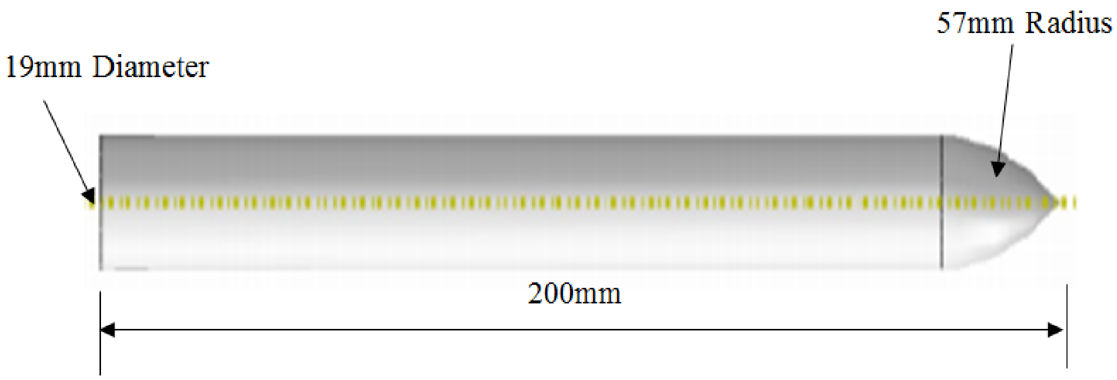



**Fig.2.** Geometry of 0.4kg Projectile

## 4. Detail of Experimentation

The testing of concrete plates subjected to ogive nosed steel projectile impact were conducted with the help of a pneumatic gun set up, consisting of a single-stage compressor of maximum working pressure 60 kg/cm$^2$, a cylindrical pressure vessel, a seamless steel barrel of length 19 m and bore diameter 20 mm, an automated actuator and a pressure switch to regulate the incidence velocities. The barrel was inflexibly supported at regular intervals in order to ensure its horizontal alignment. The concrete plate was mounted on a rigid steel platform and all of its four edges were well clamped to maintain the fixed boundary condition with respect to all degrees of freedom. The distance of the mounted plate from the muzzle end was provided to be 1m. The incidence velocity of the projectile was varied by regulating the air pressure in the pressure vessel. A high-speed video camera Phantom V411 was used to record the perforation phenomenon, and to measure the incidence and residual velocity of the projectile. The typical frame rate was considered in the range 7000 - 9000 per second to maintain visibility and proper visualization of the perforation process. Three number of non-flickering LED lights were installed to maintain the required illumination for high-speed videography. A robust steel catcher box filled with the cotton rag was placed at a distance of 1.5 m behind the concrete plate to safely catch the perforated projectile. The schematic view of the pneumatic gun experimental setup is shown in Fig. 3. The projectile followed its central axis during and after perforation of plain and reinforced concrete plate and struck at the centre of the span in each test, see Fig. 4.

