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Performance of one-way concrete slabs with and without hole

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Abstract
Several utility requirements necessitate the installation of holes in certain concrete structures. Due to the reduction in concrete area in the cross-sectional dimension, the structural component may exhibit complex behavior. Thus, the study investigates the behaviour of plain cement concrete (PCC) and reinforced cement concrete (RCC) one-way slabs with holes and its effect. Eight numbers of PCC and RCC slabs with and without holes were made in various (i.e., circular, square, and hexagonal) shapes by maintaining the same area of opening. Load versus mid span deflection response curve, load carrying capacity, failure modes and energy absorption capacity were investigated and considered as indicators of structural slabs performance. It has been observed that PCC and RCC slabs with circular holes exhibited greater load carrying capacity than slab models prepared with hexagonal and square holes. The slabs with square hole experiencing more cracks compare to circular and hexagonal holes present in slabs because of sharp edge corners. Slabs with circular hole exhibited greater energy absorption capacity than the slabs with hexagonal and square holes. Finally, it can be stated that the geometric configuration of the hole substantially impacts the performance of slabs, and opting for circular holes is the most favourable choice.

Key words: One-way slab, holes, load carrying capacity, failure mode, energy absorption

1. Introduction

A concrete slab is a flat, horizontal surface that is often used in building construction. It is a two-dimensional part of a building structure that has a very thin dimension in contrast to its length and width. Reinforced concrete slabs are generally used in many parts of the buildings, such as the roofs, floors, ceilings and bridge decks. The slab can be supported by walls, steel beams, piers and the earth or reinforced concrete beams that are usually cast at the same time as the slab. In industrial buildings, it is common practice to cut holes in the floors or ceilings to allow for the passage of utilities like ducts, pipes, internet cables and water lines. The holes in concrete constructions may cause a variety of issues, such as a decrease in the structural components resistance, an increase in deflection and the occurrence of numerous cracks in the vicinity of the holes. Reference (Silpa and Sreevalli, 2021) illustrates the analytical and experimental studies, numerical simulations of slabs, diverse load-resisting mechanisms to prevent progressive collapse and strengthening techniques, thereby enriching the overall understanding of researchers in this domain. The two-way slabs were studied by Mota and Kamara (2006), where authors have demonstrated how to select the locations and sizes of openings for both the new and existing slabs. Guan and Polak (2007) have applied the finite element method to investigate the influence of openings and shear stud reinforcement on the behaviour of reinforced concrete slab-edge column connections. The hybrid strengthening technique composed of carbon fiber-reinforced polymer (CFRP) laminates on the tensile surface and steel fiber-reinforced concrete (SFRC) overlay on the top compressive surface was employed by Bonaldo et al. (2008) to increase the flexural resistance of existing reinforced concrete (RC) slabs. Dong and Zhu (2011) have presented the test results of temperature distribution, central vertical deflection and edge horizontal deflection of a two-way concrete slab with two edges clamped and two edges simply supported in fire. Lambe and Siddh (2017) have investigated the shear bond behaviour of the simply supported composite slab by considering variation in three different parameters, the shape of a sheet, thickness of sheet and shear span. Sayhood et al. (2018) have introduced different strengthening techniques on slab specimens, where, first and second methods include applying either near surface mounted (NSM) or near reinforcement mounted (NRM) ferrocement layers. While the third method includes applying a concrete layer reinforced with welded wire fabric mesh of various diameters. The fourth and fifth methods include fixing CFRP rods and laminates, respectively, on the bottom surface of slabs. Mahlis et al. (2018) have investigated the behavior of two-way RC beamed slabs with openings introduced after casting. Chung et al. (2018) used the yield line method to predict the load bearing capacities of the donut-type voided two-way slabs with reasonable accuracy. Hadi and Muttashar (2020) have presented an analytical method to examine the effect of opening on the area load capacity of square and rectangular slabs. The effect of middle, side and corner openings on the reinforced concrete two-way slabs was investigated by Shabestani et al. (2022). El-Taly et al. (2020) have evaluated the structural behavior of restrained and unrestrained two-way solid slabs using experimental investigation. Aminitabar et al. (2021) have employed the finite element numerical method to investigate the effects of openings on the resistive behavior of concrete slabs. Özbayrak and Altun (2022) have conducted an experimental study to show the effects of slab openings on seismic behaviour of buildings. It was observed by the authors that in cases where there were 25% or more openings in the slab, rigid diaphragm behaviour decreased in the structure. Shill et al. (2022) studied the structural performance of large scale two-way concrete slabs reinforced with Fibre-reinforced polymer (FRP) rebars, and their performances were compared against conventional steel reinforced concrete. Zhan et al. (2022) have conducted a series of monotonic static loading tests with concentrated central load on composite orthotropic two-way slabs with perfobond rib shear connectors. John et al. (2023) have investigated experimentally the structural capacity, shear behaviour and two-way load distribution of the composite slabs consisting of a steel deck and concrete. Jian et al. (2023) investigated the mechanical properties and develop a load-carrying capacity estimation method for reinforced concrete slab culvert rehabilitated with a grouted corrugated steel plate. Design of simply supported composite slabs of steel and concrete using metaheuristic optimization algorithm was carried out by Teixeira et al. (2023). Jain and Hussain (2023) implemented a numerical investigation on two-way voided slab using ABAQUS with replacement of conventional steel by GFRP reinforcement bars. Abuzaid et al. (2024) have targeted to enhance slurry infiltrated fibrous concrete (SIFCON) by including both long and short fibers, with the goal of increasing ductility and mechanical properties behavior.

