Falling weight impact response of prestressed concrete slabs with manhole

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Abstract. Blast and impact resistance structures have become an indispensable requirement for the design of concrete structures due to the prominent danger imposed. The increasing number of accidents and global terrorism on public civil structures pose a serious threat to the infrastructure and human life. It has been seen that prestressing of concrete can improve the impact resistance of the structures. The objective of this paper is to investigate the response of reinforced concrete slabs, prestressed in its transverse direction by steel wires of 7 mm diameter against impact load imposed by a hammer falling from 5 m height tested and calibrated using ANSYS Autodyne software package. The control slab is compared with slabs having opening/cut-out of different aspect ratio and at different positions. Three different sizes for the hole/opening is considered here provided the area of the opening/hole is kept constant. Post analysis, the most optimum size of the hole was found out to be 500 mm x 500 mm and its position was at the edge of the slab.

Keywords: Prestressing, reinforced concrete slab, impact load, ANSYS Autodyne

1. Introduction
The major threat posed on our built environment is by impact loads which give potentially dangerous consequences. The damaging impact loads usually include vegetation, automobiles, or other objects hurled toward built structures during hurricanes, large vehicular impacts on bridge-piers, impact loads from explosions, ship impact, aeroplane impact, rock-fall impact, or missile impact etc. The major challenge faced by modern engineers is to mitigate the detrimental effects of impact loads on the structural integrity of the infrastructure and thereby making it more resilient [12]. Many studies have proven that the load carrying capacity and toughness of concrete specimens can be increased by increasing the percentage of steel fibre, by providing a high percentage of reinforcement [11], and also by changing reinforcement configuration [3,7,10]. In contrast to the alteration in reinforcement arrangement, the energy absorption capacity and damage resistance of reinforced concrete (RC) slabs are not much influenced by the increase in reinforcement ratio [3,10] despite the increase in the drop height [8].
In another study, two prestressed concrete rock-shed frames were given a heavy impact by dropping a mass of up to 5000 kg to investigate its impact resistance capacity [2]. The rigid connection at the column junction of ‘T’ shaped fully-rigid frame resulted in its higher energy absorption capacity when compared to the inverted ‘L’ type frame (‘Γ’ shaped).

The examination of available literature revealed that the attempts to investigate the structural behaviour of prestressed concrete are very rare. A few studies reported on prestressed concrete are limited to the dynamic response of prestressed concrete sleepers under single and repeated impacts [1,4,5]. In the present study, the effect of impact loading on reinforced concrete slabs with openings of different aspect ratio at different positions and which is prestressed by steel wires of 7 mm diameter in the transverse direction is studied here.

2. Methodology

2.1. Experimental Study

A prestressed concrete square plate of size 800 mm and thickness 100 mm was cast using concrete mix proportion 1:1.74:1.68 (C: FA: CA). The expected characteristic compressive strength of concrete was 40 N/mm². The water-cement ratio used was 0.35. The final strength achieved after 28 days of curing was 48.4 N/mm² with a standard deviation of 1.60. High Yield Strength Deformed bars of 8 mm diameter at 140 mm spacing was used in both main and transverse spans of the concrete plates. Also, 10 numbers of 4 mm diameter prestressing wires were provided at a spacing of 80 mm center to center with an eccentricity of 25 mm from the center of the plate thickness (figure 1). These prestressing wires were pre-tensioned by pulling the wires with the help of a 50t capacity hydraulic jack before casting the concrete plates to obtain a stress of 10% of unconfined compressive strength (48.4 N/mm²). Impact test was performed on the plates using a heavy steel mass of 243 kg (figure 2) by dropping it from a height of 1 m. Displacement sensors were placed in the center and quarter span of the bottom surface of the plate to measure the displacement. This experiment was conducted by Vimal Kumar et.al. funded at Department of Civil Engineering, Indian Institute of Technology, Roorkee [11].