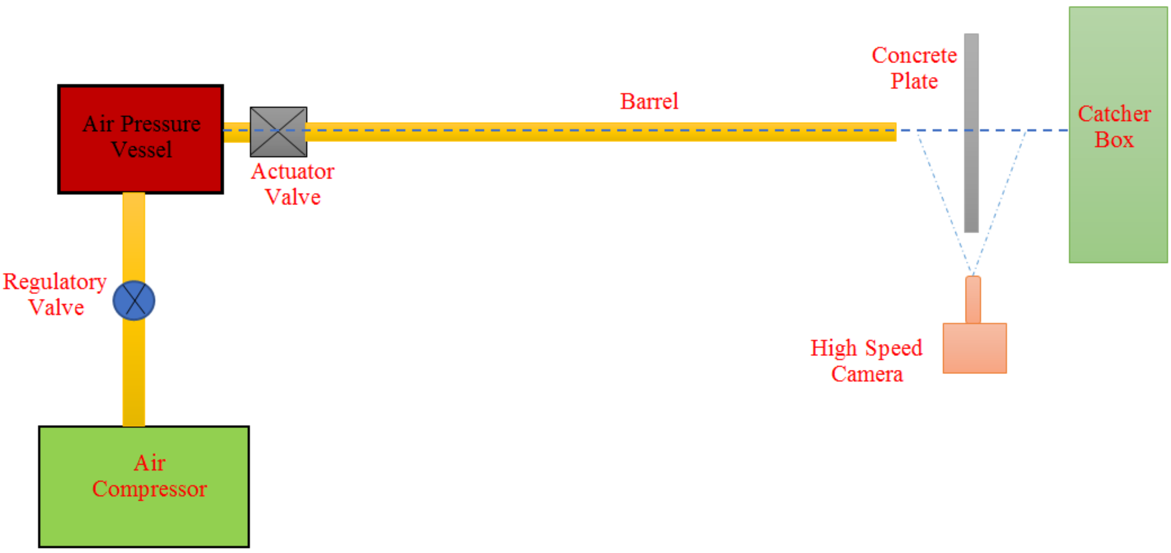



**Fig.3.** Schematic view of the experimental setup of the pneumatic gun

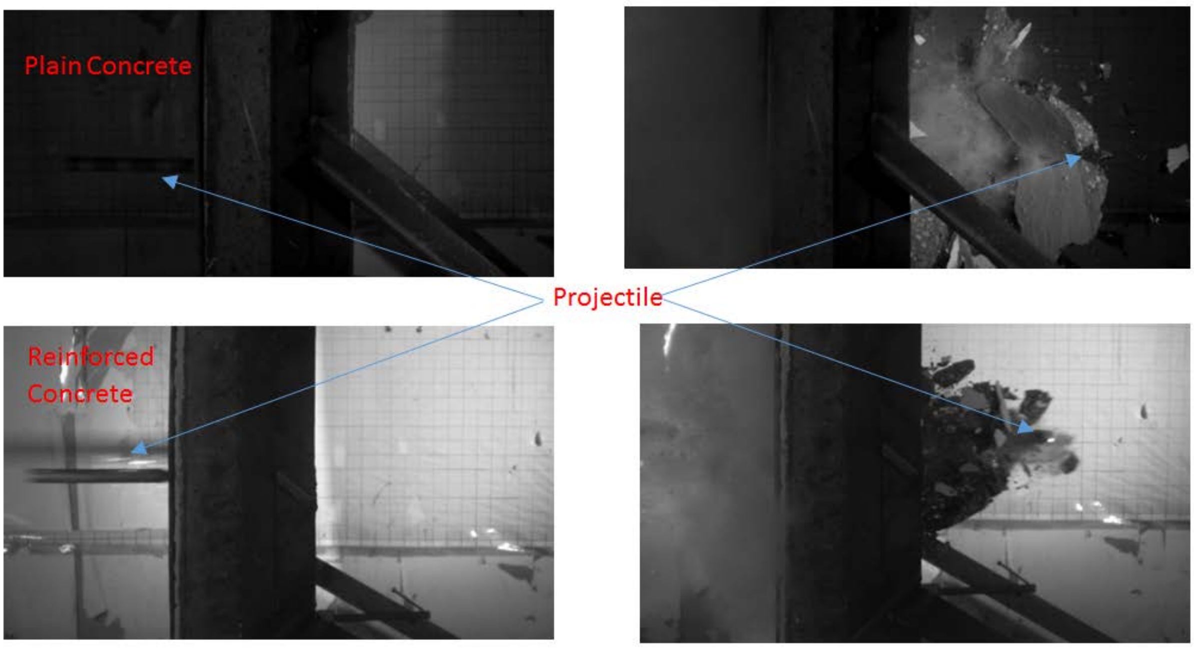



**Fig.4.** Typical perforation phenomena in plain and reinforced concrete plates

## 5. Evaluation and quantification of Damage

The damage induced in the concrete plates was found to be dependent upon the type of concrete and the incidence velocities of the projectile. The perforated and non-perforated plain concrete plates experienced visible cracking and cratering at the front and rear concrete surfaces (Figs. 5 and 8) while the reinforced concrete plates observed only cratering at both the concrete surfaces (Figs. 6 and 9). The evaluation of the damage of plain concrete plates has been described by measuring the width as well as number of cracks formed at front and rear concrete surfaces and by measuring the size of the crater in terms of the equivalent diameter at the front and rear surfaces. Similarly, the damage evaluation of reinforced concrete plates has been carried out by measuring the size of the crater in terms of equivalent diameter, formed at front and rear surfaces.

