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Shear performance of high-strength flat slabs with service ducts

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ABSTRACT

This study aims to experimentally investigate the two-way shear performance of high-strength concrete flat slabs containing integrated ducts. A total of eight slab specimens containing ducts were manufactured, along with one solid slab functioning as the reference. The experimental program focused on two primary parameters: the horizontal distance of the duct opening from the column face (evaluated at 0, 50, and 100 mm for 50 × 50 mm and 50 × 150 mm openings) and the effect of duct width (evaluated at 50 and 150 mm). The performance of slab specimens was adversely affected by increases in duct width and nearness to the column face. As the duct width expanded from 50 mm to 150 mm, an apparent reduction in load capacity occurred, peaking at 43.9% at the column face. Similarly, closer placement of the duct led to a steeper reduction. Serviceability decreased considerably, with specimens having wider ducts at 0 mm or 50 mm often failing to reach the service load. In contrast, those at 100 mm experienced excessive deflection, up to 94% higher than the control, indicating a severe loss of stiffness. Toughness consistently declined, with a maximum reduction of 51.9% at the column face. It was observed that all slab specimens, even the solid control specimen, exhibited the same failure mode, known as punching failure.

1. Introduction

Reinforced slabs that lack beams or girders are referred to as flat slabs, and their behavior, whether one-way or two-way, depends on the ratio between the short and long span lengths. The load is transferred directly to the column, as the slab rests directly on it. Slabs of uniform thickness, devoid of column capitals or drop panels, are also known as flat plates [1]. Concrete buildings utilizing flat slabs are a widely adopted form of reinforced concrete construction, particularly prevalent in medium-height office structures. In recent decades, reinforced concrete structures featuring flat slabs have evolved into a prevalent and practical option for residential and commercial buildings worldwide, owing to their numerous benefits. The essential aspect in the construction of reinforced concrete flat slabs lies in the column–slab connection, which must provide sufficient deformation capacity and resistance to punching shear in the connection zone [2, 3]. Flat slab systems are also widely employed in institutional buildings such as schools, hotels, and hospitals. They allow for quick and easy formwork preparation, facilitating efficient concrete casting and construction. The use of flat slab systems shortens the construction process by enabling the application of extensive table formwork [4]. Punching shear failure is a critical issue in flat slabs, primarily caused by high stress concentrations surrounding column connections, resulting in a brittle failure mode in cone-shaped areas that happens without sufficient alert [5–7]. Once initiated, punching failure results in a complete loss of shear capacity at the slab-column connection, leading to rapid slab separation and posing a significant threat to the integrity of the structure [8]. The absence of beams allows for reduced story heights, which in turn lowers costs related to cladding runs, vertical partitions, mechanical systems, piping, and other construction elements, most notably in buildings with medium or high rises. This system saves roughly 10% of the vertical structural members and contributes to a reduction in foundation loads. Generally, flat slab systems provide flexibility in partition placement and facilitate easy access for maintenance and repair activities [9]. However, flat slab systems are also afflicted with several structural issues. The absence of deep beams or shear walls results in limited transverse stiffness, which can lead to substantial lateral displacements that damage non-structural components, even in moderate earthquake events. The systems are also susceptible to brittle punch-through failures due to the shear forces and moment imbalances that occur between slabs and columns [10]. Over the past two decades, concrete technology has made substantial progress, enabling the production of mixes with compressive strengths exceeding 100 MPa using conventional materials [11]. In particular, high-strength concrete (HSC) is appropriate for structural elements subjected to high compressive stresses, such as deep beams, arches, shells, and folded plates [12–14]. It enables the reduction of cross-sectional areas, thereby optimizing space utilization and decreasing material consumption [15]. To preserve the functional advantages of flat slab systems, building services should be constructed within the slab thickness, thereby minimizing the need for ceiling drops and unused space [16, 17]. Such integration promotes a more environmentally sustainable and economical construction strategy by diminishing the consumption of natural resources and energy in buildings with multiple stories. Moreover, the thermal mass of concrete enables the integration of heating or cooling pipes inside the slab [18]. Although the building codes recommended that the incorporated ducts should not pass through the critical sections, and their height should not be greater than 1/3 of the slab thickness. In practical applications, these services are frequently situated adjacent to the connections between slabs and columns in flat slab systems, and the required duct depth sometimes exceeds the code's limit. The two-way shear performance of high-strength reinforced concrete (HSRC) flat slabs containing built-in ducts represents a key factor in contemporary structural systems with multiple stories and long spans.

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Nomenclature

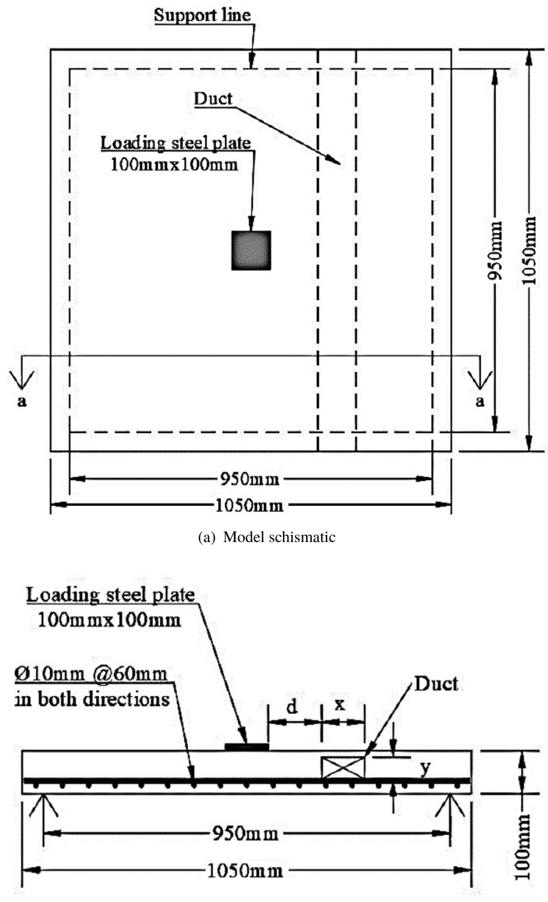
d	Horizontal distance between column and duct	SC	Control specimen
HSC	High-strength concrete	SCC	Self-compacting concrete
NSC	Normal-strength concrete	w/c	Water cement ratio
Pu	Ultimate load	x, y	Duct dimensions ($Width \times Height$)
S	Slab specimen	Δs	Service deflection

