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Performance of prestressed concrete targets against projectile impact

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ABSTRACT

Energy dissipation in prestressed concrete targets has been studied against the impact of long rod steel projectiles. Experiments have been carried out wherein prestressed concrete plates of thicknesses 60, 80 and 100 mm were subjected to impact by 1 kg steel projectiles at normal incidence velocities close to ballistic limit. An initial prestress of 10 and 20% of unconfined compressive strength 40 MPa has been induced in the target through pre-tensioning of 4 mm diameter high strength (1646 MPa) steel wires. The reinforcement has also been provided in the prestressed concrete targets to enable a direct comparison of their performance with the equivalent reinforced concrete targets. The prestressing in concrete has been found to be effective in globalizing the induced damage and thus enhancing ballistic resistance. The influence of prestress has become more prominent with increase in target thickness and decrease in projectile velocity. The experimental findings have been reproduced through finite element simulations on a commercial finite element code to understand the individual characteristics of prestressing wire, reinforcement and concrete. The prestressing force has been numerically transferred in concrete by introducing initial stress in the strands and then performing quasi-static simulation. The simulations for projectile perforation have been subsequently carried out employing Holmquist–Johnson–Cook model for concrete and Johnson–Cook elasto-viscoplastic model for both reinforcement and prestressing strands. The finite element simulations predicted the ballistic limit of the targets within 11% accuracy.

1. Introduction

Concrete is the second largest material used by human beings after water. It is highly durable, fire and corrosion resistant and non-porous. Introduction of steel as reinforcement enabled the concrete to cover large space and sustain intensive loads under tension, flexure, torsion and shear. A consistent improvement in strength and performance over last few decades transformed the concrete into most suitable construction material for nuclear, strategic and protective structures. Prestressed concrete is generally employed to reduce sections and crack width in structural elements by eliminating flexural tension; and therefore it is preferred in pressure vessels and large span structures. Studies on the perforation capacity of 250 mm thick full-scale (2 m × 2 m) reinforced and prestressed concrete walls against 47 kg hard missiles described that the just perforation velocity for prestressed concrete wall was higher than that of the reinforced concrete wall but the prestressed concrete wall suffered 35% more rear surface damage [1–3] than the reinforced concrete wall. The provision of transverse reinforcement had no influence on the perforation capacity of reinforced concrete wall due to localized damage however it increased the capacity of prestresssed concrete by 10–15%. Holquist and Johnson [4] 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. For thick targets the radial prestress improved ceramic dwell behavior because of high surface pressure. The study of blast load resisting capacity of the concrete has demonstrated that an initial prestressing resulted in reduced deflections (both maximum and residual) in concrete elements, and has also been found effective in delaying the appearance and growth of flexural cracks [5]. The prestressing in concrete has improved the flexural capacity of the beams by reducing tensile damage. As the strength increased from 42 to 70 MPa, and the initial stress in strands, 315 to 630 MPa, the capacity to perform under blast loads improved. It has been noted however, that increasing the prestress level in beams may increase the diagonal shear cracks toward the support which might prove to be detrimental under blast loading.

The prestressed concrete has attracted very limited attention in the open literature possibly due to the fact that the introduction of prestress in concrete is a complicated process (through both

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experimental and finite element procedures). Authors could not find any study available on the performance of prestressed concrete against projectile impact.

The present experimental and finite element investigations aim to explore the possible influence of the magnitude of prestress on the energy absorption capacity of prestressed concrete against projectile impact. The prestressed concrete plates of thicknesses 60, 80 and 100 mm were subjected to impact by 1 kg ogival nosed steel projectiles at normal incidence velocities close to ballistic limit. An initial prestress of 10 and 20% of unconfined compressive strength 40 MPa was induced in the target through pre-tensioning of 4 mm diameter high strength (1746 MPa) steel wires. The deformed reinforcing steel bars of ϕ8 mm @ 100 mm c/c have also been provided to enable a direct comparison with the non prestressed concrete targets. The effect of the magnitude of prestress has been studied on the experimental results and the results have been compared with the non prestressed concrete targets. The experimental findings have been reproduced through finite element simulations on ABAQUS/Explicit finite element code to obtain further insight of prestress concrete behavior. The prestressing force has been numerically transferred in concrete by introducing initial stress in the strands and then performing quasi-static analysis. The simulations for projectile perforation have been subsequently carried out by employing Holmquist–Johnson–Cook model [6] for concrete and Johnson–Cook elasto-viscoplastic model [7–8] for reinforcement as well as prestressing strands.