The specimen designation of perforated plain and reinforced concrete plates with respect to their projectile incidence velocities have been mentioned in the first column of Table 2. The plain concrete plates experienced brittle failure at all the incidence velocities (158 - 220 m/s), showing the thick radial cracks across the thickness originated from the centre of the plate and traversed over the entire span of the plate leading to its failure through splitting (Fig. 5). It should be noted that the number of radial cracks formed in all the thicknesses of plain concrete plates was found to be three or four, see Fig. 5. The width of crack at the front and rear concrete surfaces was found to be in the range of 2-5 mm and 2-8 mm, respectively. The cracks were found to be inclined to the horizontal and vertical axes at different angles, see Fig. 5. The reinforced concrete plates, on the other hand, did not experience any visible cracking describing the influence of reinforcement, see Fig. 6. The incidence velocities of the projectile for reinforced concrete targets were in the range 168-218m/s.

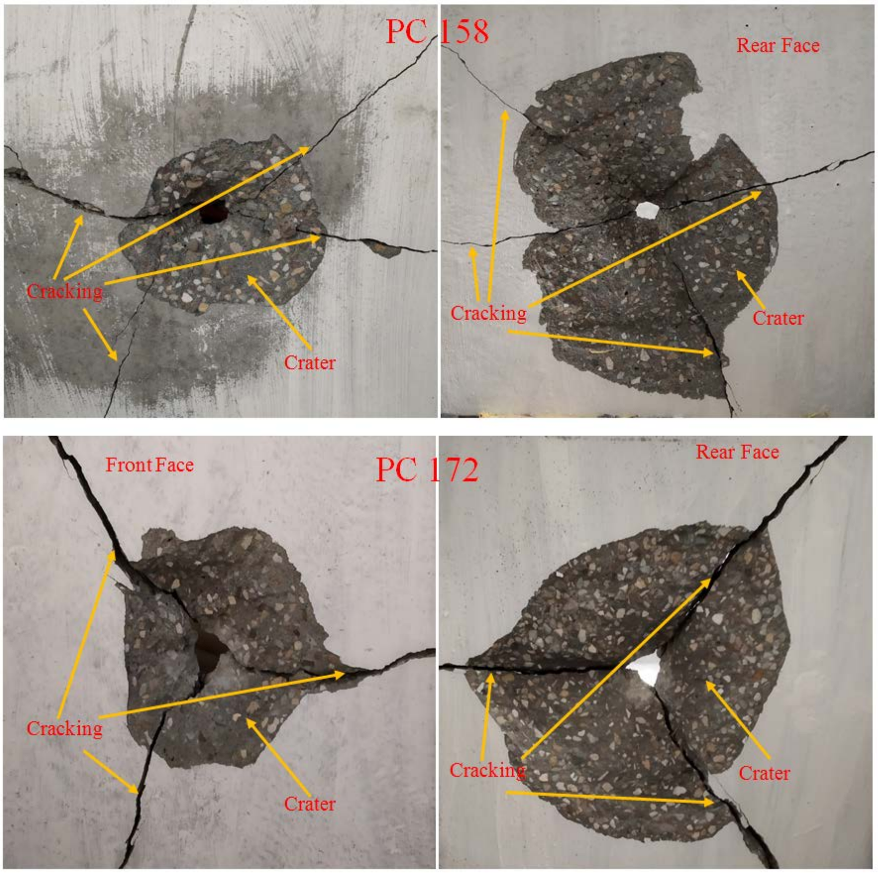



**Fig. 5.** Typical perforated plain concrete plates

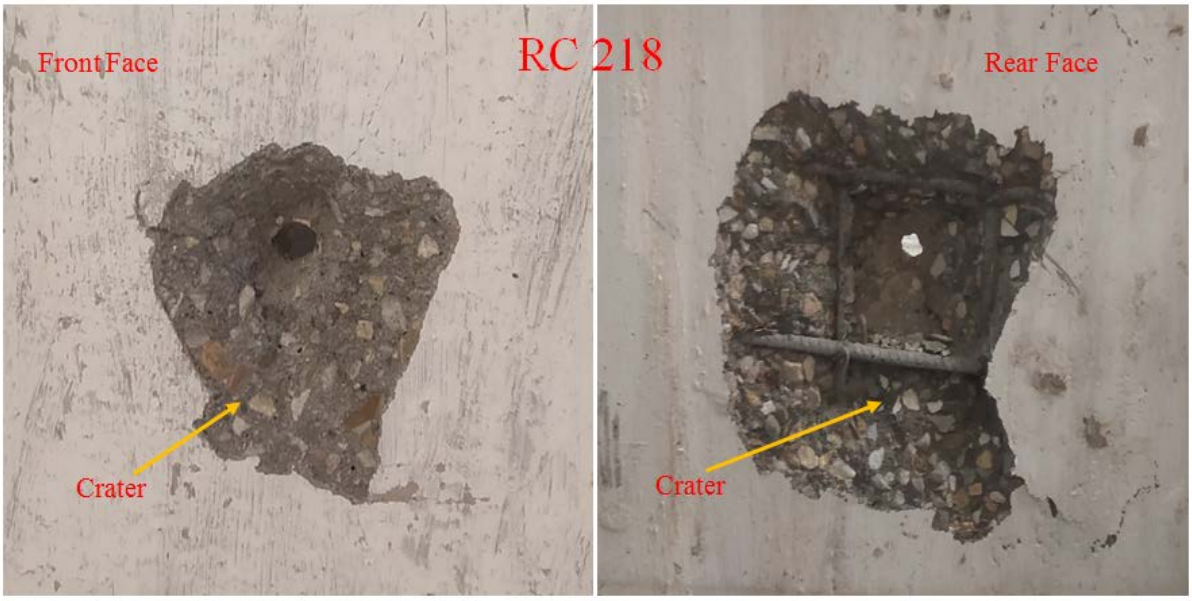
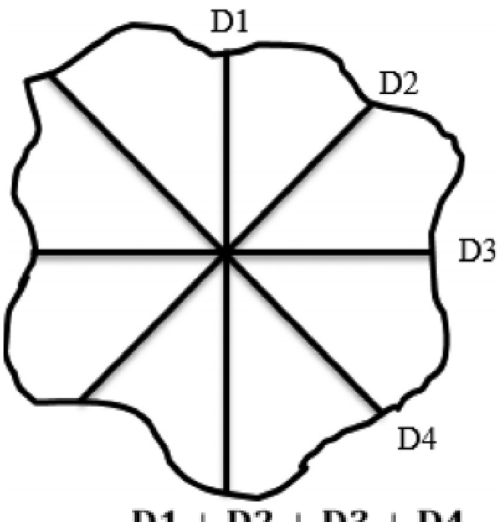



**Fig. 6.** Typical perforated reinforced concrete plate

The damage in terms of cratering formed at front and rear concrete surfaces was measured in terms of the equivalent diameter of the crater. The equivalent diameters at the front and rear concrete surface were measured as the average of four diameters as indicated in Fig. 7. The equivalent diameters of front and rear surface craters thus obtained for the plates with respect to their incidence projectile velocities and type of concrete are presented in Table 2. It should be noted that the size of crater at the front concrete surface showed insignificant variation with respect to either projectile velocity or type of concrete while the size of the rear surface crater has been found to have a significant influence of the incidence velocity, see Table 2. For a given concrete type, the diameter of the rear surface crater decreased with an increase in the incidence velocity. As such no exact correlation of the size of the crater could be found with the type of concrete. However, the rate of decrease in the size of crater with increasing velocity was found to be higher in reinforced concrete than in plain concrete, see Table 2.




$$\mathbf{D} = \frac{\mathbf{D1 + D2 + D3 + D4}}{\mathbf{4}}$$

**Fig. 7.** Measurement of equivalent (D) diameter of the front and rear surface crater [5]

Table 2. The variation in the size of the crater at the front and rear concrete surfaces

