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Study of induced prestress on deformation and energy absorption characteristics of concrete slabs under drop impact loading

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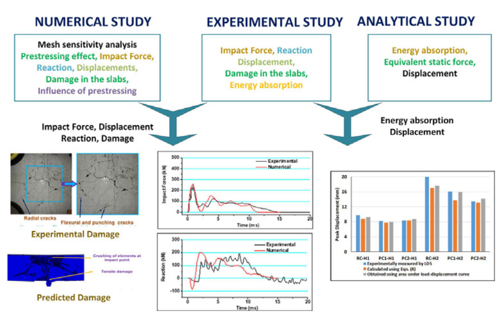
HIGHLIGHTS

- Prestressed and reinforced concrete slabs studied under drop impact.
- Prestressed concrete offered better resistance due to improved stiffness.
- Punching cracks were observed with the increase in drop height in reinforced concrete slabs.
- Numerical results accurately reproduced the impact and reaction time response of slabs.
- Numerical simulations also enabled to develop insight into the mechanics of reinforcement and prestressing wires.

GRAPHICAL ABSTRACT



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ABSTRACT

The drop impact resistance of concrete slabs with induced initial stress was investigated through detailed experimentation and the results thus obtained were reproduced through the numerical simulations performed on ABAQUS/Explicit code. Concrete slabs of span 800 mm and thickness 100 mm pre-tensioned to 10% and 20% of the characteristic compressive strength of concrete (40 N/mm^2) were subjected to impact by a freely falling hammer (243 kg) from predefined heights. The impact force, reaction-time response and deflection of these slabs were measured. Influence of induced prestress was studied on the damage resistance and energy absorption characteristics of prestressed concrete slabs and the results were compared with the equivalent reinforced concrete slabs. The induced initial stress has been found to enhance the stiffness and thus reduced the resultant deflection of slabs but increased the peak impact and reaction forces. The reinforced concrete slabs experienced flexural cracks leading to punching of concrete. Prestressed concrete slabs developed low density cracks without any visible punching action. However, splitting was observed with increase in prestressing force. Numerical results predicted the peak impact and reaction forces within 15% deviation and reproduced the damage with reasonable accuracy. Simulations also described the mechanics of prestressing wires and the reinforcement.

1. Introduction

The prestressing of concrete elements is primarily carried out to reduce crack width and thickness in strategic, pressure retaining and large span structures such as nuclear containment, rock shelter, long span bridge, community hall and industrial floor. Such

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prestressed concrete members are often subjected to impact loads generated due to internal plant accidents in nuclear power plants, automobile accidents on bridges, toppling of rocks over rock shelters and falling of equipment on industrial floors [1]. These structures are generally designed for static loading conditions and the uncertainty in the loading is accounted for by considering a certain constant safety/load factor. The design based on the assumed constant factor of safety although enhances the dynamic response to a certain extent, however, it is incapable of addressing the localized deformation and the actual structural behaviour under impact loads [2].

Structural elements of plain, reinforced and fiber reinforced concrete have been studied under impact loading to investigate the energy absorption capacity and the characteristics of the induced damage [3–6]. The performance of concrete filled steel tubes has also been explored under impact loading [7–9]. The concrete filling of steel tubes has demonstrated in precluding local deformation under impact loading and increasing the moment carrying capacity of a given section. The presence of steel surface around the concrete core has been found to increase the lateral strength of the column and thus enhance its load carrying capacity. In another experimental study [10], the reinforced concrete slabs subjected to impact by freely falling steel ball described little influence of the percentage of reinforcement on the resultant dynamic deflection. Othman and Marzouk [11], on the other hand, reported an inverse trend on peak displacement, residual displacement and scabbing of slabs due to an increase in the reinforcement. The deflection at the center of the slab has been seen to have reduced due to increase in its thickness [12]. Thicker slabs with relatively higher stiffness have experienced lesser deflection and relatively lower damage at front and back surfaces under impulsive loads.

The ballistic performance of the double layered target with front reinforced concrete and the backing steel plate has been studied against non-deformable steel projectiles [13]. The resultant magnitude of damage in the reinforced concrete target obtained experimentally at different incidence velocities was compared with the probability of failure of the structure computed based on Monte-Carlo approach, and a close correlation between the experimental and probabilistic assessment was found. In another study [14], the double layer reinforced concrete-steel containment was found safe against the hard steel missile impact if the missile velocity was lesser than 65% of the containment outer (reinforced concrete) wall's ballistic limit. However, if the impact velocity was more than 90% of the outer wall's ballistic limit, the probability of failure of double wall containment was very high.

