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Review Article

Behavior of Normal Reinforced Concrete Two-Way Slabs with Openings: A Review

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Abstract

The structural performance of two-way reinforced concrete slabs is significantly influenced by the presence of openings, which are frequently required for functional elements like staircases, lift shafts, and utility ducts. These apertures diminish slab stiffness and affect punching shear strength due to their size and placement. This review integrates experimental, analytical, and computational analyses to assess the influence of slab openings on structural performance. It discusses essential factors, including opening dimensions, configuration, positioning, and reinforcement techniques. The predicted reliability of design codes, such as ACI 318-19 (American Concrete Institute), Eurocode 2, and fib Model Code, is demonstrated, with an emphasis on their limitations in addressing opening effects. The results demonstrated that apertures adjacent to columns markedly reduce punching shear resistance by interrupting the critical shear perimeter and exacerbating stress concentrations. Nevertheless, the strategic positioning of reinforcements and the optimization of opening layouts alleviate these consequences. This literature review highlights the need for enhanced design specifications to guarantee safety and performance in reinforced concrete slab systems with apertures.

1. Introduction

Two-way reinforced concrete (RC) slabs are a category of RC plates that demonstrate structurally intricate behavior. The concurrent tolerance of flexural and torsional moments, along with the manifestation of curvature in several directions, complicates the analysis of these behaviors of these structures [1-2].

In a construction, the necessity for an aperture in the slab for architectural elements, staircases, lift shafts, pipelines, and utility ducts is unavoidable. The openings, to some extent, reduce the rigidity of the roof system and collapse load due to their proportions in relation to the slab dimensions [3]. Punching shear must be meticulously assessed during the design phase, ensuring that all designs prioritize safety. Nevertheless, because of insufficient experimental data, the impact of slab openings on punching shear behavior was either overlooked or addressed using approximate methods [4].

The [5] recommended that openings of any dimension are permissible in slab systems if analysis demonstrates compliance with all strength and serviceability criteria, including deflection restrictions as shown in Figure 1, and as follows:

Openings shall be allowed in slab systems devoid of beams in accordance with (a) through (d):

a) Openings of any dimension are allowed in the area shared by intersecting middle strips; nevertheless, the overall amount of reinforcement in the panel must meet or exceed the requirements for a panel without openings.

b) In two intersecting column strips, apertures shall not exceed one-eighth of the width of the column strip in either span. A quantity of reinforcement at least equivalent to that disrupted by an aperture shall be incorporated on the sides of the opening.

c) At the junction of one column strip and one middle strip, no more than one-fourth of the reinforcement in either strip shall be disrupted by apertures. A quantity of reinforcement at least equivalent to that disrupted by an aperture shall be incorporated on the sides of the opening.

d) If an opening is situated within 4h (h is the thickness of the slab) of the edge of a column, concentrated load, or reaction area, the segment of b_o (perimeter of critical section for two-way shear in slabs and footings, mm) enclosed by straight lines extending from the centroid of the column, concentrated load, or reaction area and tangent to the opening's boundaries shall be deemed ineffective.

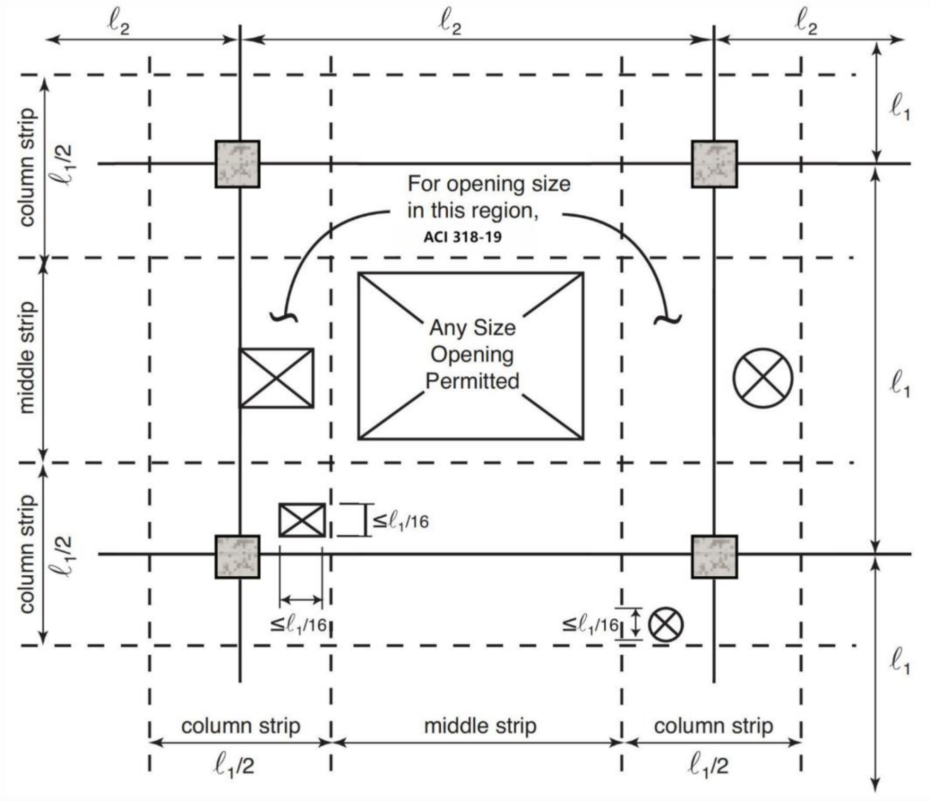


Figure 1. Suggested opening sizes and locations in flat plates with $l_2 \geq l_1$ [5].

In addition to flexural requirements, the aperture must be placed within a column strip of a flat slab or within 10 times the thickness of the slab from a load or reaction zone that is concentrated. This will cause the slab's shear strength to decrease. The impact of the slab opening is assessed by decreasing the perimeter of the critical section b_o by a length equivalent to the projection of the aperture, defined by two lines running from the centroid of the column and tangent to the opening, as illustrated in Figure 2(a). Slabs equipped with shear-heads, which facilitate the passage of slab shear to the column, mitigate the impact of the opening, resulting in b_o a reduction of to just half the length defined by the tangential lines, as shown in Figure 2(b).