Al-hafiz et al. (2013) have introduced a technique to strengthen opening provided in a one-way slab by using steel plates and steel connectors. Ali et al. (2015) have analyzed glass fiber-reinforced polymer (GFRP) one-way concrete slabs by considering the most influencing parameters such as the cross sectional shape of GFRP bars, reinforcement ratio, the concrete characteristics strength, and adding polypropylene fibers to the concrete mixture. Authors showed that, the tested slabs with GFRP square bars improved the deflection and cracking behavior as well as the ultimate load. Al-Azzawi and Al-Asdi (2017) have studied the behavior of one way reinforced concrete slabs with and without styropor blocks. Al-Gasham et al. (2019) have presented an experimental investigation to assess the effect of voids' size on the structural behavior of one-way slabs. Yaseen and Al-Ahmed (2022) have observed the significant effect of openings on the behavior of the slabs. Where, the decreases in the ultimate load from 39kN to 24.7kN, on the other hand, the reduction in the deflection at ultimate load from 67 mm to 35 mm. El-Mandouh et al. (2023) demonstrated the different effective strengthening techniques to improve the flexural strength of one-way reinforced concrete (RC) slabs.

2. Research significance

In accordance with the findings of the literature review, it is evident that there is a lack of comprehensive research on the behaviour of one-way concrete slabs with various shaped holes. Consequently, experimental models were produced and their tests were performed to obtain the load-displacement characteristics of one-way slabs, both with and without holes. The load versus mid span deflection response curve, load carrying capacity, failure modes and energy absorption capacity were considered in the present work as indicators of structural slabs performance.

3. Materials

The description of materials used in this work to prepare the different configurations of plain cement concrete and reinforced cement concrete slabs with and without hole are presented in this section.

3.1. Raw materials

In order to prepare concrete, cement is a necessary ingredient. In this investigation, type-II grade 43 ordinary Portland cement (OPC) with a specific gravity of 3.15 is employed. A locally accessible washed natural river fine aggregate or sand was used in the concrete compositions. The specific gravity of sand equal to 2.66 was found after test. Fig. 1 depicts the particle size distribution of fine and coarse aggregates. After sieve analysis, the sand was identified as zone III. In this investigation, the coarse aggregates consisted of locally available 20 mm crushed granite aggregate with a specific gravity of 2.79. Water is essential to concrete because it activates the binder and creates a workable mixture. The pH value of the water was found to be around 7.7 (see, reference Dey et al. 2023). In this work, 3 mm diameter Galvanized Iron (GI) bar was used as reinforcement. The yield and ultimate strength of the bar were found after laboratory tensile test 355 N/mm^2 and 565 N/mm^2 respectively.