| Specimen Designation | Front Surface | | | | | Rear Surface | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | D1 (mm) | D2 (mm) | D3 (mm) | D4 (mm) | D (mm) | D1 (mm) | D2 (mm) | D3 (mm) | D4 (mm) | D (mm) |
| PC158 | 150 | 160 | 175 | 175 | 165 | 420 | 330 | 280 | 400 | 357.5 |
| PC172 | 165 | 185 | 180 | 175 | 176.25 | 430 | 330 | 205 | 420 | 346.25 |
| PC190 | 210 | 225 | 190 | 230 | 213.75 | 360 | 390 | 300 | 300 | 337.5 |
| PC205 | 180 | 185 | 190 | 175 | 182.5 | 430 | 310 | 250 | 330 | 330 |
| PC220 | 155 | 140 | 130 | 130 | 138.75 | 360 | 325 | 270 | 325 | 320 |
| RC180 | 110 | 105 | 100 | 160 | 118.75 | 270 | 280 | 280 | 390 | 305 |
| RC192 | 145 | 150 | 120 | 120 | 133.75 | 240 | 260 | 390 | 290 | 295 |
| RC202 | 200 | 130 | 150 | 170 | 162.5 | 220 | 270 | 260 | 300 | 262.5 |
| RC218 | 140 | 120 | 90 | 130 | 120 | 200 | 230 | 180 | 230 | 210 |

The damage is also induced in the non-perforated plain and reinforced concrete plate. The specimen designations with respect to incidence projectile velocities and type of concrete are mentioned in the first column of Table 3. The projectile penetrated up to some extent in all the non-perforated concrete plates and then it has fallen down at the front face of the plate. One plain concrete plate (PC130) was found as non-perforated at 130m/s incidence projectile velocity. Also, the thick radial cracking and cratering were noticed at the front surface while no cratering was observed at the rear surface of the concrete plate, see Fig. 8. The width of cracking at the front and rear surfaces was found to be the same and in the range of 2-4mm, respectively. The penetration depth of projectile and equivalent crater diameter at the front surface of plain concrete were also found to be 32mm and 140mm, respectively. The two non-perforated reinforced concrete plates (RC150 & RC168) were also observed at 150m/s and 168 m/s incidence projectile velocities, see Fig. 9. The projectile had penetrated in the RC150 and RC168 plates about 45mm and 53 mm, respectively. Cratering formed at front concrete surfaces of RC150 and RC168, and its equivalent diameters were found to be 176.25mm and 171.25mm, respectively. A small amount of concrete material has also ejected out from the rear surfaces of both the concrete plates, see Fig. 9.