![Figure 1. Detailing of reinforcement bars in prestressed concrete plate [11]](image1)

![Figure 2. The detail of weight assembly used in the experiment [11]](image2)

The maximum displacement obtained at the center span of the plate is 16.09 mm (figure 3).
2.2 Finite element modelling for experimental calibration

A prestressed concrete square plate of 800 mm size and 100 mm thickness was modelled using design modeler in ANSYS workbench (figure 4). The reinforcement details were given as per the experiment (figure 5). Material properties of concrete such as compressive strength 48.4 N/mm$^2$, Young’s modulus of 34785.05 N/mm$^2$ and Poisson’s ratio of 0.18 is given.

Mesh convergence study was performed and the optimum mesh size obtained was 15 mm. Contacts between reinforcements and concrete were given. Prestressing of concrete was done in static structural by bolt pre-tensioning method. The load given to obtain 10% prestress was 59769 N. The boundary conditions given for prestressing are (i) Rotational constraint for prestressing wires and main reinforcements (ii) the sides of the concrete plate along the direction of prestressing wires were free to move along the direction of prestressing and in vertical direction (iii) the other two sides are free to move only in the direction of prestressing (iv) standard earth gravity is given. Average normal stress for the whole structure after prestressing was obtained as 4.84 MPa approximately 10% prestressed.

The impact analysis is done using ANSYS Autodyn. To reduce the time for solving, the hammer was moved to a position just above the concrete slab and an initial velocity of 4.4274 m/s is given for the hammer to generate the required momentum. The analysis end time was set to 20 ms. Material model used for concrete is Standard RHT Concrete model. Steel used for reinforcements are modeled using Johnson Cook strength model. The supports along with the hammer are modeled with Rigid EOS with the density equal to that of structural steel. The major boundary conditions for this analysis are that all fixed condition to the supports, lateral constraints on the Hammer and the standard earth gravity to all bodies. Subsequently, the hammer is free to move only in vertical direction. Gauges are set at center and quarter span to measure the displacements and strain rates. In addition, the top edges

Figure 3. Displacement Vs Time graph obtained from experiment [11]

Figure 4. Model Geometry

Figure 5. Reinforcement details
are constrained not to move in the vertical direction as well according to the experimental setup. The results from Autodyne showed the maximum deformation of the plates at the center span as 16.908 mm.

The values of displacement obtained from experiment and from the software were compared. The comparison data is shown in the table below (table 1) and the calibration results are shown in figure 6.

**Table 1. Comparison of experimental to numerical model.**

| Method               | Maximum Displacement | Maximum deflection Error % |
|----------------------|----------------------|-----------------------------|
| Experiment           | 16.090 mm            | Error % = \[rac{(16.908-16.09)}{16.09}\]x 100 = 5.0839% |
| Autodyne Software    | 16.908 mm            |                             |

![Figure 6. Comparison of experimental and numerical time deflection curves](image)

From the FE model, we see that there isn’t much variation while comparing experimental and numerical results and the error margin obtain was 5.0839%. Hence the mesh convergence size and the material properties used in the calibration model can be used for the proposed study.

### 2.3 Numerical modelling of prestressed slabs with manholes

The mesh size, material properties and boundary conditions used in the proposed study is the same as that used in the calibration model. A one-way concrete slab with dimensions of 3000 mm length, 1000 mm width and 150 mm thickness, was modelled. 10 mm diameter bars of 11 numbers are provided as the longitudinal reinforcements and 10 mm diameter bars at 250 mm center to center spacing are provided as the transverse reinforcements [6]. The prestress wires are given according to the ratio of the volume of main reinforcements to the volume of prestressing wires as per the experimental setup. Therefore 18 numbers of 7 mm diameter wires along the transverse direction, i.e., each one has a length of 1000 mm are used as prestressing wires. A total of 10 number of models of the slab were modelled, which include a control slab without opening, and the rest 9 models having an opening of different aspect ratio at three different positions. The area of the opening is kept constant. The three different sizes are 500 mm x 500 mm, 555.556 mm x 450 mm and 625 mm x 400 mm. The positions considered are [i] center of the slab [ii] with 3 prestress wires to the shorter span [iii] with 6 prestress wires to the shorter span. The prestressing analysis was carried out for all the models in the same way as in the calibration process. The designation, prestress wire spacing, hole size, position, and average prestress value at midplane is given in the table below (table 2).
Table 2. Model details.