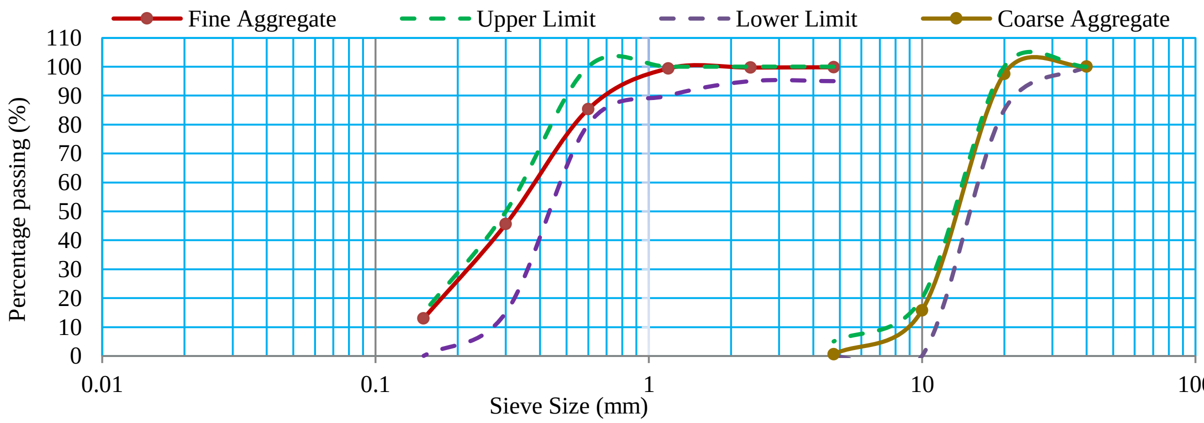


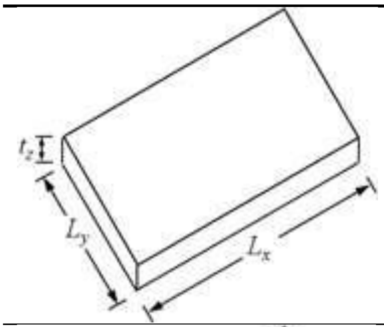
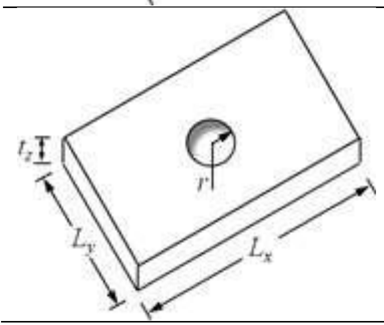
Figure 1. Particle size distribution of the aggregates.

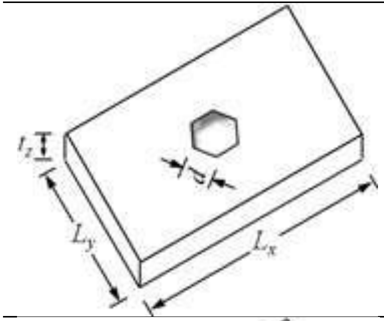
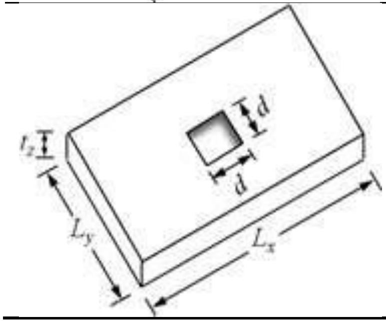
3.2. Mix proportions, casting and curing of specimen

M25 grade of concrete was considered in the present work. IS 10262 (2019) gives the procedure for designing concrete mixes based on the strength and workability requirements. Subsequently, IS 456 (2000) is also referred, which provides guidelines for the design and construction of reinforced concrete structures, including factors for mix design, load calculations, and structural detailing. The provisions in IS 456 (2000) were again followed for slab design, considering factors such as span, thickness and load distribution.

After mix design, the mixing proportion of M25 grade concrete was found to be 193.00 kg of water, 410.00 kg of cement, 607.20 kg of fine aggregate and 1175.25 kg of coarse aggregate per cubic metre of concrete, with a water-to-cement ratio of 0.47. Ultimately, the adopted mixing ratio was 1:1.48:2.87. To produce a consistent color, coarse and fine particles were thoroughly mixed with cement. Thereafter, water was delicately added to the mixture to ensure that no water was lost during mixing. Finally, each slab specimen was casted and cured for 28 days in the laboratory ambient conditions. The details of the different configurations of slab specimens are presented in the Table 1 as well as in Fig. 2. Based on the IS 456 (2000), the size and placement of the holes in the slabs were obtained by specific guidelines to confirm the structural integrity as well as proper load distribution. The area of an hole in a slab should not be greater than 1/8th of the total area of the slab. IS 456 (2000) also recommends that the holes of any size may be placed within the middle half of the span in each direction. For this present study, the areas of the holes were kept constant across all slabs, ensuring that the size was proportionate and did not overly compromise the structural performance.