Although ducts fulfill essential roles in mechanical, electrical, and plumbing (MEP) systems and post-tensioning applications, they interfere with internal stress distribution and reduce the effective concrete cross-section, possibly impairing shear resistance. Despite the improved compressive strength and durability offered by high-strength concrete (HSC), its inherent brittleness and limited post-cracking ductility may diminish shear capacity. Thus, investigating the influence of duct positioning and width on punching shear capacity and establishing adequate detailing strategies is essential to ensure the structural integrity [19–21]. Hallgren, 1998 [21] investigated the impact of concrete made from high-strength HSC (60 to 120 MPa) on the structural performance of slabs supported by columns, focusing on both strength and deformation. The slabs had been the same in size and shape as slabs of normal-strength concrete (NSC) ($f'c = 28.9\ MPa$) that had been tested earlier. Based on the findings, all test slabs failed due to punching shear. The punching shear strength of the slab was approximately equal to that of identical slabs made entirely of HSC and was about 60% higher than the punching shear strength of the identical NSC slabs. Kim, 2006 [22] tested the internal connection between columns and slabs using concrete with high strength, while subjected to lateral and vertical monotonic loads, to assess its capacity and performance. It was determined that the shear capacity of the column-slab joint using 70 MPa grade of concrete at high strength was evaluated to be safe, similar to that of the case using normal-strength concrete, under Building Code Requirements for Structural Concrete (ACI 318-99) and Commentary. The cumulative energy dissipation amount remained almost constant until the horizontal displacement reached 1%, after which the amount of slab reinforcement increased. The vertical load applied to the slab decreased, resulting in a higher value as the horizontal displacement increased. Ammash et al., 2012 [23] proposed a novel, easy, precise equation to evaluate the punching shear resistance of beamless slabs made with high- and normal-strength reinforced concrete. The punching shear strength calculation using the suggested equation has been compared to experimental findings from fifty-eight case studies. The proposed equation considered various factors, including the compressive strength of the concrete, the depth of the slab, the percentage of tension reinforcement in the slab, and the position of the critical section. The results demonstrated that the proposed equation is a straightforward yet accurate formula for determining the punching capacity of concrete, regardless of whether it is regular or high-strength. y. The increase in compressive strength of concrete leads to a rise in concrete punching strength. The increase in thickness of the slab increases its punching capacity. As the thickness of the slab increases from 75 mm to 300 mm, the increase is approximately 600%-700%. Abdollahi et al., 2017 [24] investigated the performance of flat slabs constructed with reinforced concrete that had an opening, dividing them into two groups: the first fabricated using HSC (approximately 130.1 MPa) concrete and the second using NSC (approximately 35.9 MPa) concrete. The findings revealed that the inclusion of concrete with high strength in the laboratory model contributed to a substantial increase in the maximum load, a slight rise in the final deflection, and an improvement in the ductility of the sample. The influence of using concrete with high strength on the increase in maximum load and vertical displacement for the slab that has a larger opening was more significant than for the slab with a narrower opening. The generality of the gain in the maximum load in the investigation was attributed to the slab having square holes, resulting in an 86.33% increase. High-strength concrete had a greater effect near the column. Mehdi & Al-Tameemi, 2024 [25] examined seven lightweight concrete flat slabs to investigate the influence of having inset pipes horizontally extending through these slabs throughout their thickness on the punching shear capacity. The findings showed decreases in punching shear of 28%, and 15% compared to the control specimen, when the duct neared the loading zone for specimens having 0 *mm*, and 50 *mm* distances from the loaded zone, in that order. Replacing the lightweight concrete with high-strength concrete surrounding the pipelines led to improvements in the ultimate load values by 25% and 10% for models with ducts situated at 0 *mm*, and 50 *mm* from the loaded zone, respectively. Al-Bahrani & Al-Tameemi, 2025 [?] conducted an experimental program in the present investigation to study the influence of utilizing a hybrid concrete section on the punching shear behavior of normal concrete flat slabs with integral pipelines. They found that using 48 *MPa* strength concrete instead of 25 *MPa* concrete in the region around the pipelines led to an enhancement in the punching shear strength up to 25%, compared to the control specimen. Furthermore, the use of the hybrid section was diminished as the pipeline moved away from the loaded area. The current investigation presents a novel experimental exploration of the two-way shear performance of high-strength reinforced concrete flat slabs equipped with ducts integrated throughout the slab thickness. In contrast to prior studies that have predominantly investigated standard concrete or flexural behavior, the present study explicitly evaluates the impact of duct position and width on punching shear resistance. The incorporation of service ducts within high-strength concrete slabs leads to complex stress redistributions and underlying shear weaknesses that remain largely unexplored in published studies. The outcomes provide valuable evidence on how the positioning of constructed ducts affects both the load-carrying capacity and serviceability capacity of high-strength flat slabs.

2. Experimental Setup and Preparation

2.1 Specimens

In the present study, each slab specimen was similar in dimensions, with a thickness of 100 *mm* and a size of 1050 *mm* by 1050 *mm*. A steel plate, shaped like a square with 100 *mm* on each side, was located in the center of the upper surface, where the load was applied. By utilizing this setup, the column load action was simulated, a crucial part of the investigation. Each slab specimen features the same reinforcement for the tension region, which consists of steel bars spaced evenly in two directions, arranged at 60 *mm* intervals in the bottom part of the slab, and includes a 15 *mm* concrete cover overlay, as shown in Fig. 1.



(a) Model schismatic

(b) Cross-Section a-a

Figure 1. Dimensions of the tested specimen and details of reinforcement.