2. Preparation of prestressed concrete specimens

A concrete mix was designed for obtaining 28 days unconfined compressive strength of 48 MPa in accordance with the requirement of Indian Standard; IS10262. Trials were conducted with various configurations of cement, potable water, river sand and coarse aggregate. The final composition of the mix had 440 kg cement, 0.4 water cement ratio, 730 kg dried river sand and 1050 kg basalt coarse aggregate of average size 10 mm in one cubic meter concrete as per the requirement of IS456 (2000). The concrete was casted in the controlled laboratory environment at 20–30 °C temperature. The slump of concrete was measured between 95 and 110 mm. In each casting, five cubes of 150 mm were also prepared along with the plate specimens. The typical uniaxial compression tests performed on cube specimens after 28 days curing in potable water at normal temperature resulted an average compressive strength 46–51 MPa.

The concrete specimens of span 450 mm × 450 mm were introduced a unidirectional prestress of 10% and 20% of unconfined compressive strength with the help of ϕ4 mm high strength (1650 MPa) steel wires, stretched across target span at the center of thickness to enable development of uniform compressive stress at the cross-section. The target was also reinforced with ϕ8 mm deformed steel bars of tensile strength 415 MPa @ 80 mm c/c both ways with a clear cover of 15 mm. The strength of the prestressing wires was measured by carrying out tension tests on controls universal testing machine. An especially designed prestressing bed of mild steel girders enabled casting of multiple specimens simultaneously. The prestressing strands were inserted through the square shaped steel target molds fixed with the prestressing bed to introduce initial stress in the concrete specimens. A total number of 13 and 22 strands were inserted in the target to induce 10% and 20% prestress respectively, see Table 1. Each strand, anchored at one side with the I-section girder, was stretched from the other side with the help of a hollow hydraulic jack and introduced an initial tension of 10, 14 and 16.5 kN for inducing 10% prestress and 13, 16 and 18 kN for inducing 20% prestress in 60, 80 and 100 mm thickness respectively. Thus, an initial stress of 4.8, 5.0 and 4.76 MPa corresponding to 10% and 10.5, 9.7 and 8.8 MPa corresponding to 20% prestress was induced in 60, 80 and 100 mm thickness respectively at anchorage take up, see Table 1. The strands were held in position with the help of steel wedges. The total losses in pretress due to elastic shortening, friction, creep and shrinkage were assumed to be 15% of the initial stress (at anchorage take up) as per the recommendation of IS 1343 (2012). Authors, also explored literature on this subject and found that the 15% loss of prestress is quite an established assumption and has been justified in the previous studies on prestressed concrete and also recommended in the standards on prestressed concrete, please see [9–11]. The effective prestress in the target after deducing the losses was calculated to be 4.09, 4.24 and 4.05 MPa corresponding to 10% and 8.9, 8.3 and 7.5 MPa corresponding to 20% prestress for 60, 80 and 100 mm thickness respectively, Table 1.

The concrete was poured in the square steel molds, carefully compacted with the needle vibrator avoiding contact with the strands, and surface finished. The curing of concrete was done with the help of wet gunny bags for 28 days. The wedges were subsequently released to enable transfer of stress in the body of concrete.

3. Ballistic experiments

The experiments were conducted with 1 kg ogival nosed hardened steel projectiles impacted on prestressed concrete targets at incidence velocities in the range 90–225 m/s. A pneumatic gun comprising of a single stage compressor of 60 kg/cm^2 working pressure, a pressure reservoir and 19 m long steel barrel, capable of launching 1 kg projectile up to a velocity of 300 m/s was employed to carry out the ballistic experiments, see Fig. 1. In the present study, the air pressure used to launch the projectile was up to 50 kg/cm^2. A pneumatic actuator which enabled opening a mechanical ball-valve system was used to release the air pressure and thus launch the projectile on the targets at normal incidence. A robust steel fixture was designed for rigidly holding the targets and maintaining fixity at the (target) edges. The incidence and residual velocities and the perforation phenomenon were recorded with the help of a high speed

Table 1
Calculations for inducing initial pre-stress in concrete targets.

Target thickness (mm)	Effective cross-sectional area (mm^2)	No. of wires	Force in each wire (kN)	Initial stress in target (MPa)	Losses (15% of initial stress) (MPa)	Effective stress in target (MPa) = initial stress in target − losses
Calculation of effective stress for inducing 10% prestress in the target						
60	27,000	13	10	4.81	0.72	4.09
80	36,000	13	14	5.0	0.76	4.24
100	45,000	13	16.5	4.76	0.71	4.05
Calculation of effective stress for inducing 20% prestress in the target						
60	27,000	22	13	10.50	1.58	8.9
80	36,000	22	16	9.78	1.46	8.3
100	45,000	22	18	8.80	1.30	7.5

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