Table 1. Dimensions of the different configurations of slabs.

Model	L_x (mm)	L_y (mm)	t_z (mm)	r (or) d (mm)	Area of the hole (mm^2)	Description of the model and symbol
	800.00	400.00	35.00	--	--	Slab without hole. In case of PCC, symbol is SPWH In case of RCC, symbol is SRWH
	800.00	400.00	35.00	25.00	1963.50	Slab with circular hole. In case of PCC, symbol is SPWCH In case of RCC, symbol is SRWCH

	800.00	400.00	35.00	27.49	1963.50	Slab with hexagonal hole. In case of PCC, symbol is SPWHH In case of RCC, symbol is SRWHH
	800.00	400.00	35.00	44.31	1963.50	Slab with square hole. In case of PCC, symbol is SPWSH In case of RCC, symbol is SRWSH

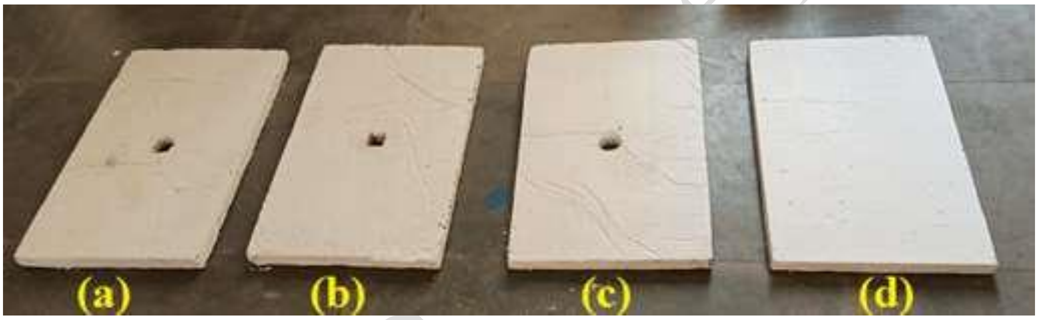


Figure 2. Slab specimens with hole: (a) hexagonal, (b) square, (c) circular and (d) slab without any hole.

4. Experimental programme

As per IS 456 (2000), a slab is referred to as a one-way slab when the ratio of the longer span (L_x) to shorter span (L_y) is larger than 2. A one-way slab is often supported by two parallel walls or beams. In the present study, the slab was subjected to gradual loading in the laboratory using a Universal Testing Machine (UTM). The UTM applied incremental loads to the slab, simulating real-world conditions and allowing for an in-depth analysis of its behavior under load, including the assessment of ultimate load capacity, cracking patterns, and failure modes.

In this work, the slabs are subjected to distributed load through the loading pad or dolly for small area and often treated as concentrated loads for simplicity in analysis. The one-way concrete slabs with and without holes were tested under the load applied at the mid of the slab. This loading configuration was chosen to replicate the effects of localized loading, which is typical in certain structural applications, such as point loads from concentrated machinery loads, a scenario frequently observed in industrial environments. The UTM with a capacity of 600 kN was considered for the present experiments. Fig 3 illustrates the graphical representation of reinforcement detailing and test setup. Fig. 3(c) represents the test setup. The edges of slabs were supported on two parallel simply supports. The tests were run until the point of failure and the ultimate load was recorded.