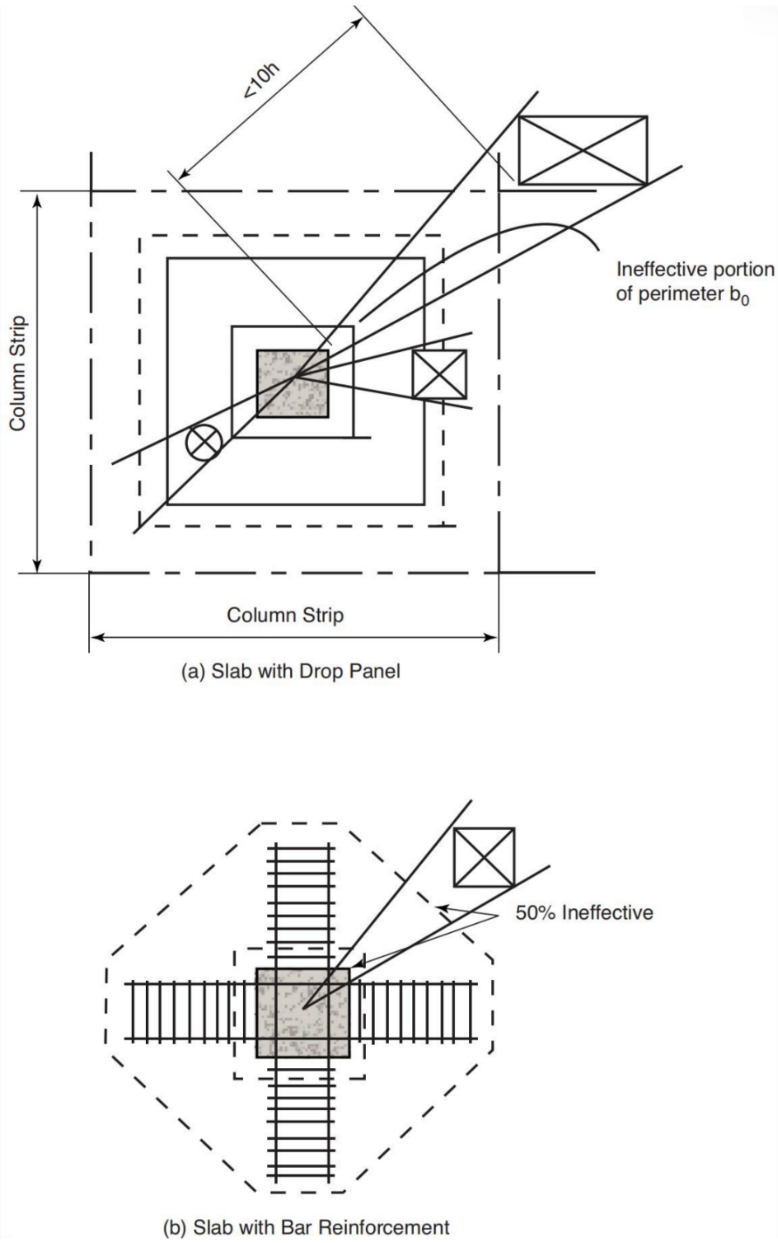


Figure 2. Reduction to perimeter of critical section b0 for a flat plate or flat slab with openings in column strips or within a distance of 10 times the thickness of the slab from a column: (a) no shear-heads; and (b) with shear-heads [5].

The existing design guidelines for punching shear aimed to correlate the impact of openings on a slab's ultimate capacity according to their dimensions and positioning by diminishing the control perimeter. ACI 318 [5] and fib Model Code [6] established the critical shear perimeter at a distance of d/2 from the loaded region (column), whereas NBR 6118 [7] and [8] define the control perimeter at a distance of 2d from the column's face, with d representing the effective depth of the slab. The [8], fib Model Code [6], and NBR 6118 [7] defined the control shear perimeter as having circular ends, but [5] used a rectangular configuration for the critical shear perimeter as illustrated in Figure 3. All design regulations diminished the critical shear perimeter according to the dimensions and position of the aperture, wherein a segment of the control perimeter situated between two tangents drawn from the column's center to the opening's outline is deemed ineffective. The control perimeter was decreased only if the distance between the column perimeter and the opening edge complies with the values specified in each design code.

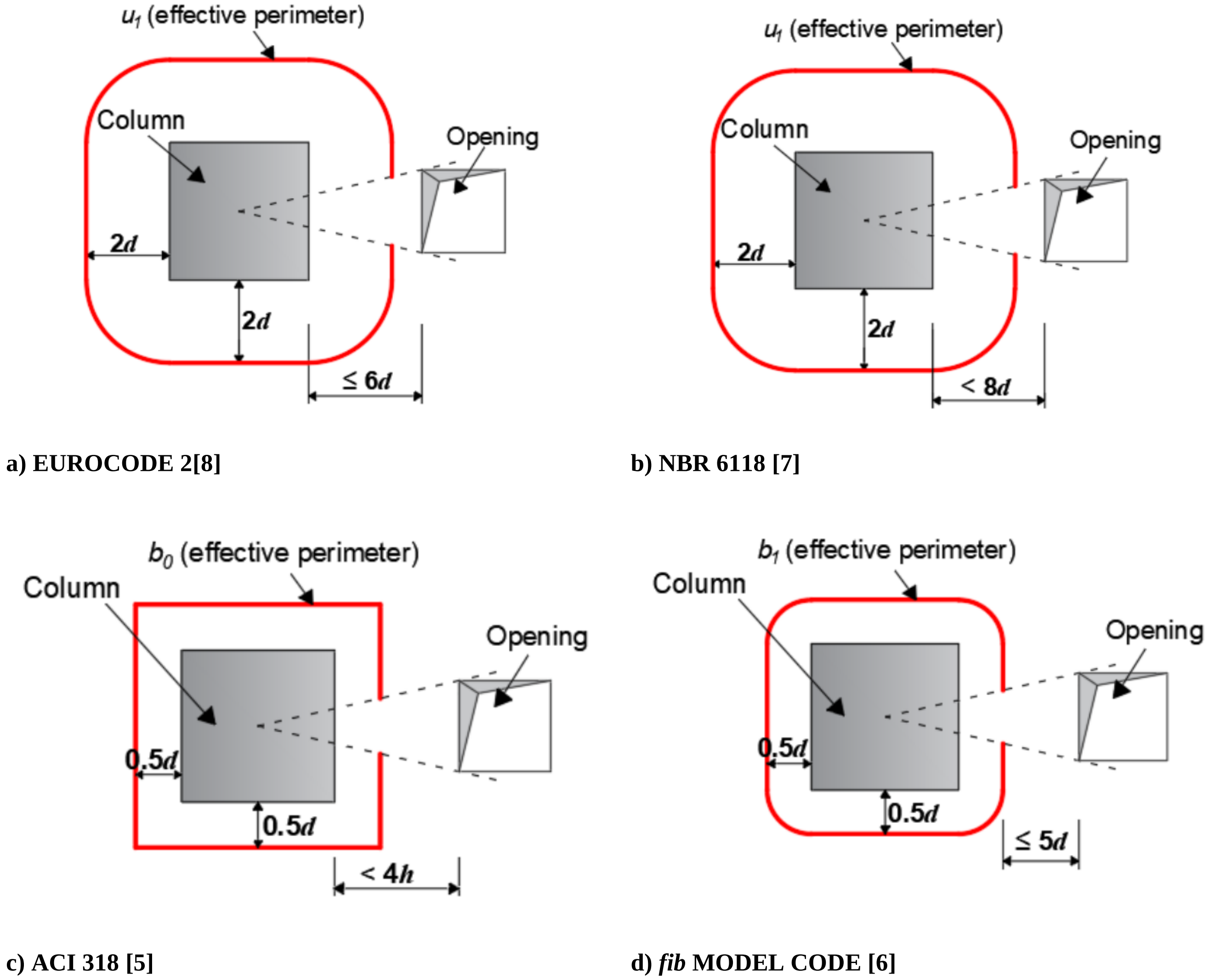
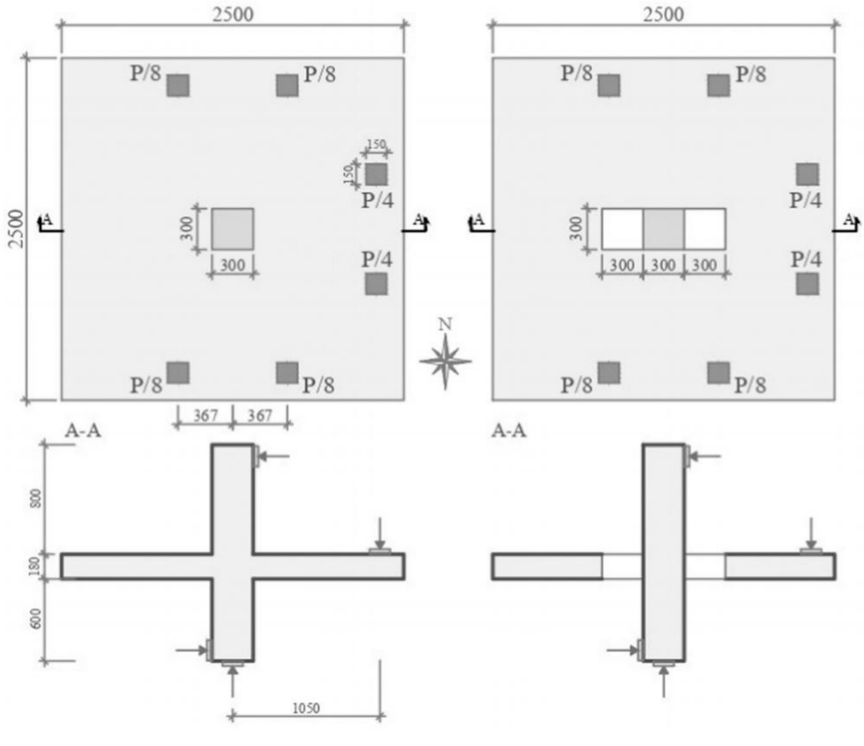