To prevent flexural failure and ensure appropriate behavior during shear failure caused by punching, the specimens were designed under the guidelines outlined in the ACI 2019 code. In Fig. 1, the duct geometry and position within the slab are readily apparent. Although all slab specimens have consistent dimensions and reinforcement setups, each displays a unique geometric layout. This characterization was purposeful, as the specimens were intended to examine how punching shears perform under various conditions. A labeling system was established to facilitate the recognition of essential attributes of each specimen. Inbuilt slab specimens are distinguished by the tagging system $S.y.x.d$, which takes into account their geometric characteristics of ducts. In this format, (S) refers to a slab specimen, (y) indicates the height of the duct in centimeters, (x) represents the width of the duct in centimeters, and (d) signifies the horizontal distance between the column face and the corner of the duct, likewise in centimeters. Using such a simplified procedure is beneficial for a precise and reliable distinction between different slab types, thereby facilitating comparisons more efficiently. Table 1 illustrates the details of the specimens tested for the current study. Using two variables, distance from the column face and duct width, a parametric study evaluated the behavior of flat slab specimens with prefabricated ducts. Based on these parameters, the two-way slab specimens were grouped and arranged as illustrated in Table 1. The first investigated variable was the distance of the duct opening to the face of the column, which consisted of three horizontal distances: 0, 50, and 100 *mm*. Evaluations were conducted on duct sizes of 50×50 *mm* and 50×150 *mm*. The second variable was the width of the duct, for which three width values were adopted, namely 50, 100, and 150 *mm*. Additionally, this parameter was evaluated at two different positions: 0 and 50 *mm* from the face of the column.

2.2 Test Setup

In this experiment, slab specimens were mounted on a rigid steel frame with dimensions of 1050×1050 *mm*. An existing steel frame was fitted to the specimen's dimensions, ensuring a simple support system for testing. Tests were conducted on every slab specimen using a hydraulic jack that can handle loads of up to 2000 *kN*. Loads have been exerted on the steel plate placed on the middle upper face of the slab specimens. This plate had dimensions of 100×100 *mm* and a thickness of 20 *mm*; precision cut to guarantee accuracy in dimensions. Using this approach, a concentrated load is imposed centrally on the steel plate and then transmitted over to the slab. At each step, the specimen response was tracked and documented by measuring and reporting the corresponding deflections induced by the load at incremental steps of 5 *kN*. Under the slab tension surface, a dial gauge was mounted on a steel plate welded to the steel frame. To record the deflections, the dial gauge was set at the middle span length. The path lines were marked by a pen on the bottom face of the slab specimen during loading to follow crack development. Figure 2 demonstrates the supporting and loading of the specimens.

2.3 Materials properties

Casting specimens is carried out using ordinary Portland cement and following the Iraqi Standard Specification I.Q.S. No. 5, 2019 [26].

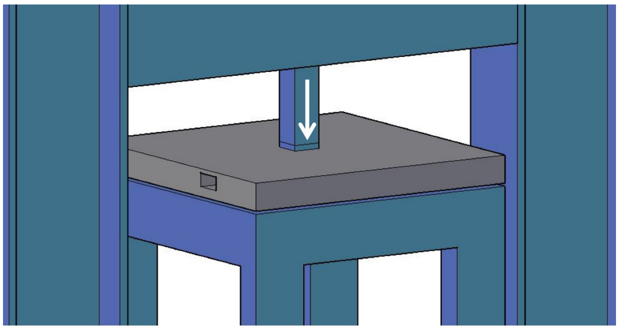


Figure 2. Test setup.

Table 1. Tested specimens with their groups.

Parameters	Specimens	Duct dimension (*mm*)		Horizontal distance to column face (d) (*mm*)
		Duct height (y)	Duct width (x)	
Control	S.C	—	—	—
Distance from column face (x)	Group-1			
	S.5.5.0 S.5.5.5 S.5.5.10	50	50	0 50 100
	Group-2			
	S.5.15.0 S.5.15.5 S.5.15.10	50	150	0 50 100
Height of duct (a)	Group-3			
	S.5.5.0 S.5.15.0	50	50 150	0
	Group-4			
	S.5.5.5 S.5.15.5	50	50 150	50

The fine aggregate used in mixes was sieved to achieve a gradation with a maximum particle size of 4.75 *mm*. The physical, chemical, and gradational characteristics of the fine aggregate comply with the requirements of the Iraqi Standard No. 45/1984 [27]. A regionally accessible coarse aggregate of gravel had been sieved to sizes between 5 *mm* and 14 *mm* and graded to meet Iraqi Specification No. 45/1984 [27]. In the tension regions, the slab specimen was reinforced with steel bars of 10 *mm* diameter. 3 steel bar specimens were tested for tensile strength based on ASTM A615-16 specifications [28]. The yield and ultimate strength for 10 *mm* rebar was experimentally found to be about 520 *MPa* and 650 *MPa*, respectively. High-strength concrete mixes are fundamentally affected by the addition of chemical admixtures, especially superplasticizers, a carefully controlled water-to-cement ratio, and an increase in the amount of cement. As a result of this advanced approach, a more intricate design process is necessary than is usually used when designing conventional normal-strength mixtures. To achieve the desired strength characteristics, several mixes were created at the beginning of the current study, aiming to identify the optimum combinations. During the experiments, it was found that the mix proportion outlined in Table 2 with (w/c) of 0.26 offered satisfactory workability and mechanical characteristics, especially in terms of compressive strength.

Table 2. Mix the proportion of concrete.

Material	Quantity (kg)
Cement	498
Silica fume	049
Fine Aggregate	627
Coarse Aggregate	1100
Superplastizer	09.6
Water	129

In the present work, Hyperplast PC260 was used for each of the tested specimens, aligning with the requirements of ASTM C494-18 [29]. A summary of Hyperplast PC260's features can be found in Table 3. In terms of performance, Hyperplast PC260 is considered a highly effective superplasticizer. To assess the fresh characteristics of the self-compacting concrete (SCC) mix, several standard tests were performed per the instructions of the European Federation of National Associations Representing Producers and Applicators of Specialist Building Products for Concrete (EFNARC) [30]. The chosen tests consisted of the slump flow (EFNARC, 2005), T_{500} time [30], and J-ring test [31], which are commonly employed for evaluating the main rheological properties of SCC: flowability, viscosity, and passing ability, respectively. These factors are essential to ensure that the mix can effectively occupy formwork and flow across reinforcement with no mechanical compaction required, thereby keeping consistency and inhibiting segregation. Testing outcomes are compared with the regulatory limits suggested by EFNARC [30] to ascertain their relevance for in situ application. Test results for fresh characteristics are listed in Table 4. Figure 3 displays the slump flow test and T_{500} test apparatus used.