The available studies on prestressed concrete elements under impact loading are limited to the testing and design of railway sleepers [2,15]. The cracks in the sleepers have transformed from flexure to combined flexure-shear and finally into the shear mode of failure due to increase in the loading rate. The rate of crack propagation in a sleeper was governed by the stiffness of the track system such that hard track had relatively faster crack propagation and experienced longer cracks [16]. In another study, the model and steady-state analysis of prestressed concrete beams were performed using ABAQUS finite element code [17]. The natural frequency of beam has been found to have reduced due to the provision of an opening at the shear zone. Jing et al. [18] investigated the influence of lateral vehicle impact on the behaviour of full-scale prestressed concrete bridge girder and observed localized failure at the impact location due to crushing and punching of concrete. The ballistic resistance of plain, reinforced and prestressed concrete plates studied by carrying out the experiments and finite element simulations described best performance of prestressed concrete due to globalization in the induced damage as a result of initial prestressing of concrete [19,20].

There is limited understanding of the behaviour of prestressed concrete under impact loading despite significant utility of the material in various applications. Authors could not find any study in the available literature on the drop impact response of prestressed concrete slabs.

The present study attempts to investigate the response of prestressed concrete (PC) slabs against a 243 kg steel hammer falling freely from 500 and 1000 mm height. The square slabs of span 800 mm $\times$ 800 mm, induced with an initial stress of approximately 10% and 20% of characteristic compressive strength (40 N/mm^2) were subjected to impact at the center. The dynamic responses such as impact force, support reactions and resultant displacement have been studied and compared with the equivalent non-prestressed concrete slabs. The damage mechanisms observed in the prestressed and non-prestressed concrete have also been compared and discussed. Numerical simulations of the actual problem have also been performed on ABAQUS/Explicit finite element code for a detailed investigation of induced prestressing on the response of slabs and to further explore the damage mechanics of prestressed and reinforced concrete slabs. A simplified analytical model based on the principle of mechanics has been introduced for calculating the peak displacement in the slabs and it has thus facilitated a direct comparison with the actual and computational results.

2. Concrete mix design

The concrete mix was designed as per the requirement of Indian Standard IS 456 (2000) and IS 10262 (2009). The Ordinary Portland Cement (OPC) 43 grade, the coarse aggregate of nominal size 10 mm and river sand were used for the preparation of the concrete mix. The aggregate passing from 10 mm and 4.75 mm sieve was considered for the mix design, respectively, as coarse and fine aggregate. The quantity of required material was calculated using the weigh-batching method of concrete mix proportioning. The ratio of the cement, fine and coarse aggregate was considered to be 1:1.74:1.68, respectively, with water-cement ratio limited to 0.35 for obtaining the characteristic compressive strength of 40 N/mm^2 (IS 456; 2000). A small quantity of water-reducing agent, 0.4%, was also added to the concrete mix. The 28 days average target strength of the tested concrete cube (150 mm) samples at loading rate approximately 140 kg/sq.cm/min (IS 516:1959) was found to be 48 N/mm^2 with a standard deviation of 1.60 N/mm^2.

3. Preparation of reinforced and prestressed concrete slabs

The reinforced and prestressed concrete slabs of identical span (800 mm $\times$ 800 mm) and thickness (100 mm) were casted with the help of specific moulds designed for each concrete. Each reinforced concrete (RC) slab was casted in separate mild-steel moulds with internal dimension, 800 mm $\times$ 800 mm. High strength (Fe 500) deformed reinforcing bars of ϕ 8 mm @ 140 mm c/c were provided across both spans with a clear cover of 10 mm from the bottom of slab, see Fig. 1. The reinforcing bars were tested under tension on a Universal Testing Machine (UTM) and their average yield and ultimate strengths at loading rate 1 mm s^{-1} were found to be 609 and 745 N/mm^2, respectively, see Fig. 2.

The procedure of casting the prestressed concrete slabs was almost same to that of the reinforced concrete slabs except that the initial pretension was introduced in these slabs with the help of high-strength indented steel wires of diameter ϕ4 mm (Fig. 3 and Fig. 4) used in accordance with IS 6003 (2010). The yield and ultimate tensile strength of these wires tested on Olsen H75KS universal testing machine were approximately 1600 and 1770 N/mm^2, respectively, at the strain rate 1.2×10^{-5} s^{-1}. The stress-strain