Figure 3. Effective control perimeters according to different codes [9].

2. Opening Effects on Two-Way Slab-Column Connections

The placement of openings in proximity to slab-column connections is a prevalent practice in flat slab architecture, owing to many benefits for technical installations. This location, however, conflicts with the most critical area of the slab, where punching shear failures may occur and often dictate the design at the ultimate limit state.

According to the [10] conducted a comprehensive testing program on five slabs (2500x2500x180 mm) to investigate the punching shear resistance of slab-column connections as shown in Figure 4, focusing on moment transfer, shear reinforcement, and neighboring apertures. Their findings indicated that apertures adjacent to columns markedly diminished punching strength by reducing the shear-resisting perimeter and amplifying shear force concentration.



(a) (b)

Figure 4. Main dimensions and load arrangement (Note: dimensions in mm); (a) Slab without opening (Plan with Section), (b) Slab with opening (Plan with Section) [10].

The research showed that positioning shear reinforcement adjacent to apertures significantly improved resistance and deformation capacity. The analysis of the shear field revealed significant shear stresses in the corner regions adjacent to big apertures, which corresponded with the identified failure zones. Comparisons using design codes (ACI 318-19, fib MC2010, FprEN1992-1-1:2023) indicated that these codes yielded cautious or inconsistent projections for slabs featuring apertures.

Reinforcing a slab with openings with shear bolts is a method to avert punching failure in slab-column connection systems generally. Apertures adjacent to columns should be avoided or accounted for precisely. The [11] examined six flat slab-column specimens (1800x1800x120 mm), comprising three with two openings (150x150 mm) adjacent to the column (200x200 mm) and three without openings. Within each group, one slab was devoid of shear reinforcement, one was retrofitted with shear bolts arranged in an orthogonal configuration, and one in a radial configuration. The strengthened slab-column connections with two openings did not achieve the maximum lateral load comparable to that of the unstrengthen slab without openings. Figure 5 depicts the specimen details.

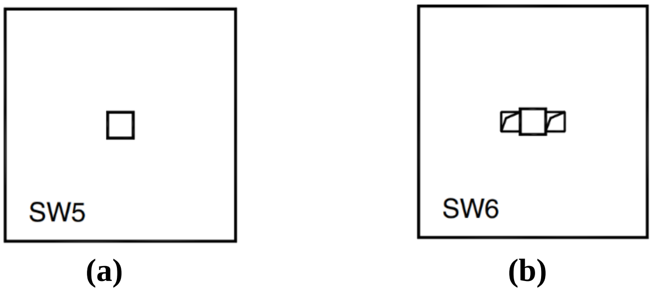


Figure 5. Specimens (a) without openings, (b) with openings [11].

Openings adjacent to columns elevate shear stress, particularly in interior connections. Stresses comply with code restrictions if openings are adequately spaced, with maximum shear occurring at half of the slab depth from the column. Wider and closer apertures exert a more significant influence.

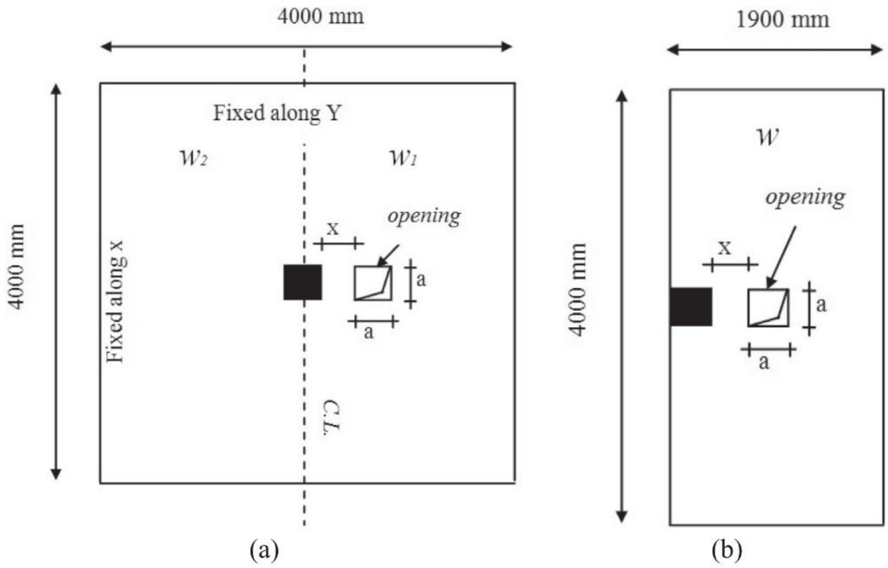


Figure 6. Dimensions and boundary conditions of the connections; a) interior column; b) edge column. w_1, w_2 are distributed loads in the sides of span in MPa [12].

In their 2020 research, [12] examined the impact of apertures on the punching shear strength of reinforced concrete slab-column connections subjected to vertical loads by a finite element model. They analyzed eight interior and eight edge connections as shown in Figure 6, each including a single opening (150 x 150 mm or 250 x 250 mm) positioned at varying distances from the column (0, 75, 150, and 300 mm), and contrasted these with connections devoid of openings as a reference point.

The principal observations were as follows:

1. Elevated Shear Stress Adjacent to Openings: Openings situated adjacent to the column markedly elevated shear stress in slab-column connections. The increased openings and reduced distance to the column exacerbated this stress, frequently above the ACI 318-19 code limitations for both interior and edge connections. Shear stresses remained within code parameters when openings were located a minimum of 1.2 times the effective depth of the slab from the column.
2. Critical Shear Section: Maximum shear loads were detected at sections positioned at half the slab depth (d/2) from the column, corroborating ACI 318-19's guideline for the critical shear section distance from the column, which was consistent irrespective of opening size or connection type.
3. Complex Stress Distribution with Apertures: The openings adjacent to the connectors induced concentrated shear stress at the crucial region, exacerbating the punching shear issue. The shear stress distribution on one side of the critical section largely agreed with ACI 318-19 projections for interior connections but diverged for edge connections with finite element model findings indicating lower values than code predictions at certain locations.
4. Effects of Opening Size and Distance: Interior connections were more influenced by openings than edge connections, with larger openings and those nearer to the column resulting in a more pronounced rise in shear stress. Openings located 150 mm or more from the column generated stresses that were below code forecasts.