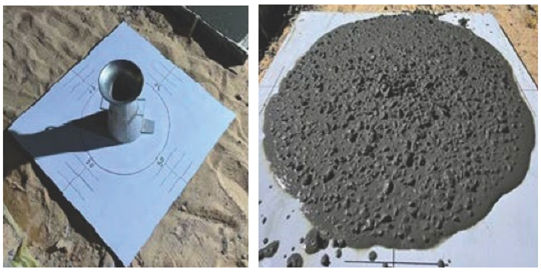
Table 3. Properties of Hyperplastic.

Property	Color	Air entrainment	Specific gravity	Freezing point
Specification	Yellowish to brownish liquid	Typically, less than 2% additional air is entrained above the control mix at usual dosages.	1.1±0.02	≈ −7°C

To evaluate the hardened mechanical behavior of the concrete mix, compressive strength using 150 *mm* cubs [32], splitting tensile strength using 100 × 200 *mm* cylinders [33], and flexural (rupture) strength tests using 100 × 100 × 400 *mm* prisms [34] were performed using a total of three samples for each strength. Testing these properties is essential to determining a material's resistance to axial compression, indirect tension, and flexural stresses, respectively. These values represent the typical performance of the mix based on the three samples. The results for the compressive, flexural, and splitting strengths, in megapascals, were as follows: 105, 8.64, and 4.72, respectively.

Table 4. Fresh properties test results.

Test Type	Results
G-ring	7.8 *mm*
T_{500}	3.6 *sec*
Slump Flow	690 *mm*



(a) Test apparatus (b) Slump

Figure 3. Slump flow and T_{500} test apparatus.

3. Result And Discussion

3.1 Experimental Results and Performance Metrics

Loadings were applied to all slab specimens until failure. Load data were collected at each step to determine the relationship between load and mid-span vertical displacement. Using recorded data, the cracking load and load capacity were calculated, while service deflection and toughness were computed based on these values. Each slab specimen was compared to a reference load equivalent to 65% of the ultimate load of the control specimen (0.65 *Pu* of *SC*) to evaluate its service performance [35]. Deflections at mid-span were compared. The procedure enabled direct comparison of deformation behavior across duct configurations. The degree to which a material can absorb energy before fracture is referred to as toughness, and this was evaluated in the present investigation. The toughness was evaluated by calculating the area under the load–deflection curve, derived from the experimental data, as described in the manuscript [36]. Table 5 shows the findings and all relevant calculated values for each tested slab specimen.

3.2 Parametric Study

3.2.1 Distance from column face (d)

Group One (with a Duct of 50 × 50 *mm*) In this group of slab specimens, the influence of the horizontal distance between the duct and the column face was investigated, using a duct size of 50 × 50 *mm*. The presence of a duct within the slab thickness resulted in a decrease in load and toughness. At the ultimate stage, the impact of the existence of the duct was more significant and pronounced as it approached from the column face. The ultimate load was reduced by 36.1%, 19.6%, and 16.1% for distances of 0, 50, and 100 4, respectively, relative to the (S.C) control specimen. Figure 4 exhibits the load-to-mid span vertical displacement for all tested slab specimens in the current group of specimens. The service deflection in specimens S.5.5.5 and S.5.5.10 increased by 9.8% and 9.1% compared to the reference specimen S.C. In contrast, specimen S.5.5.0, with a duct located on the column face, failed before reaching the service load limit of the control specimen. Figure 5 shows the influence of distance from the column face on service deflection. The toughness value for slab specimens with duct was lower than that of the control solid specimen, and this impact was more significant at the column face, with a reduction of 51.9%. When moved away from the column face, the reduction was 42% and 26.4% regarding 50 *mm* and 100 *mm* distances, respectively, indicating less impact. This reflects the negative influence of the duct's presence on the slab energy dissipation, where the area under the load to mid vertical displacement curve was reduced more as the duct got closer to the column face. Figure 6 illustrates the relative effect of the presence of the duct compared to the slab control specimen over three distances from the column face on load and deflection. The presence of ducts within a slab decreases the effective cross-sectional area, alters the flow of internal shear stresses, and reduces the moment of inertia, compromising its stiffness and strength.

Table 5. Result of the test and calculated data.

Specimens	Cracking Load (kN)	Service Load (0.65Pu) of SC (kN)	Service Deflection (Δs) (mm)	Ultimate Load (kN)	Ultimate Deflection (mm)	Toughness (kN.m)
S.C	80	182	5.12	280	10.46	1.823
S.5.5.0	30	Failed	—	179	7.37	0.877
S.5.5.5	35	182	5.62	225	7.80	1.057
S.5.5.10	30	182	5.59	235	9.08	1.341
S.5.15.0	20	Failed	—	157	11.63	1.129
S.5.15.5	20	Failed	—	174	12.82	1.379
S.5.15.10	60	18	2 9.94	191	11.62	1.473

This effect is most pronounced near the column face, where stress concentrations are highest and punching shear is a critical concern. However, as the duct is situated farther from the column, its influence becomes less prominent because of lower local stresses. Furthermore, it was also prevalent during the cracking stage because the slab relies on its uncracked concrete section to resist bending and shear in the early loading phase. When comparing the behaviour of the tested specimens with that of the voided slab specimen (S.5.5.0), the load capacity at a distance of 50 *mm* and 100 *mm* was found to be approximately 31.3% and 25.7% better, respectively. The same response was noted regarding toughness, with enhancements of roughly 52.8% and 20.5% for distances of 50 *mm* and 100 *mm* over the slab specimen (S.5.5.0).