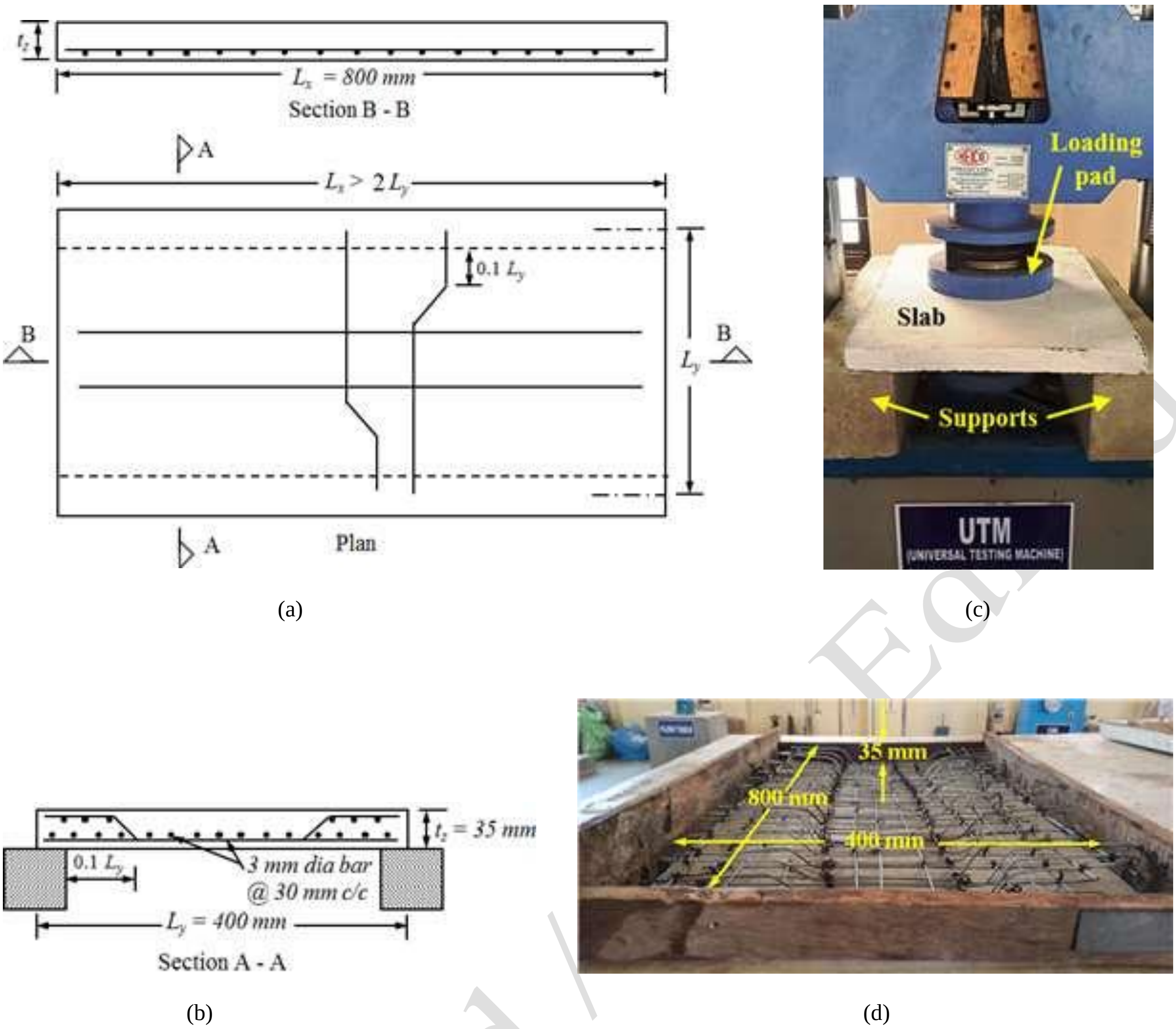


Figure 3. Graphical representation of reinforcement detailing and test setup.

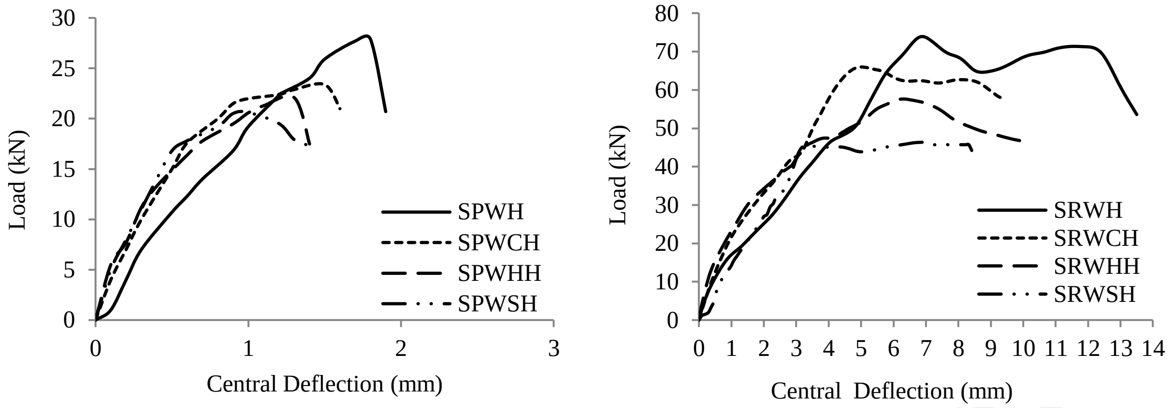
An actual R.C.C. roof slab has a plan dimension of 4 m × 2 m, with a slab thickness of 175 mm and utilizes M25 grade concrete and Fe415 grade steel reinforcement. The design was carried out in accordance with the provisions of the Indian Standard IS 456 (2000). Subsequently, the design results of slabs were scaled down by a factor of 1:5, both the dimensions of the slab and the reinforcement areas are reduced by the same factor to maintain the strength to size relationship. The detailed configurations are presented in Figure 3. This approach is widely accepted and frequently employed in structural engineering research to predict real world behavior with high accuracy, particularly when full-scale testing is impractical due to cost, space or logistical limitations. Though the absolute values may differ due to scale, the governing mechanisms and response trends continue to be valid and insightful for extrapolation.