3. Influence of Openings on Two-Way Slabs with Different Concrete Types

Fibrous concrete in two-way slabs increases load-bearing capacity, mitigates cracking, and boosts ductility. Fibers evenly distribute loads, minimizing slab thickness requirements while enhancing durability and resistance to impact and fatigue. Openings in concrete construction influence load distribution, diminishing strength and stiffness. Fiber reinforcement, such as steel or polypropylene, enhances tensile strength, crack resistance, and structural longevity.

According to the [13] examined the influence of different fiber types on the structural performance of flat two-way slabs, highlighting slabs with and without a central square opening. Four fiber types (hooked end, straight, corrugated steel, and polyolefin) were evaluated to ascertain the impact of fiber morphology and classification on flexural performance. As shown in Figure 7, the slabs had dimensions of 800 × 800 × 100 mm, reinforced with ϕ 12 mm steel bars in both directions (5 bars each), and included a 25 mm concrete cover. The slabs were supported by a 700 × 700 mm steel frame, allowing for a clear span of 700 mm. Slabs featuring apertures possessed a central opening measuring 150 x 150 mm, with loading applied centrally on a 200 × 200 mm steel plate.

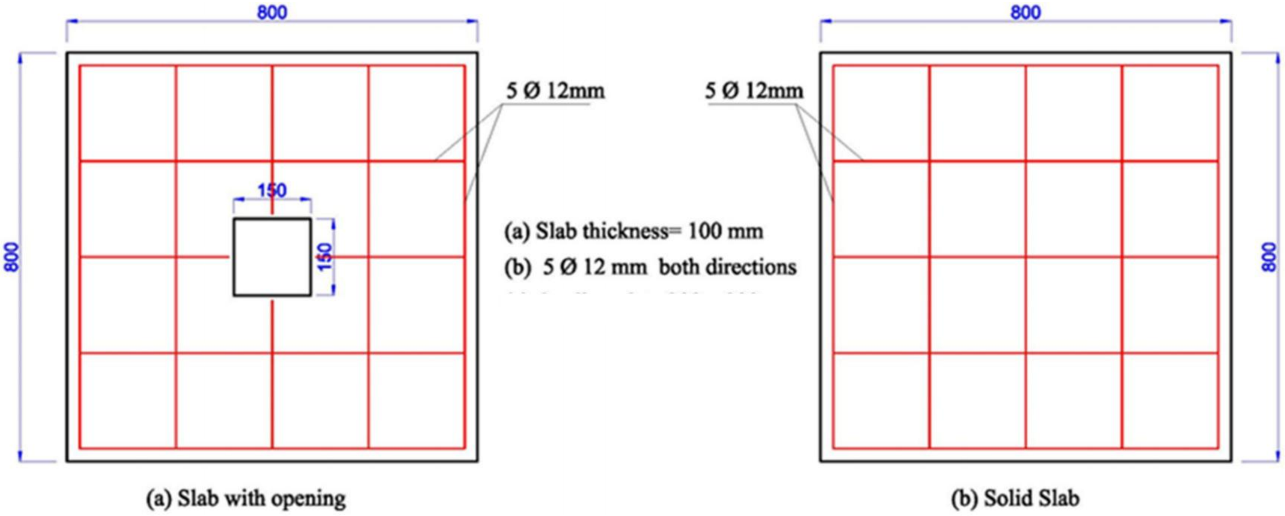


Figure 7. Two-way reinforced slab details (dimensions are in mm) [13].

The primary findings indicated that the incorporation of fibers enhanced compressive strength, particularly with hooked-end and corrugated steel fibers. Fiber-reinforced slabs demonstrated elevated cracking loads, with hooked-end fiber-reinforced slabs demonstrating a 43% enhancement for solid slabs, whilst polyolefin fiber-reinforced slabs had a 19% increase. Fiber reinforcement enhanced ductility and postponed cracking, especially in slabs with apertures, which exhibited superior load-bearing capacity and increased deflections. The study concluded that fiber reinforcement, particularly with hooked-end steel fibers, markedly improves ductility, fracture resistance, and flexural strength, especially in slabs with openings.

High-strength lightweight concrete (HSLWC) provides superior compressive strength and diminished weight, improving load reduction and seismic resilience. Openings in HSLWC slabs influence stress distribution, yet their decreased density and enhanced crack resistance contribute to structural integrity and durability.

Another research [14] investigated the seismic performance of nine full-scale slab-edge column connections (1600x1200x130mm) constructed from Normal-Strength Concrete (NSC, $f'c$ = 28 MPa) and High-Strength Lightweight Concrete (HSLWC, $f'c$ = 49 MPa). The study comprised five NSC specimens and four HSLWC examples, encompassing both those with and without apertures. The punching shear strength was assessed with multiple international building codes, including IBC (2021) [15], ACI (2019) [5], NZS (2006) [16], JSCE (2007) [17], and Eurocode 2 (2008) [8]. The specimen dimensions are demonstrated in Figure 8. The specimen designation was as follows: The first three characters, SEC, denoted slab-edge column connection. The fourth character denoted the compressive strength of concrete: N represented normal strength concrete with *f'c*= 28 MPa, whereas H signified high strength lightweight concrete with *f'c*= 49 MPa. The fifth character indicated the presence of an opening in the slab-edge column connection (*W* = without opening, O = with opening). The specimen number was denoted by the sixth letter.

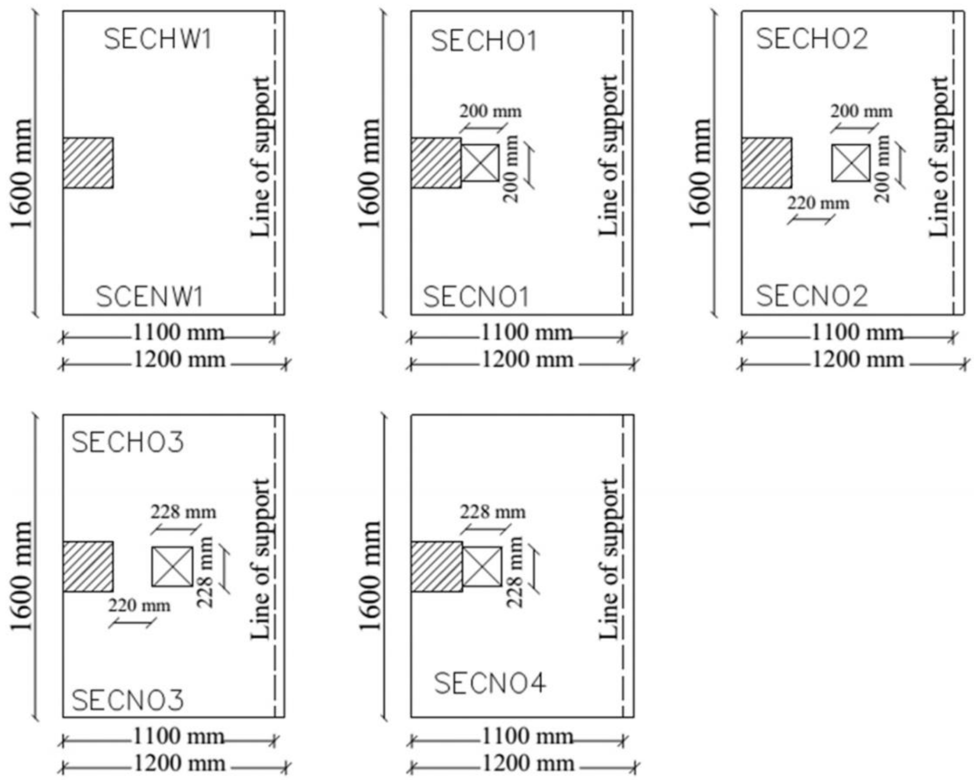


Figure 8. Plan view of test specimens [14].