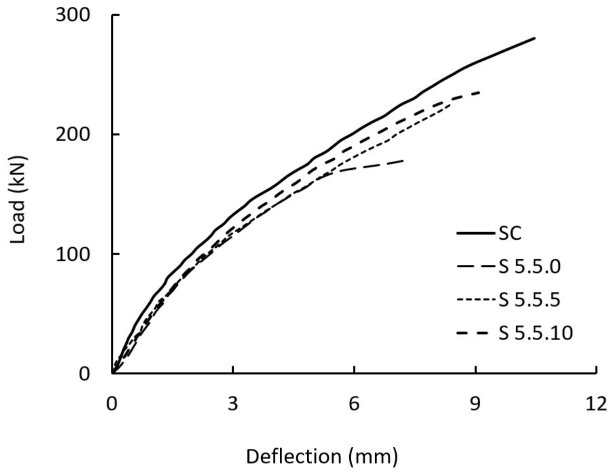


Figure 4. Load-mid span vertical displacement of specimens in Group 1.

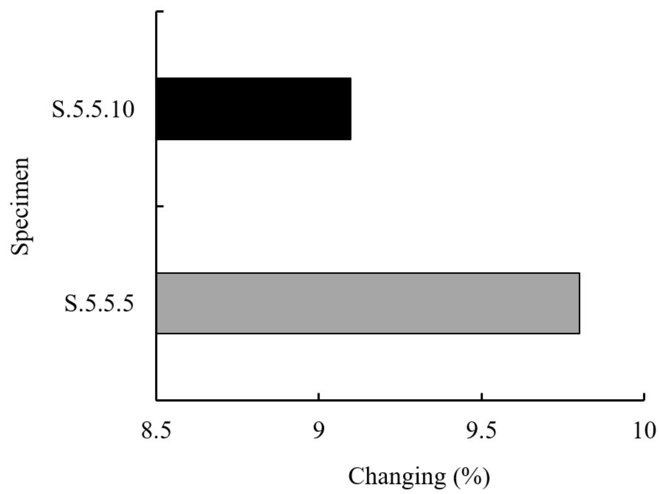
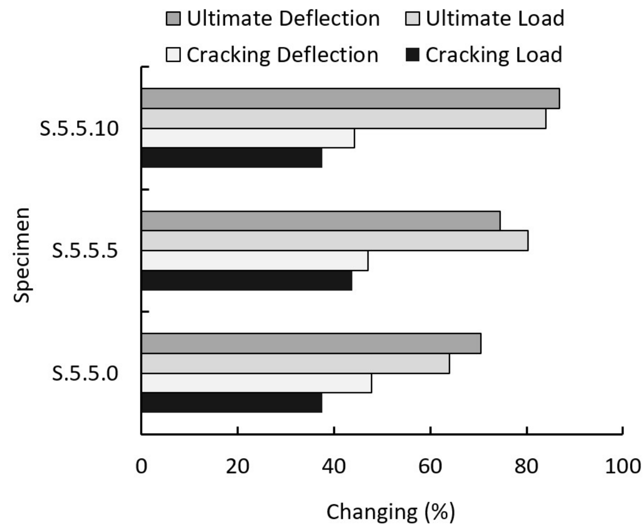
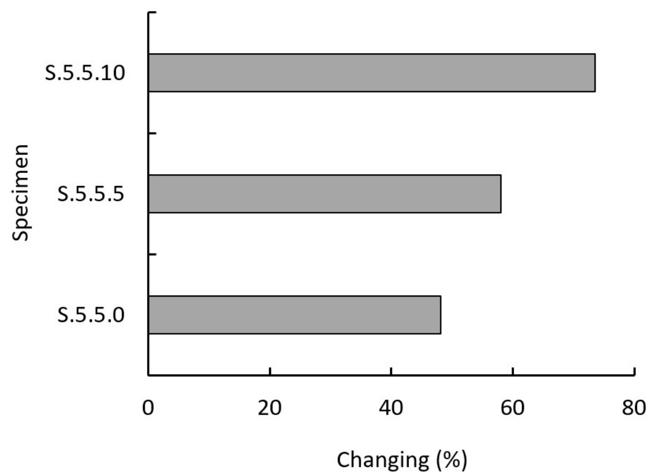


Figure 5. Effect of duct position on service deflection of Group1 specimens compared to S.C specimen.

Group Two (with Duct of 50×150 *mm*) The current group of specimens represents the second, and the influence of the distance between the duct in the slab specimen and the face of the column was examined. Specimens in the current groups were evaluated for slab behavior at three distances in the presence of a 50×150 *mm* duct. As found in the previous three groups, the presence of a duct through the slab thickness adversely impacted the load and toughness of the tested specimens. This effect diminished as it stayed away from the face of the column. The ultimate load was reduced by approximately 43.9%, 37.9%, and 31.8% over three distances between the duct and the column face, equal to 0, 50, and 100 *mm*, respectively, compared to the (S.C) control specimen. Figure 7 exhibits the load to mid-span deflection curve for all specimens tested in group four. The specimens S.5.15.0 and S.5.15.5 did not reach the service load level of the control specimen S.C. However, the specimen S.5.15.10, located 100 *mm* from the column face, recorded a service deflection of 9.9 *mm*, exceeding the value of the control specimen S.C by about 94%. In line with the load behavior, the toughness dropped, and the decline ranged from the most significant decrement at the column face to a smaller one when the duct was farther from the column's face. So, it was observed that the toughness was diminished by 38.1% at the column face ($d = 0$), by 24.3% at a distance of 50 *mm*, and by 19.2% at a distance of 100 *mm*.



(a) Load vs deflection



(b) Toughness

Figure 6. Comparative influence with respect to S.C specimen; (a) on load and deflection, (b) on toughness.

Figure 8 illustrates the relative influence of the duct's existence compared to the slab reference specimen at three different distances from the column face. Including ducts inside the thickness of a concrete slab introduces several structural issues, namely by reducing the effective concrete area and impairing the regularity of stress transfer, most notably in critical zones near the column region. Consequently, the slab loses its shear capacity and flexural rigidity, with the most profound impact occurring at the column periphery where punching shear stresses peak. As the distance from the column increases, the magnitude of these influences lessens due to the decrease in the shear flow. The significance of ducts is more evident during the cracking stage than during the last loading stage, as the slab initially relies on its uncracked concrete section to resist bending. Under early loading, flexural cracks typically form first on the tension face due to tension stresses. On the other hand, shear cracks develop later, and shear stress becomes the dominant factor. Ducts reduce the uncracked concrete area and change stress distribution, so their existence substantially affects the cracking load, where the remaining uncracked concrete section plays an important role. The load capacities of the tested specimens at distances of 50 *mm* (S5.15.5 specimen) and 100 *mm* (S5.15.10 specimen) were approximately 10.8% and 21.7% greater than that of the voided slab specimen (S5.15.0), respectively. A similar trend was seen in toughness, with an improvement of as much as 22.2% and 30.5% at 50 *mm* and 100 *mm* distances compared to the slab specimen (S.5.15.0).