5. Results and discussions

The results of the investigation are detailed in the section. Specifically, the load versus deflection response curve, load carrying capacity, failure modes and energy absorption capacity were analysed.

5.1. Load-deflection curve and failure modes

The main test results of load and deflection in the mid-span of one-way PCC and RCC slabs with and without hole are shown in Fig. 4 and Table 2. Table 2 shows the results of the investigations, which provide the values of the load at first crack (P_{cr}), deflection at first crack load (Δ_{cr}), ultimate load (P_u), deflection at ultimate load (Δ_u) and deflection at failure load (Δ_f). Concrete cracking is challenging to detect, hence the cracking load P_{cr} was calculated by observing the load at the first turning point of the load-deflection curve.



(a) (b)

Figure 4 Comparison of load-displacement graphs of: (a) PCC Slab and (b) RCC slab.

Table 2. Experimental Results of Loads and Deflections.

Model	P_{cr}	Δ_{cr}	P_u	Δ_u	Δ_f
SPWH	24.00	1.40	27.90	1.80	1.90
SPWCH	21.50	0.90	23.40	1.50	1.60
SPWHH	19.50	0.90	22.10	1.30	1.40
SPWSH	17.80	0.60	20.60	1.00	1.30
SRWH	49.10	4.50	73.34	6.57	12.80
SRWCH	43.45	3.13	65.60	4.61	8.80
SRWHH	39.87	2.60	56.87	5.84	9.42
SRWSH	32.58	2.40	45.89	6.48	7.88

The PCC slabs, namely, SPWH, SPWCH, SPWHH and SPWSH have showed linear elastic behaviour up to first crack load of 24.00 kN, 21.50 kN, 19.50 kN and 17.80 kN respectively as shown in Fig. 4(a). As depicted by the crack pattern in Fig. 5(a-d), the slabs exhibited a brittle mode of failure after the first crack. From Fig. 4 as well as Table 2, it can be observed that the slab model SPWCH exhibited greater load carrying capacity than slab models SPWHH and SPWSH. Upon observing the results of the tested slabs, it was discovered that slabs with hole have a lower load-bearing capacity than slabs without hole. The absence of reinforcing material in concrete is primarily responsible for the brittle/sudden mode of failure.

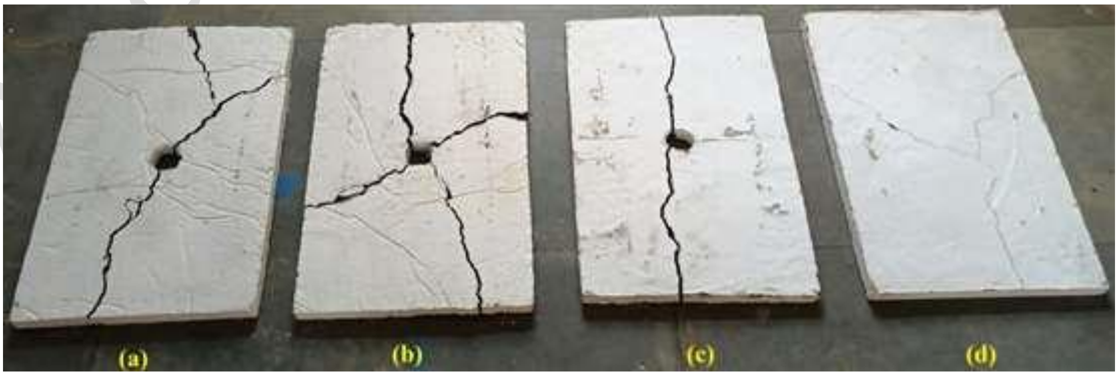


Figure 5. Crack pattern in PCC slab with: (a) hexagonal, (b) square, (c) circular and (d) slab without any opening.