They concluded that the punching shear strength projections from International Building Code (International Code Council 2021), American Concrete Institute (ACI 318-19), New Zealand Code (New Zealand Standard NZS 3101: Part 1 2006), and Eurocode 2 (Eurocode 2 2008) were conservative for HSLWC, with ACI and NZS yielding the most precise forecasts. Nonetheless, the Japan Society of Civil Engineering (JSCE 2007) forecasts were marginal or hazardous for both NSC and HSLWC. The ultimate punching load of HSLWC was markedly greater than that of NSC. The increase was 72% for connections without apertures and up to 81% for connections with openings adjacent to the column face. The increase for connections located two slab depths away from the column varied from 65% to 73%. The study indicated that opening widths up to one-seventh of the column strip width were permissible in certain instances, despite ACI (2019) [19] restricting the opening size to one-eighth of the strip width. The study determined that whereas certain international codes yield reliable forecasts for punching shear strength, more conservative thresholds, such as those in (JSCE-2007) [17], were inappropriate for high-strength concrete. Creating openings in HSC (High Strength Concrete) and NSC (Normal Strength Concrete) slabs adjacent to column connections can compromise structural integrity, leading to stress concentrations and possible failure. It may affect load distribution, augment deflection, and jeopardize overall safety and durability.

In their 2019 study, [15] examined nine full-scale, 1800 x 1800 x 120 mm slab-column connections constructed from high-strength concrete (HSC) and normal-strength concrete (NSC) subjected to seismic loading to assess the relevance of punching shear design provisions from ACI 318-2014, ECP 203-2017 (Egyptian code), and JSCE-2007. The variables encompassed concrete strength (normal-strength concrete at 25 MPa and high-strength concrete at 75 MPa) as well as the presence, dimensions, and positioning of openings adjacent to the column face, as shown in Figure 9. The specimen designation was elucidated as follows: The initial three letters, SCI, denoted an interior slab-column connection. The fourth letter denoted the compressive strength of concrete: N represented normal-strength concrete with $f'c = 25\,MPa$, whereas H signifies high-strength concrete with $f'c = 75$ MPa. The fifth letter denoted the slab-column connection, indicating whether it included an opening (*W* = without opening, *O* = with opening). The sixth letter denoted the number of specimens. (Note: The locations and dimensions in the case of HSC were analogous to those of NSC, so the letter N was replaced by H).

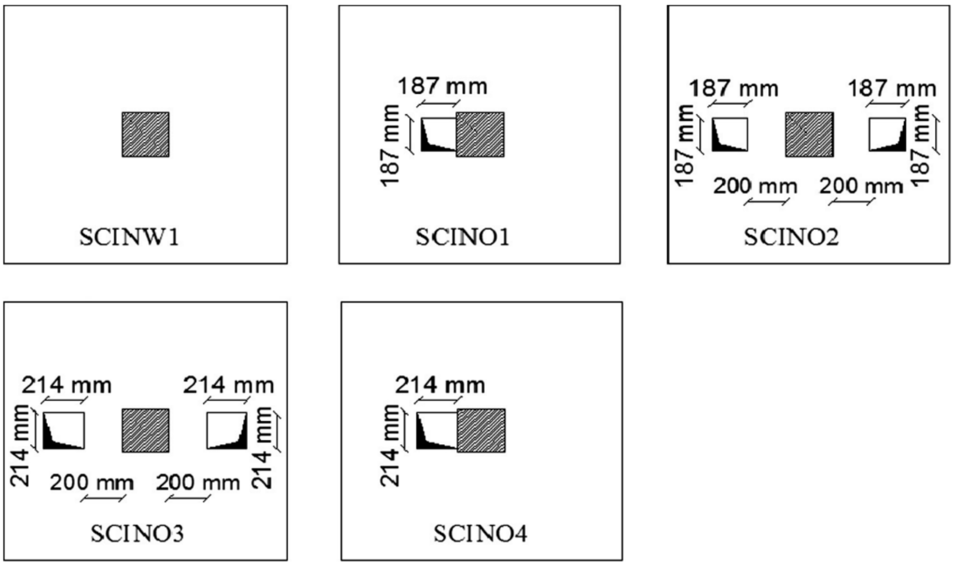


Figure 9. Plan view of and size of openings of test specimens [15].

Enhancing concrete strength from Normal Strength Concrete (NSC) to High Strength Concrete (HSC) resulted in a 58% increase in the ultimate punching load for solid connections and a 52% increase for connections with apertures (one-eighth of the column strip width, positioned at the column face). Nonetheless, NSC connections demonstrated superior ductility, with displacement ductility factors diminishing by roughly 36% in solid HSC specimens and by 49-51% in HSC connections featuring openings in diverse locations. The ACI 318-2014 equations yielded conservative estimates for punching shear in both NSC and HSC specimens, whereas ECP 203-2017 was conservative for NSC and marginally safe for HSC. Conversely, JSCE-2007 demonstrated safety for NSC but posed risks for HSC. Although the ACI and ECP codes restrict opening dimensions to one-eighth and one-tenth of the column strip width, an opening size of up to one seventh was determined to be safe. The suggested finite element model effectively predicted punching shear strength and deformation for normal-strength concrete (NSC) and high-strength concrete (HSC) connections subjected to cyclic loading.

4. Behavior of Different Shape of Openings in Two-Way Slabs

A flat slab including rectangular and circular openings can be utilized in practice. Circular and rectangular openings in two-way slabs can reduce their load-carrying capacity and affect their bending and shear behavior. These openings create stress concentrations, potentially leading to localized failure. Proper reinforcement and design adjustments are necessary to maintain slab strength. Circular openings exert a greater beneficial influence on slab deflections than rectangular ones. Slabs featuring smaller circular apertures reduce deflections in comparison to those with larger circular apertures. Conversely, smaller rectangular apertures yield reduced deflections in comparison to larger rectangular openings. This indicates that the dimensions and configuration of the open substantially affect the deflection characteristics of slabs.

According to the [16] investigated the performance of flat reinforced concrete slabs with different opening sizes and shapes through experimental and analytical approaches. The slabs produced for the investigation measured 750x500x150 mm, both with and without opening. The openings were rectangular and circular, with rectangular dimensions of 150x100 mm and 200x150 mm and circular diameters of 110 mm and 150 mm. The slabs were fortified with 8 mm-diameter steel bars positioned at 100 mm intervals in both directions, with a 20 mm cover. The research indicated that slabs with diminutive apertures (150x100 mm rectangular and 110 mm circular) had decreased deflections. The deflection for the 150x100 mm rectangular opening was 25.52% lower than that of the 200x150 mm rectangular opening, while the deflection for the 110 mm circular opening was 11.39% less than that of the 150 mm circular opening. Conventional slabs (without apertures) had superior load-carrying capacities, demonstrating increases of 33.72% to 36.86% relative to slabs with rectangular openings and 3.52% to 23.52% greater compared to slabs with circular openings. The initial failure load for slabs with apertures was diminished by 25–35% in comparison to those without openings. Furthermore, slabs devoid of apertures had equal stress levels that were 34–38% greater than those with rectangular openings and 16–30% higher than those with circular openings.