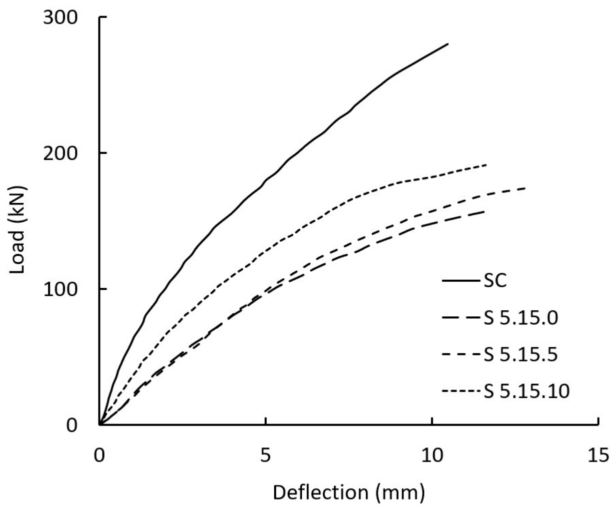
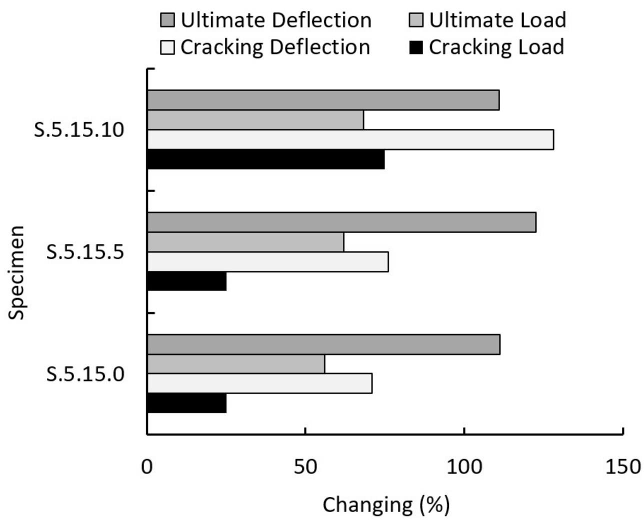
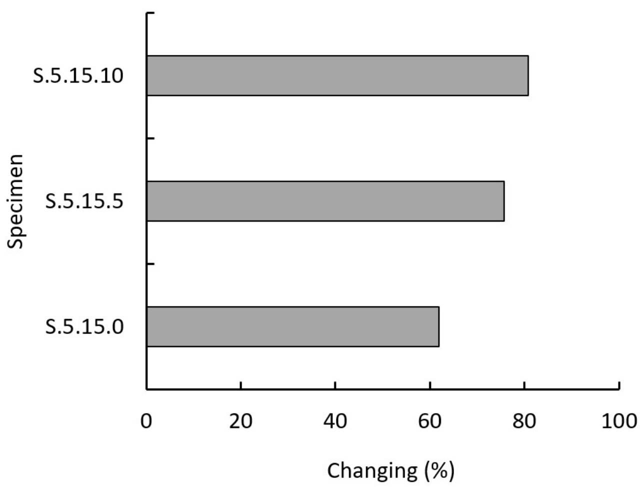


Figure 7. Load-mid span vertical displacement of specimens in Group 2.



(a) Load vs deflection



(b) Toughness

Figure 8. Comparative influence with respect to S.C specimen to the S.C specimen; (a) on load and deflection, (b) on toughness.

3.2.2 Width of ducts (x)

Group Three (Specimens at $d = 0$) The comparison between the behavior of the slab specimens S5.5.0 and S5.15.0 is intended to investigate the influence of duct width constructed through slab thickness adjacent to the face of the column on shear behavior (horizontal distance $d = 0$). When the width of the duct was increased from 50 *mm* to 150 *mm*, the maximum load declined. The maximum load was diminished by around 36.1% and 43.9% as the width was measured by 50 and 150 mm, respectively, compared to the control solid slab specimen (S.C). Figure 9 illustrates the load to mid-vertical displacement curves of these slab specimens. Not all specimens have attained the control specimen's service load limit, which suggests they were weak.