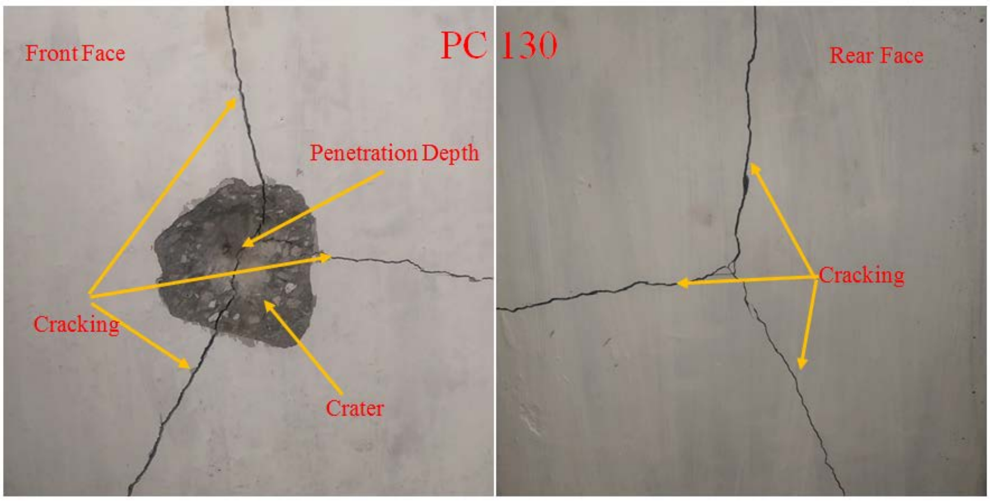



**Fig. 8.** Typical non-perforated Plain concrete plate

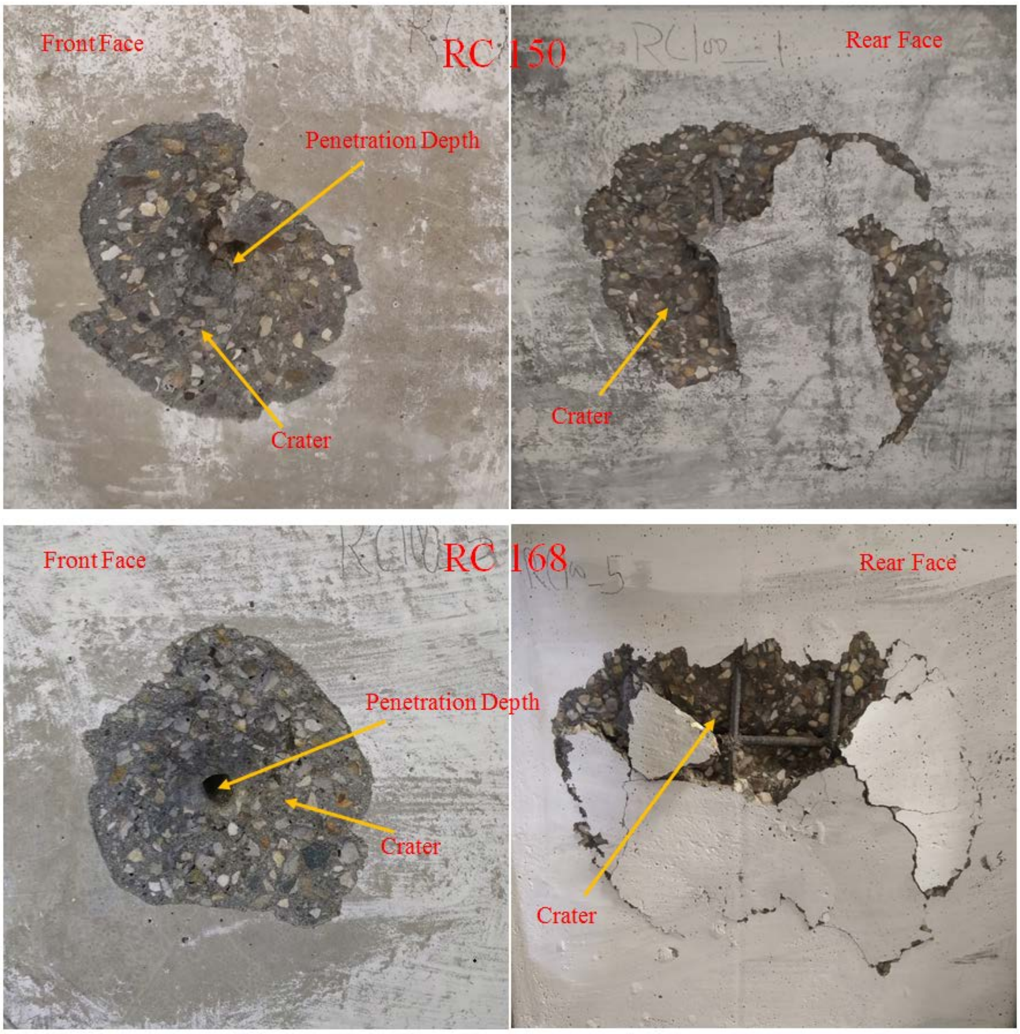



**Fig. 9.** Typical non-perforated reinforced concrete plates

Based on experimental results prior to 1943 from the ordnance department of the US army and the BRL, the Army Corps of Engineers developed the ACE formula for penetration and scabbing limit [14]. The equation of penetration depth in SI units is as follows;

$$\frac{\mathbf{x}}{\mathbf{d}} = \frac{\mathbf{3.5\times10^{-5}}}{\sqrt{\mathbf{f_c}}}\left(\frac{\mathbf{M}}{\mathbf{d^3}}\right)\mathbf{d^{0.215}V_0^{1.5}} + \mathbf{0.5}. \tag{1}$$

The equation for scabbing limit is as follows:

$$\frac{\mathbf{h_s}}{\mathbf{d}} = \mathbf{2.28} + \mathbf{1.13}\frac{\mathbf{x}}{\mathbf{d}}, \tag{2}$$

where $\mathbf{x}, \mathbf{d}, \mathbf{M}$ **and** $\mathbf{V_0}$ are the penetration depth, diameter, mass, and impact velocity of the projectile, respectively, and $\mathbf{f_c}$ and $\mathbf{h_s}$are the unconfined compressive strength and thickness of concrete plate, respectively.