The findings demonstrated that the existence and dimensions of openings substantially influenced the structural efficacy of flat slabs, reducing their load-bearing capacity, augmenting deflections, and modifying stress distributions.

The configuration, quantity, and location of apertures in flat slabs substantially influence punching shear capacity. Openings situated nearer to the column diminish shear strength, with rectangular apertures exerting the most significant effect, followed by square and circular openings. Augmenting the number of apertures decreases punching capability, with rectangular openings exerting the most significant impact.

The [17] studied fourteen flat slabs (1000 x 1000 x 80 mm) with two different numbers of openings 2 and 4, with three shapes: circular, square, and rectangular. The openings were placed at two different distances from the column face: 1H (H is slab thickness) and 4H. Openings at 1H drastically reduced punching shear capacity, while openings at 4H had minimal impact, with rectangular openings reducing capacity by up to 8.98% for 4 openings at 4H. Increasing the number of openings from 2 to 4 significantly reduced punching capacity, regardless of the shape. Additionally, slabs with openings at 1H had significantly lower ultimate rotations compared to slabs with openings at 4H. Analytical predictions using ACI 318-19 and Eurocode 2 showed that ACI 318-19 provided more accurate results, with a mean experimental-to-analytical ratio of 1.04, compared to 0.93 for Eurocode 2. ACI 318-19 consistently predicted more conservative results, especially for rectangular openings, with errors up to 8% lower than experimental values for these specimens, while predictions for square and circular openings were within 5% of experimental values. The study concluded that the shape, number, and location of openings significantly affect punching shear strength, and that further research is needed to refine predictions, particularly for different opening shapes.

They stated that circular openings had the least effect on punching capacity, followed by square and rectangular openings, with rectangular openings causing the most reduction. Figure 10 and Figure 11 show the details of the specimens. The nomenclature for specimens was selected to reflect the number, shape, and position of openings in that specific sequence; for example, specimen 2S1H indicated that it possesses 2 square apertures situated 1H from the column's face on both sides of the column.

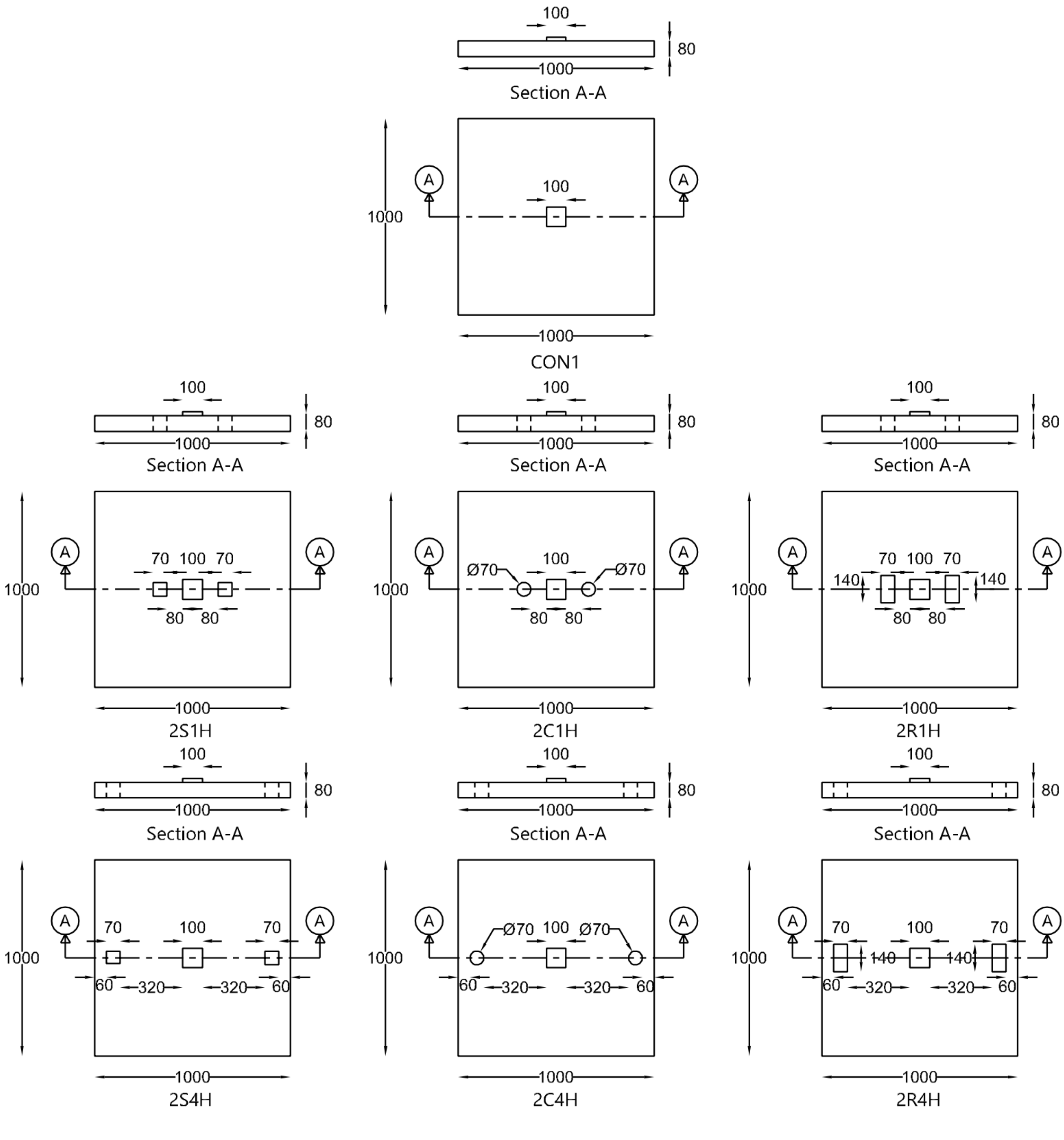


Figure 10. Layout of specimens with 2 openings (Units: mm) [17].