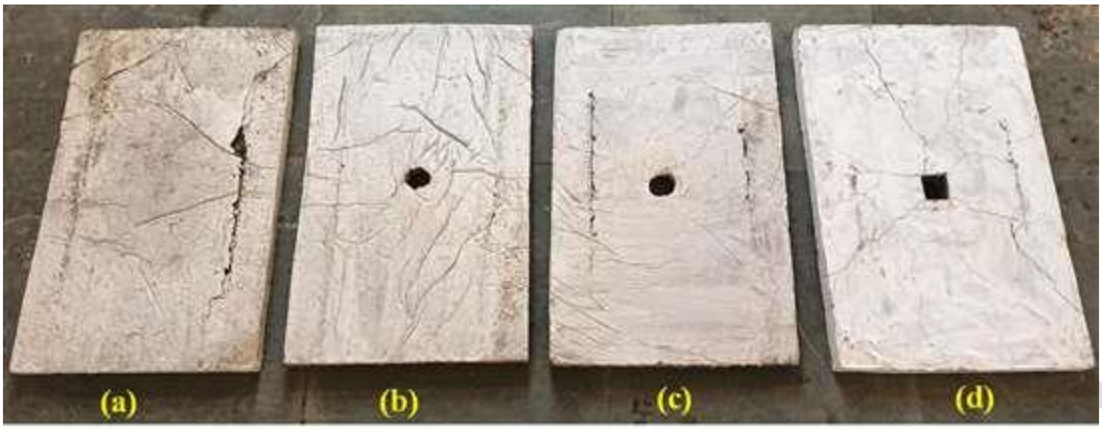


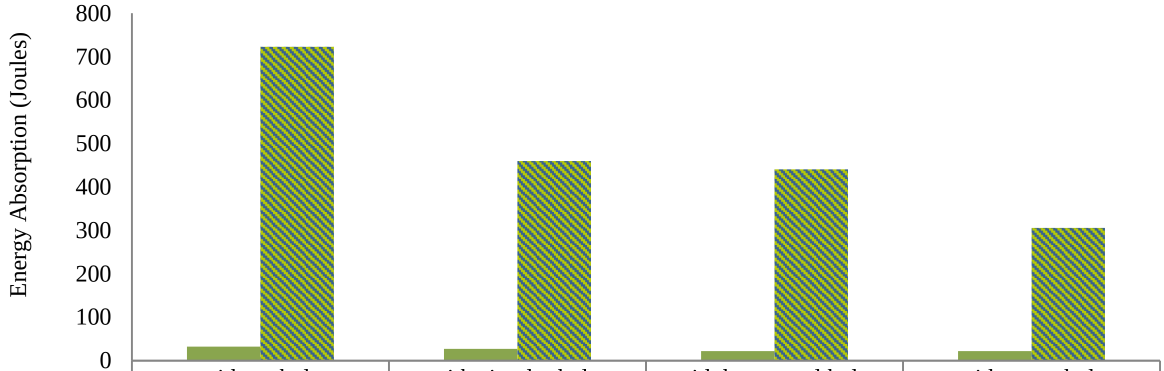
Figure 6. Crack pattern in RCC slab: without (a) opening and with (b) hexagonal, (c) circular and (d) square opening.

As depicted in Fig. 4(b), RCC slabs exhibited linear elastic behaviour until the load nearly reaches a constant value at the onset of the first crack. The reductions in the ultimate load carrying capacity of specimens SRWCH, SRWHH and SRWSH were 10.55%, 22.46%, and 37.43%, respectively, in comparison with the SRWH reference model. Fig. 6(a-d) depicts the crack patterns on the tension face i.e., bottom side of the slabs that led to the failure of RCC slabs. The RCC slabs failed as a result of the bending moment. There was no sign of a catastrophic type of failure. Since the yield strain of the steel in the RCC slab was attained before the failure strain of the concrete. A substantial number of cracks appeared beneath the loads on the specimens bottom surface at first, and then spread towards the supports. Yield lines are formed in the areas with high stress levels when a slab undergoes failure due to loading. The slabs with square holes have sharp edges at the corners of holes where stress concentration is high in compare to circular and hexagonal holes and this causes development of more cracks. It has been observed that the slabs with circular hole showed higher load carrying capacity than the slabs with hexagonal as well as square holes. Hence, the shape of the hole has a significant influence on the load carrying capacity of slabs. However, the areas of the holes in each model remain same. In addition, it must be noted that the maximum deflection occurs in the centre of the slabs.