| Model No. | Designation          | Prestress wires spacing (mm) | Hole Size (mm)     | Position of hole | Average Prestress value at midplane of concrete (N/mm²) |
|-----------|----------------------|------------------------------|--------------------|------------------|--------------------------------------------------------|
| 1         | T174                 | 174.118                      | No hole            |                  | 4.84                                                   |
| 2         | T151-500X500M        | 151.25                       | 500 x 500          | Middle           | 4.84                                                   |
| 3         | T151-500X500Q        | 151.25                       | 500 x 500          | Quarter          | 4.84                                                   |
| 4         | T151-500X500E        | 151.25                       | 500 x 500          | Edge             | 4.84                                                   |
| 5         | T147.5-555.556X450M  | 147.5                        | 555.556 x 450      | Middle           | 4.84                                                   |
| 6         | T147.5-555.556X450Q  | 147.5                        | 555.556 x 450      | Quarter          | 4.84                                                   |
| 7         | T147.5-555.556X450E  | 147.5                        | 555.556 x 450      | Edge             | 4.84                                                   |
| 8         | T143-625X400M        | 143.375                      | 625 x 400          | Middle           | 4.84                                                   |
| 9         | T143-625X400Q        | 143.375                      | 625 x 400          | Quarter          | 4.84                                                   |
| 10        | T143-625X400E        | 143.375                      | 625 x 400          | Edge             | 4.84                                                   |

Rigid supports are given on opposite sides of the slab. The hammer has dimensions of 0.15 x 1.25 x 0.75 m [9]. It is dropped from a height of 5 m. The impacting surface of the hammer is hemispherical. The material used is rigid structural steel. The figure below shows some of the models and reinforcement details (figure 7).

![Figure 7](image_url)

**Figure 7.** (a) T174  (b) T151-500X500 M  (c) T151-500X500Q  (d) T151-500X500 E

The impact analysis conditions are also same as that of the calibration model. The analysis end time is set as 40 ms. The initial velocity of the hammer for 5m is given as 9.9028 m/s. All the material properties are the same. The Autodyn model of T174 is shown below (figure 8).
3. Results and Discussions

The displacement versus time history of all the models is obtained from the output of Autodyne. The table below gives the maximum displacement obtained from the gauge lying below and in line with the hammer (table 3).

**Table 3. Maximum Displacement obtained for models.**

| Model No. | Designation          | Maximum Displacement (mm) |
|-----------|----------------------|---------------------------|
| 1         | T174                 | 33.049                    |
| 2         | T151-500X500M        | 53.332                    |
| 3         | T151-500X500Q        | 54.647                    |
| 4         | T151-500X500E        | 31.640                    |
| 5         | T147.5-555.556X450M  | 57.833                    |
| 6         | T147.5-555.556X450Q  | 54.088                    |
| 7         | T147.5-555.556X450E  | 31.702                    |
| 8         | T143-625X400M        | 46.203                    |
| 9         | T143-625X400Q        | 47.998                    |
| 10        | T143-625X400E        | 31.705                    |

The obtained output, displacement Vs time graphs of each hole size are plotted in excel and compared with the base model (figure 9 (a-c)).
From the comparison, we can understand that in all cases edge position is best suited for providing a hole, because it showed minimum deflection in all cases. In order to find out the suitable size for the hole, all the edge hole graphs of various sizes are compared (figure 10).
From the comparison, we find that the results are nearly the same, however, the hole size of 500 mm x 500 mm showed the least displacement progressively.

4. Conclusion
From this study, we can conclude that the best position for the hole/opening is edge position and the optimum size for the hole is 500 mm x 500 mm or square hole of any size. The possible reason for edge position to be the best position is that, in this case the prestress energy is used up entirely by the impactor with more central cross section, while in the other cases the cross-sectional area where prestress is concentrated is less and hence they are less effective. Also, the entire energy is absorbed by the concrete surrounding the hole when impacted head-on, whereas, in the case of the hole near the support, most of the energy is transferred to the support instead of being absorbed by the concrete near the hole.

5. References
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