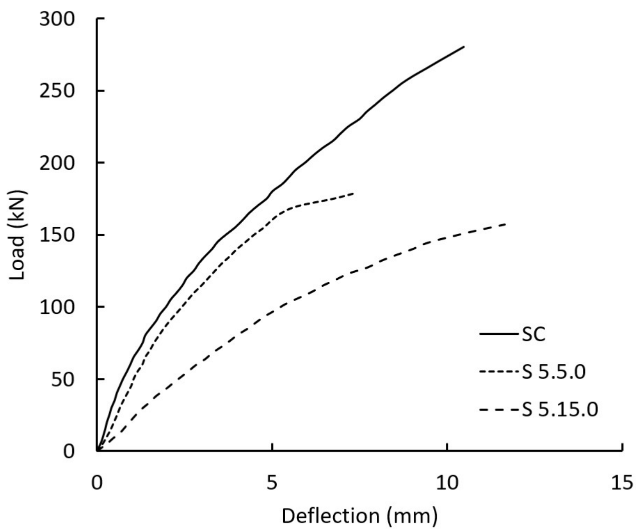
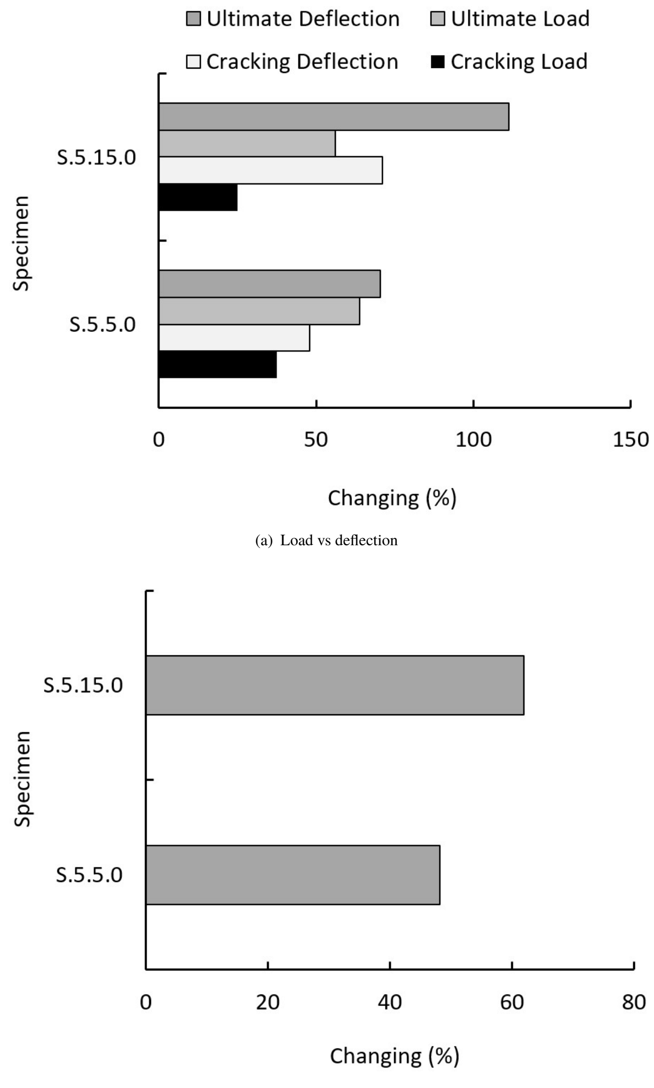


Figure 9. Load-mid span vertical displacement of specimens in Group 3.

This indicates that the presence of ducts weakened the slab's capacity to carry service loads. The duct width has considerably influenced the toughness value. The toughness was decreased; however, compared to the reference solid slab specimen (S.C), the increase in width does not result in a direct proportional decrease in toughness. The result revealed that the specimen (S5.5.0) with a 50 *mm* duct width suffered from the most significant drop in toughness by 51.9%. Furthermore, the other slab specimen with a duct width of 150 *mm* in specimen S5.15.0 shows a relatively close decline in toughness by approximately 38.1%. The increase in the toughness S5.150.0 can be considered an incorrect indication because the two specimens exhibited weaker stiffness and failed before reaching the service load level of control specimen due to the presence of the large ducts. Therefore, it produced greater deflection, even in the early loading stage, which made the toughness seem larger. Figure 10 demonstrates the relative influence of the width of the duct compared to the solid slab reference specimen (S.C) at different values. The influence of duct width was likewise investigated compared to the slab specimen with a smaller duct width (S.5.5.0) to get a more comprehensive evaluation of shear behavior under increasing duct width. It was discovered that increasing the duct width from 50 *mm* and 150 *mm* led to a drop in load capacity equal to 12.3%. Based on the findings, increasing the duct width noticeably reduces the maximum load the slab can sustain. This reduction can be attributed to the disruption of the internal load path and the reduced effective concrete area, which weakens the slab's resistance to shear forces. Conversely, the increased deflection in the wider-duct specimens could indicate a more prolonged failure process, although accompanied by a lower load capacity. Toughness was also negatively affected by the presence of ducts. When the duct width was increased to 150 *mm*, and compared to the slab specimen with a 50 *mm* duct width as the baseline, a further decline in load capacity was observed, confirming that larger duct openings weaken the slab's shear resistance progressively. Interestingly, in this specific comparison, the specimen with 150 *mm* duct showed a higher toughness value compared to the 50 *mm* duct specimen. This indicates that although the overall toughness was still lower than in the solid slab.

3.3 Group Four (Specimens at $d = 50$ *mm*)

According to the current group of specimens, the shear performance of slabs containing duct in three distinct width values was studied. These specimens involved a duct with a slab thickness designed to assess the duct width at a distance equal to 50 *mm* between the duct and the column face. Changing the width of the duct to be larger in the 50 and 150 *mm* range contributed to reducing the ultimate load.



(a) Load vs deflection

(b) Toughness

Figure 10**.** Comparative influence with respect to S.C specimen; (a) on load and deflection, (b) on toughness.

The ultimate load in the tested slab specimens lowered by about 19.6% and 37.9%, corresponding to specimens measuring a width of 50 and 150, in that order, relative to the reference solid specimen (S.C). Figure 11 clarifies the load-to-mid vertical displacement curves for slab specimens of the current group. Between the two specimens in the current group, only specimen S.5.5.5 reached the service load of the S.C specimen with a service deflection of 5.6 *mm*, with an increase against the S.C specimen of around 9.8%. In contrast, the other specimen S.5.15.5 did not get that. The specimen with a larger duct width of 150 mm in the S.5.15.5 specimen experienced a diminishing toughness of 24.3% relative to the control specimen SC; however, it does not represent the lower value. The increase in the toughness of S5.15.5 may be considered a misleading indication because the specimen demonstrated lower stiffness due to the presence of a large duct. Consequently, even in the early loading stage, a greater deflection occurs, making the toughness appear larger. Figure 12 displays the relative effect of the duct width relative to the solid slab reference specimen (S.C) at three distinct values. The effect of duct width was similarly examined by comparing it to the value of the slab specimen having a narrower duct (S.5.5.5) to obtain a more in-depth understanding of shear performance when duct width increases. Extending the duct width to 150 *mm* caused a reduction in load capacity of 22.7%. The experimental results suggest that increasing the duct width through the slab section negatively impacts its shear performance compared to the solid reference slab, with wider ducts leading to more significant reductions. This behavior is linked to the reduced effective cross-sectional area and the disruption of internal load paths caused by the voids created by the ducts. Variations in duct width also influenced the slabs' deflection behavior.

