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Ballistic performances of concrete targets subjected to long projectile impact

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ABSTRACT

Concrete is a widely used material in the construction of strategic and important structures such as nuclear containments, bridges, storage structures and military bunkers. In the present study perforation experiments and simulations on finite element code ABAQUS/Explicit have been carried out to understand the behavior of concrete against projectile impact. Penetration tests were conducted on square (450 mm × 450 mm) targets of plain and reinforced concrete of unconfined compressive strength 48 MPa. To investigate the effect of reinforcement, 8 mm diameter steel grid was incorporated at the center of thickness of the target. The targets were subjected to normal impact by 0.5 and 1 kg ogival nosed hardened steel projectiles of caliber radius head (CRH) 3 and length to diameter (l/d) ratio 23.7 and 11.8 respectively. The velocity regime of the projectile was considered in the range 43–178 m/s. The results thus obtained were presented and influence there on the ballistic performance due to the variation in l/d ratio of projectiles have been discussed. In comparison to plain concrete, the ballistic limit of the reinforced concrete target was found to have increased by 14%. A fair agreement was found between actual and predicted residual velocities obtained in the present study. The actual and simulated ballistic limit against 0.5 kg projectile differed by 10.8% and 5.1% for plain and reinforced concrete target respectively. This deviation has been found to be 16.1% and 6.7% respectively against 1 kg projectile.

1. Introduction

There is a variety of situations responsible for impact loading in the real world such as blast loading, projectile impact, aircraft crash, drop impact etc. In all of these situations an impulsive load causes the stress waves to propagate through the thickness of the structure, leading to its damage, in case if the magnitude of the induced load and hence the stress wave is of sufficiently high magnitude. The occurrence of damage has the same order of time that it takes the stress wave to propagate through the thickness of the structure. Studies have been performed in the past to understand various aspects of the impact response of structural elements and the resultant induced damage. A detail review has been presented by Kennedy [1] for designing the perforation and scabbing thickness of concrete barriers through the available empirical formulae based on the rigorous experimental results at a range of velocities (60–457 m/s). Frew et al. [2,3] studied the influence of the diameter of concrete target and target to projectile diameter ratio on the penetration depth and projectile deceleration against 530 mm long and 76 mm diameter ogive nosed steel projectile. Negligible change in the penetration depth and only small deceleration was found in the targets of 23 MPa concrete due to decrease in their diameter (1.83, 1.37 and 0.91 m). The experiments conducted with different hardness of projectile and concrete aggregate showed some influence on the nose erosion but small effect on depth of penetration. The depth of penetration experiments conducted by Forrestal et al. [4] on grout (13.5 and 21.6 MPa) and concrete targets (62.5 and 51 MPa) by steel projectiles (7 l/d ratio) described that the penetration depth increased in the concrete (from 200 to 1000 mm) as well as in the grout (from 200 to 900 mm) targets with the increase in striking velocity (350–1200 m/s) until the nose erosion became excessive. Hanchak et al. [5] performed perforation experiments on concrete plates of compressive strength 48 and 140 MPa reinforced with three layers of ϕ6 mm@ 76 mm c/c (both ways) bars against steel projectiles (6 l/d ratio) and observed that the ballistic resistance of the target remained almost same if the projectile perforated the target with and without hitting the embedded reinforcement. Dancygier and Yankelevsky [6] stated that (40–60 mm thick) high strength (104 MPa) concrete targets contributed to better ballistic resistance and enriched punching action than normal strength (34 MPa) concrete, however, these underwent brittle failure with relatively larger craters and fragmentation when impacted by 120 g conical nosed (3 l/d ratio) steel projectiles. Wu et al. [7] studied the ballistic performance of 250 mm thick fiber-reinforced high

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strength concrete (47–100 MPa) with and without embedded steel reinforcement (double layer ϕ6 mm@100c/c) against 693 g (3.5 l/d ratio) steel projectiles. The ballistic limit of reinforced and non-reinforced concrete targets obtained in the range of 595–669 m/s and 593–661 m/s respectively led to the conclusion that the reinforcement does not have any obvious influence on the ballistic resistance since the projectile did not hit any reinforcing bar in the reinforced concrete target. The provision of steel plate at impact and rear surface of reinforced concrete plates has also been studied to improve impact resistance, however, incorporating an elastic absorber between two layers of reinforced concrete plate has been found more effective in improving the ballistic characteristics [8]. Perforation tests conducted on 34 MPa plain concrete targets (300–700 mm thicknesses) against 4.8 kg projectile described catering at front face, tunneling at middle of thickness and scabbing at the back face [9]. Loria et al. [10] introduced the third stress invariant in the original Holmquist-Johnson-Cook (HJC) model to enhance the pressures shear behavior. The simulations carried out using the modified HJC model to predict the ballistic limit of concrete within 8% deviation. Rajput and Iqbal [11] studied the ballistic performance of 60 and 100 mm thick prestressed concrete targets by performing simulations on a ABAQUS finite element code in conjunction with original HJC model. The HJC constitutive model predicted the failure modes and perforation in concrete fairly accurately. The induced prestress in concrete was found effective in reducing scabbing and thus improving ballistic performance. Holmquist and Johnson [12] introduced radial and hydrostatic prestress in the silicon carbide ceramic targets and simulated their ballistic response against cylindrical steel/tungsten projectiles. The ceramic tiles of thickness 12.7 and 20 mm were introduced two different levels of prestress through metal confinement. Prestressing thin targets delayed the tensile failure at the rear ceramic-metal interface by facilitating the interaction of projectile for a longer duration and thereby improved the ballistic performance.