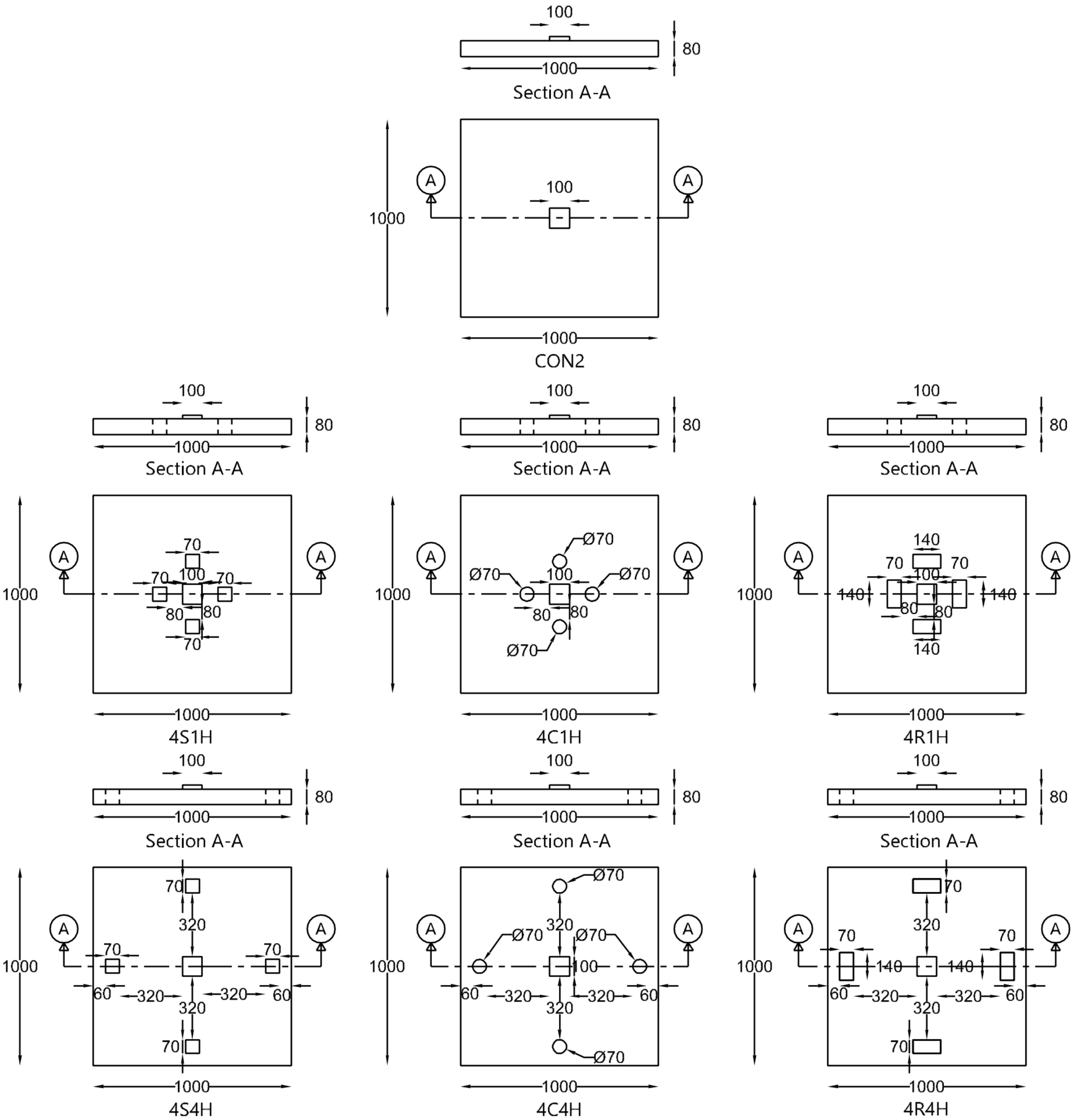


Figure 11. Layout of specimens with 4 openings (Units: mm) [17].

The existence, configuration, and quantity of openings in flat-plate slabs devoid of shear reinforcement substantially influence their punching shear capacity. Decreases in strength are associated with the reduction of the critical section perimeter. The arrangement of openings in different layouts is also crucial for slabs, where L-shaped configurations and a growing number of openings result in more significant declines. Openings also modify the slab's behavior, transitioning it from two-way to one-way action.

The researcher [18] investigated the impact of openings on the punching shear strength of flat-plate slabs with dimensions (2000x2000x200 mm) without shear reinforcement by testing eight specimens with varying layouts and numbers of openings (circular shapes with 150 mm diameter). They found that the reduction in punching shear strength was proportional to the loss of the effective critical section perimeter. All specimens exhibited brittle punching shear failure, with the reduction in shear strength aligning with the decrease in the critical section perimeter. The presence of openings also altered the slab's behavior from two-way to one-way action, especially in specimens with cracks in the East-West (E-W) direction. Figure 12 shows the details.

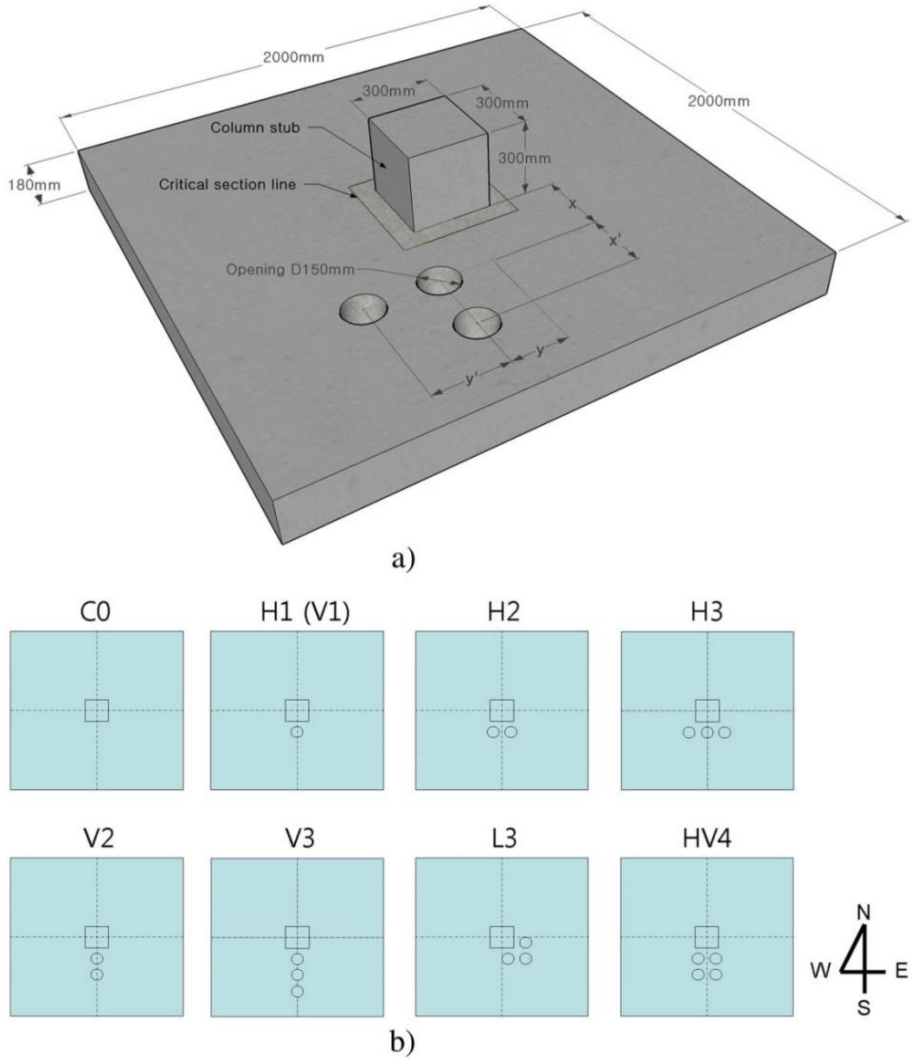


Figure 12. Geometrical description of test specimens. (a) Dimensions of test specimens and (b) geometrical configuration of openings for each specimen. (V is for vertical and H is for horizontal distribution of the openings) [18].

In the H-shaped series, increasing the number of openings reduced the punching shear strength due to the disruption of shear force transfer along the critical section perimeter, while in the V-shaped series, the strength remained nearly the same regardless of the number of openings. Openings at the corner of the column, in an L-shape, caused an additional reduction in punching shear strength. The CEB-FIP model code (1990) and fib model code (LoA II, 2010) predicted punching shear strengths close to the experimental results, while ACI 318-11 and fib model code (LoA I, 2010) were more conservative. This study highlighted that the presence, layout, and number of openings significantly influence punching shear strength, with L-shaped openings and an increasing number of openings leading to more pronounced reductions.