The penetration depth and scabbing limit of all non-perforated plain and reinforced concrete plates have been calculated, and the results have been presented in Table 3. The ACE formula has overestimated the penetration depth of both the concretes. The error in the calculated penetration depth for plain concrete was found to be higher as compared to that for the reinforced concrete, while the error in the calculated penetration depth for two reinforced concrete plated was found to be almost same. The calculated scabbing limit (93mm) for plain concrete plate (PC130) was found to be lower than that of the thickness of the plate (100mm) describing that the ACE formula has underestimated the result by about 7%. On the other hand, the calculated scabbing limits for the two non-perforated reinforced concrete plates **(**RC150 & RC168**)** were found to be higher by 3 and 12 mm than that of the actual plate thickness describing about 3% and 12% overestimation in the calculated results, however, the scabbing limits for the two reinforced concrete plates considered herein are not close to each other, see Table 3.

Table 3. Actual and calculated penetration depth and scabbing limit of non-perforated plain and reinforced concrete

| Specimen No. | Incidence Velocity (m/s) | Penetration Depth | | | Actual Thickness (mm) | Calculated Scabbing Limit as per ACE Expression (mm) | Error in Calculated Scabbing Limit |
|---|---|---|---|---|---|---|---|
| | | Actual (mm) | Calculated as per ACE Expression (mm) | Error in ACE Results | | | |
| PC130 | 130 | 32 | 44 | 37.5% | 100 | 93 | 7% (Underestimate) |
| RC150 | 150 | 45 | 53 | 16.67% | 100 | 103 | 3% (Overestimate) |
| PC168 | 168 | 53 | 61 | 15.09% | 100 | 112 | 12% (Overestimate) |

**6. Ballistic impact**

The ballistic response has been studied by varying the incidence velocity of the projectile in order to obtain the ballistic limit of the concrete plates. The incidence velocity has been carefully varied and as far as possible, the uniformity has been maintained between the two consecutive velocities for studying the influence on residual projectile velocity, see Table 4. The ballistic limit of the concrete plates has been obtained as an average of the highest projectile velocity resulting in partial penetration and the lowest projectile velocity resulting in complete perforation [6].

Table 4. Incidence and residual velocities of plain and reinforced concrete plates

| Plain Concrete Plates | | | Reinforced Concrete Plates | | |
|---|---|---|---|---|---|
| Specimen No. | Incidence Velocity (m/s) | Residual Velocity (m/s) | Specimen No | Incidence Velocity (m/s) | Residual Velocity (m/s) |
| PC220 | 220 | 102 | RC218 | 218 | 71 |
| PC205 | 205 | 75 | RC202 | 202 | 50 |
| PC190 | 190 | 45 | RC192 | 192 | 28 |
| PC172 | 172 | 18 | RC180 | 180 | 0 |
| PC158 | 158 | 0 | RC168 | 168 | Not-Perforated |
| PC130 | 130 | Not-Perforated | RC150 | 150 | Not-Perforated |

The variation of the incidence and residual velocities has been plotted in Fig. 10 for plain and reinforced concretes. The variation in the residual velocity has been found to be almost linear with the increase in incidence projectile velocity. The residual velocity curves also suggested that for a given concrete type, the difference between the ballistic response of plain and reinforced concrete plates has increased with the decrease in the incidence velocity such that a maximum difference between the ballistic performance of concretes has emerged at very low incidence velocities, see Fig. 10. The average of the highest velocity giving partial penetration and the lowest velocity giving complete perforation was taken for the calculation of ballistic limit. A fairly accurate estimate of the ballistic limit has been made by keeping the difference between the highest velocity (not perforating the concrete plate) and the lowest velocity (completely perforating the concrete plate) to a minimum. The ballistic limit of reinforced concrete plate has been found to increase by 13% due to the incorporation of reinforcing bars (0.5%), in comparison to that of the plain concrete.