The studies reported in the literature on ballistic performance of concrete targets are based on small length to diameter ratios (2–7) of projectiles. Moreover, due to complications in modelling the constitutive behavior of concrete and the embedded reinforcement there are rather few studies which address the problem numerically. The present study investigates the effect of length to diameter ratio of projectile on the ballistic performance of 50 mm thick plain and reinforced concrete targets of unconfined compressive strength 48 MPa. Hardened steel projectiles of mass 0.5 and 1 kg with l/d ratios 11.8 and 23.7 respectively were impacted on the targets close to ballistic limit velocity. The diameter (19 mm) and nose radius (3 CRH) of the ogival nosed projectiles was considered constant and their lengths were varied as 225 and 450 mm respectively in order to vary the l/d ratios. The reinforcement in the reinforced concrete target was provided as ϕ8 mm @80 mm c/c at the center of target thickness. The experiments were carried out with the help of a pneumatic gun and the simulations performed on commercial in finite element code ABAQUS [13] enabled further assessment of the experimental findings.

2. Preparation of target specimens and projectile

A concrete mix was designed for obtaining the target strength 48 MPa in accordance with IS 456:2000 and IS 10262:2009. The ordinary Portland cement, tap water, fine river sand, and basalt coarse aggregate of average size 10 mm were used for the preparation of concrete. The per cubic meter quantity of the constituents used in the mix design of concrete are presented in Table 1. The water cement ratio was restricted to 0.40 for achieving the desired strength in accordance with IS 456:2000. The slump of concrete mix was measured in the range 90–120 mm. The (150 mm × 150 mm × 150 mm) cube specimens were prepared and subjected to wet curing at 27–30 °C temperature after twenty-four hours of casting. A set of three cubes were tested after curing of 28 days. The uniaxial unconfined compression tests of the concrete cubes were carried out on a CONTROLS compression testing machine (CTM) at the strain rate $2.2 \times 10^{-5}\ s^{-1}$, and the average cube strength was recorded to be 49 MPa at 28 days.

Table 1
Constituents of concrete grade M40.

Cement	Water	Aggregate (10 mm)	Sand	Admixture
437.9	166.4	1040.92	720	0.25%

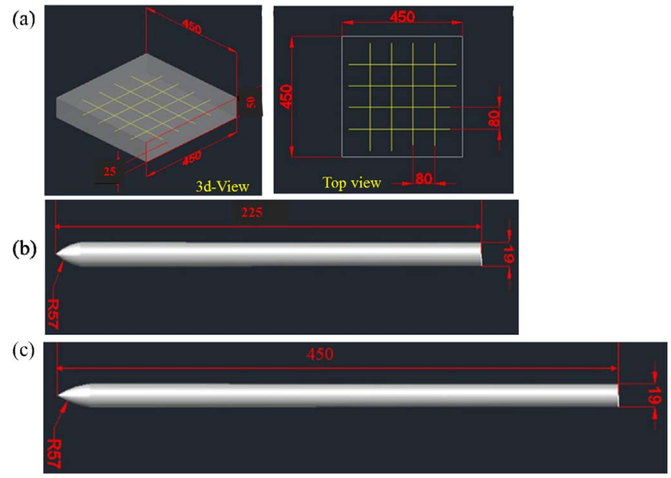

Fig. 1. Geometry of target and projectiles (all dimensions in mm) (a) reinforced concrete, (b) 0.5 kg projectile (c) 1 kg projectile.

Square plain and reinforced concrete plates were casted, edge length of plate was 450 mm and thickness 50 mm, see Fig. 1(a). A reinforcement grid Fe-415 steel reinforcement of ϕ8 mm was incorporated at the middle of the concrete plate, Fig. 1(a). High strength steel (415 MPa) projectiles of shaft diameter 19 mm and nose radius (3CRH) were machined to obtain their masses 0.5 and 1 kg and lengths 225 and 450 mm respectively, see Fig. 1(b) and (c) respectively. The projectiles were then heat treated at 800 °C temperature, oil quenched and tempered.

3. Numerical modelling

The geometric modelling of the target and the projectile was carried out on ABAQUS/CAE. The square targets of span 450 mm × 450 mm and thickness 50 mm were modelled as three dimensional deformable continuum and partitioned in three different zones in order to discretize and assign fine meshing in the contact zone, Fig. 2(a). The reinforcement modelled as three dimensional deformable truss with respect to ϕ8 mm @80 mm c/c was replicated to form a grid at the required spacing and then inserted at the middle of the concrete plate. The embedded constraints were assigned between the reinforcement and concrete to enable perfect bonding between the host and the guest elements. The ENCASTRE option has been used to enable fixed boundary condition at all the edges of concrete target, see Fig. 2(b). The concrete plate was modelled with eight node linear hexahedral reduce integration brick elements (C3D8R) of 0.001 mm size in the primary impact zone (inner circle geometry) of target. The outer region of the targets was also meshed with C3D8R elements of size 5 mm × 5 mm × 3 mm. The region between the core and the outer region was assigned with the six node tetrahedral elements (C3D4) of edge varying from 1 to 3 mm for minting compatibility between the core and the outer region, see Fig. 3(a)–(c). The aspect ratio of elements was maintained unity in the primary impact zone of diameter 19 mm. The aspect ratio however, increased slightly away from the impact zone. The reinforcement was modelled as truss elements (T3D2) with embedded constraints in the host region.