The crack propagation patterns indeed differ depending on the geometry of the holes. As observed in the study, slabs with square hole exhibited a higher concentration of cracks around the sharp corners of the holes, where stress tends to accumulate, leading to early crack initiation. This sharp corner geometry causes a more pronounced stress concentration, resulting in a larger number of cracks propagating from these points. On the other hand, slabs with circular and hexagonal holes showed a comparatively more uniform crack propagation pattern. Circular holes, due to their rounded edges, tend to have a smoother stress distribution around the perimeter, leading to fewer and less severe cracks. Hexagonal holes, while still exhibiting some stress concentration at their corners, do not result in as severe crack propagation as those with square holes. Regarding the failure mode, slabs with circular holes displayed a higher load-carrying capacity before failure compared to both square and hexagonal holes. This can be attributed to the more evenly distributed stress around the circular hole, which delays crack propagation and allows the slab to withstand higher loads before failure. In contrast, slabs with square holes failed at lower loads due to the higher stress concentration at the sharp corners, which accelerates crack formation and growth.

5.2. Energy absorption

The area under the load deflection curve was used to calculate the value of energy absorption (see reference Dey et al. 2019). The energy absorption values of all the tested models are shown in Fig. 7. It has been observed from the same figure that the energy absorption values are much greater in case of RCC slab specimens compared to PCC slabs. On the other hand, ductility is the capacity of a structure to withstand inelastic deformation prior to collapse. Higher energy absorption by a structure represents the higher ductility. Therefore, the ductility was found maximum in the RCC slab categories specimens compare to PCC slabs. From Fig. 7, it can be noticed, that the SRWHH and SRWSH models the energy absorption were decreased by 4.09%, and 33.55%, respectively, in comparison with the SRWCH model. It is required to mention that the slabs with holes have a lower energy absorption values than slabs without holes.



	without hole	with circular hole	with hexagonal hole	with squre hole
PCC slab	31.82	27.3	21.93	21.75
RCC slab	722.91	459.64	440.85	305.39

Figure 7. Energy absorption.

Furthermore, slabs with higher load-carrying capacities tend to absorb more energy, as they can undergo greater plastic deformation before failure. This was observed in RCC slabs, which showed both higher load-carrying and energy absorption capacities compared to PCC slabs. However, the relationship is not always linear, as factors such as holes shape, size, and crack propagation can influence energy absorption. Slabs with holes, despite lower load-carrying capacities, can still absorb significant energy due to their deformation characteristics.

6. Conclusions

In this experimental investigation, eight different configurations of one way slabs, namely, PCC and RCC slabs with and without holes were tested under concentrated load. The load versus mid span deflection response curve, load carrying capacity, failure modes and energy absorption capacity were investigated and considered as indicators of structural slabs performance. Based on the investigation, the following conclusion can be drawn:

- Slabs with holes have a lower load-bearing capacity than slabs without holes in both the PCC and RCC cases. Moreover, the shape of the holes has a significant influence on the load carrying capacity of slabs. The reductions in the ultimate load carrying capacity of reinforced concrete slab with circular, hexagonal and square holes were found 10.55%, 22.46%, and 37.43%, respectively, in comparison with the slab without hole considered as a reference model.
- The absence of reinforcing material in concrete slab is primarily responsible for the brittle mode of failure. However, the catastrophic type of failure can be avoided in case of RCC slabs with and without holes.
- The slabs with square holes experiencing more cracks compare to circular and hexagonal holes present in the slabs because of high stress concentration in those sharp edge corners of the square holes.
- The energy absorption values are much greater in case of RCC slab with and without hole specimens compared to PCC slabs. The slabs with circular hole showed greater energy absorption capacity than the slabs with hexagonal as well as square holes. The reductions in energy absorption of 36.42%, 39.02% and 57.76% were observed in reinforced concrete slabs with circular, hexagonal, and square holes, respectively, compared to the reference model.

Based on the study, the following recommendations for the design and placement of holes in slabs can be made:

- Shape - Circular openings are preferred due to more uniform stress distribution.
- Edge Treatment - Round or chamfer edges to reduce stress concentrations.
- Placement - Avoid placing openings in high-stress area such as near supports.

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Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability Statement

All data generated during the study appear in this article.

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