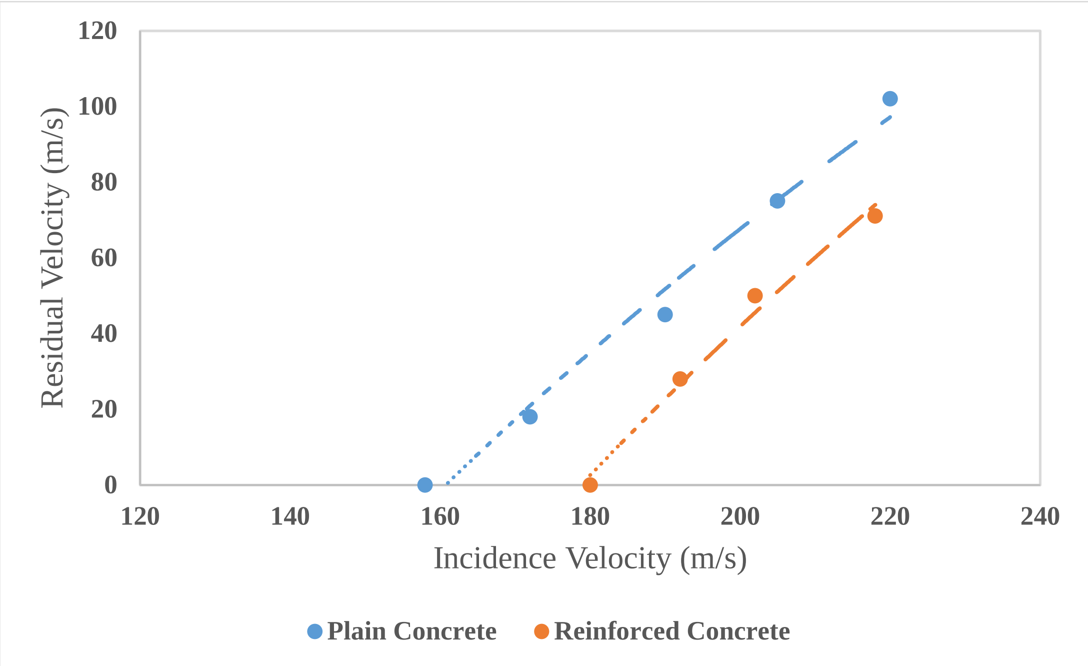



**Fig.10.** Ballistic performance of plain and reinforced concrete Plates

Table 5. Ballistic Limit

| Type of concrete | Plain Concrete Plate | Reinforced Concrete Plate |
|---|---|---|
| Ballistic Limit (m/s) | 165 | 186 |

## 6. Conclusion

The ballistic experiments were performed on plain and reinforced concrete plates of unconfined compressive cylindrical strength of 48 MPa considering the size of the plate as 600mm × 600mm × 100 mm. The induced damage, depth of penetration and the ballistic resistance of the plates was studied. The penetration depth and the scabbing limits of the non-perforated concrete plates has also been calculated using the available empirical expressions. Following conclusions have been drawn.

- Thick cracks were noticed in the plain concrete plate, and the width of the cracks were found to be in the range 2-5mm and 2-8mm at the front and rear concrete surfaces, respectively.

- Due to the incorporation of reinforcement in the concrete plates, no visible cracking was observed in the concrete plates.
- Cratering diameters at the rear surfaces of the perforated plain and reinforced concrete plates were increased with a decrease in the incidence of projectile velocities.
- Cratering diameters at the front surfaces of perforated plain and reinforced concrete plates were noticed to have insignificant changes due to a change in the incidence projectile velocities.
- The calculated penetration depths of non-perforated plain and reinforced concrete plates were overestimated, and the error in the calculated results was found to be higher in the case of plain concrete as compared to the reinforced concrete.
- The calculated scabbing limit of the one non-perforated plain concrete plate was underestimated by about 7%.
- The calculated scabbing limits for the two non-perforated reinforced concrete plates were found to be higher by 3 and 12 mm than that of the actual plate thickness describing about 3% and 12% overestimation in the calculated results.
- The variation in the residual velocity has been found to be almost linear with the increase in incidence velocity.
- For a given concrete type, the difference between the ballistic resistance of plain and reinforced concrete has increased with the decrease in the incidence projectile velocity such that a maximum difference between the ballistic performance of the two concretes emerged at very low incidence velocities.
- The ballistic limit of the reinforced concrete target was found to be 13% higher than that of the plain concrete target.

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