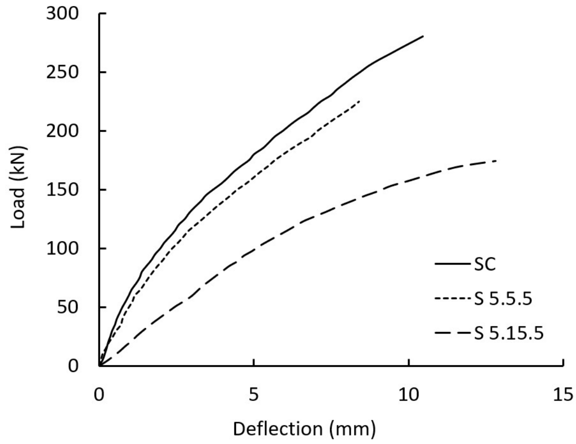
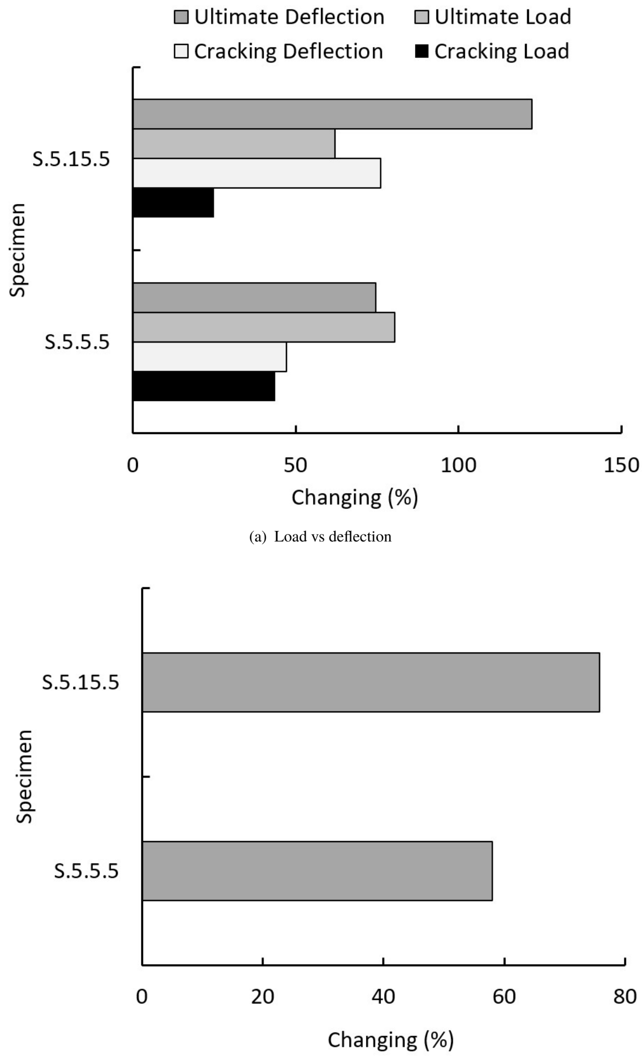


Figure 11**.** Load-mid span vertical displacement of specimens in Group 4.



(a) Load vs deflection

(b) Toughness

Figure 12**.** Comparative influence with respect to S.C specimen; (a) on load and deflection, (b) on toughness.

However, this increase in deformation did not translate into improved structural performance, as it remained associated with a reduced load-carrying capacity. The toughness of all ducted specimens decreased compared to the solid control. The reduction was most pronounced in the slab with 50 *mm*. Although the specimen with the 150 *mm* duct seemed to exhibit comparatively higher toughness among the ducted slabs, it still demonstrated inferior energy absorption when evaluated against the solid reference slab. These results confirm that increased duct width compromises strength and toughness.

4. Conclusion

The present study gives rise to several discernible conclusions, encapsulated succinctly in the following points:

The existence of a 50×50 *mm* duct slab specimen markedly diminished load capacity, particularly as the duct approached the column face, where the load capacity was reduced by 36.1% at the column face. The most severe influence concerning serviceability and toughness occurred at a 0 *mm* distance, where the specimen failed to reach the service load limit and exhibited a 51.9% drop in toughness.

Constructing a 50×150 *mm* duct in slabs drastically diminished shear capacity, and this effect was even more adverse as the duct was situated closer to the column face. As the duct was placed on the column face, the ultimate load capacity experienced its steepest reduction, about 43.9%. The column face exhibited a decline in toughness, reaching 38.1%.

The evaluation of specimens with ducts positioned at the column face ($x = 0$) highlights an evident impairment in shear strength as duct width increases. Increasing the duct width from 50 *mm* to 150 *mm* led to an apparent deterioration in load-bearing capacity, with the most severe reduction, 43.9%, recorded for the specimen containing the widest duct. The entire specimens could not reach the reference slab's service-level load threshold, highlighting their weak ability to withstand service-level demands regardless of the duct width.

In slab specimens with ducts positioned 50 *mm* from the column face, shear behavior declined as duct width increased. The ultimate load capacity demonstrated a noticeable decreasing pattern with increasing duct width, reaching its maximum reduction of 37.9% in the specimen with a 150 *mm* wide duct. Only specimen S5.5.5, with a 50 *mm* duct width, satisfied the service load limit with a 9.8% increase in deflection, while the other specimens with larger widths failed to do so.

The presence of ducts significantly affected the serviceability behavior of the slab specimens, with some showing higher mid-span deflections than the control specimen at service load. Conversely, others were unable to support the service load level achieved by the control. Notably, specimen S.5.15.10 demonstrated the most severe drop in performance, recording a deflection of 9.94 mm at service load, equivalent to a 94% rise compared to the control specimen. These findings underscore the detrimental impact of increased duct width on flexural stiffness, as wider or larger ducts compromise structural stiffness and promote excessive deflection under service loading requirements.

It can be concluded that ducts reduce slab capacity by reducing the section area available for carrying load transfers and altering the distribution of internal shear stress. High stress concentrations near the column face likely contributed to an increased vulnerability to punching shear failure. Their impact was less significant when ducts were positioned farther from the column, perhaps due to less localized stresses.

During the initial loading phase of the slab, the uncracked concrete section primarily resists bending due to the presence of the duct. Cracks usually appear on the slab's lower surface in the region furthest from the column as the slab bends under load. The first cracks to appear are bending cracks, followed by shear cracks. Consequently, cracking in a slab affected by a duct inside its thickness is significant.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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