5. Influence of Location and Size of Openings on Two-Way Slabs

The position and dimensions of apertures in two-way slabs significantly affect their punching shear capability. Proximal openings to the column compromise the slab's integrity, whereas distal placements augment strength and energy dissipation. Increased and supplementary holes diminish strength, but diagonal openings affect both punching strength and energy dissipation.

The [19] performed a three-phase study on the impact of openings in flat reinforced concrete slabs on their punching strength. The investigation commenced with the examination of full-scale slabs measuring 800x800x100 mm under punching stress. One slab functioned as a reference without apertures, while the others exhibited differences in the dimensions, positioning, and number of openings. The assessments evaluated punching strength, initial stiffness, and energy dissipation based on load displacement data. During the second phase, the researchers computed punching capacity utilizing international coding equations (TS500, ACI318-19, Eurocode-2, BS8110) and juxtaposed these with experimental findings. In the third stage, they utilized the superposition principle to assess if predictions could correspond with experimental results based on opening configurations. Figure 13 and Figure 14 illustrate the details of the specimens.

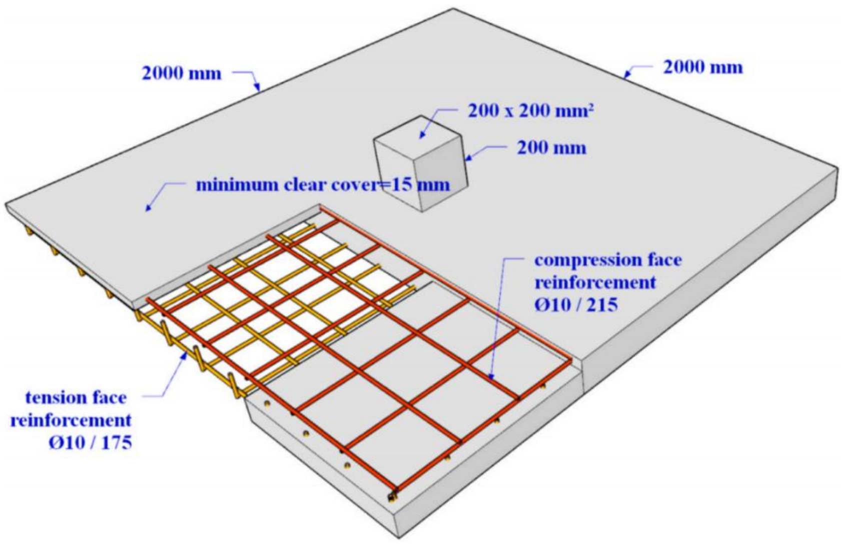


Figure 13. Geometric dimensions and reinforcement details of the test specimens [19].

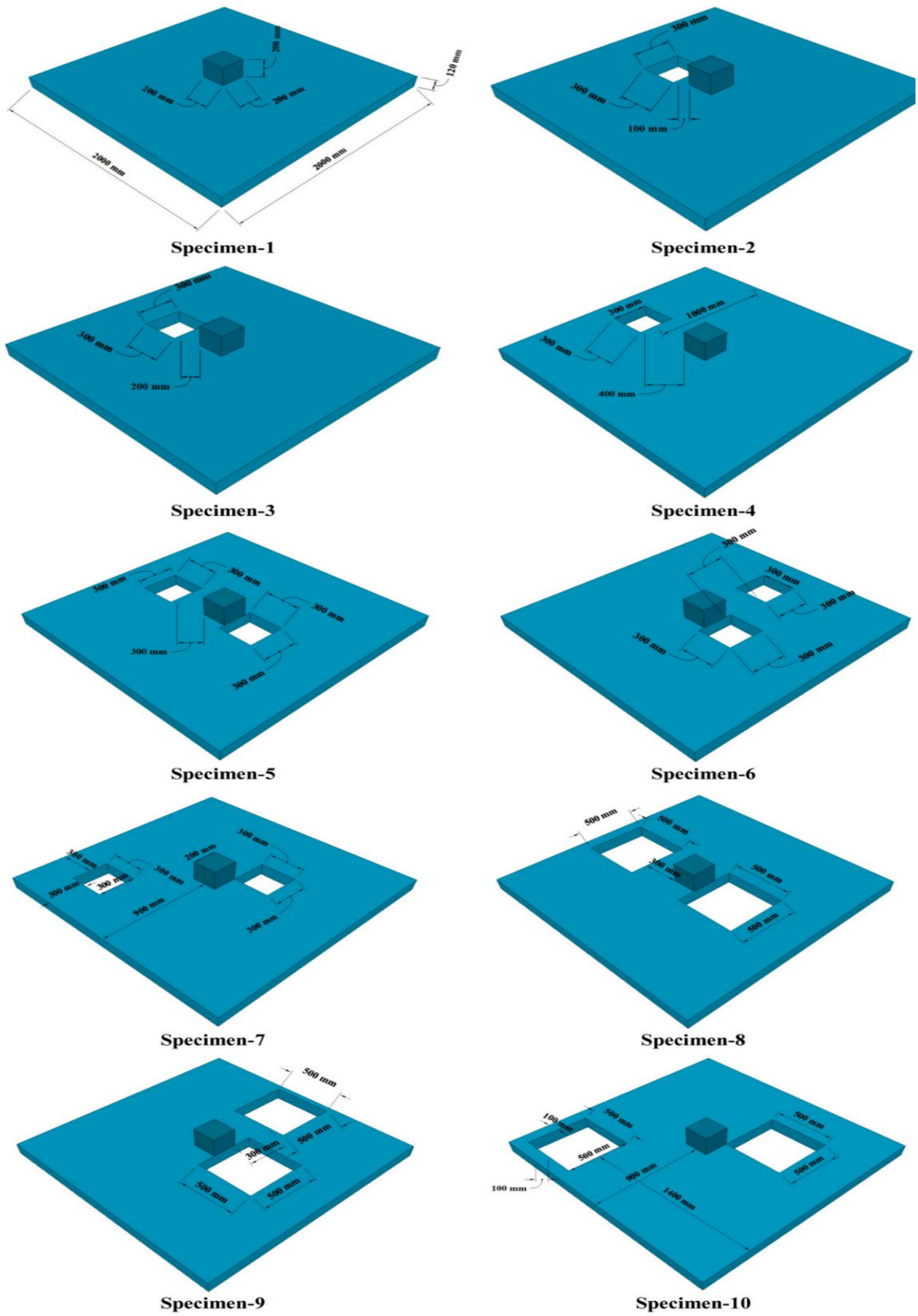


Figure 14. Position and size of openings [19].

Apertures adjacent to the column diminished punching strength by as much as 68%, whereas their relocation enhanced strength by 25% and energy dissipation by 63%. Smaller apertures diminished strength by 40%, whereas larger openings decreased strength by 22% and energy dissipation by 33%. Diagonal apertures improved both structural integrity and energy absorption. Theoretical models typically overestimate strength; however, the superposition method yielded more precise predictions, especially for diagonal openings.

Flat slabs with openings, located at different distances from the column, demonstrate punching failure, characteristic of slabs lacking shear reinforcement. Slabs with openings positioned at d (d is the average effective height of a two-way slab in two directions) and 3d from the column exhibit superior failure loads compared to slabs without apertures; however, the 2d location leads to increased displacements. Openings typically affect slab rigidity, hence diminishing displacements, with the exception of the specimen including an opening at 2d, which exhibits elevated displacements.

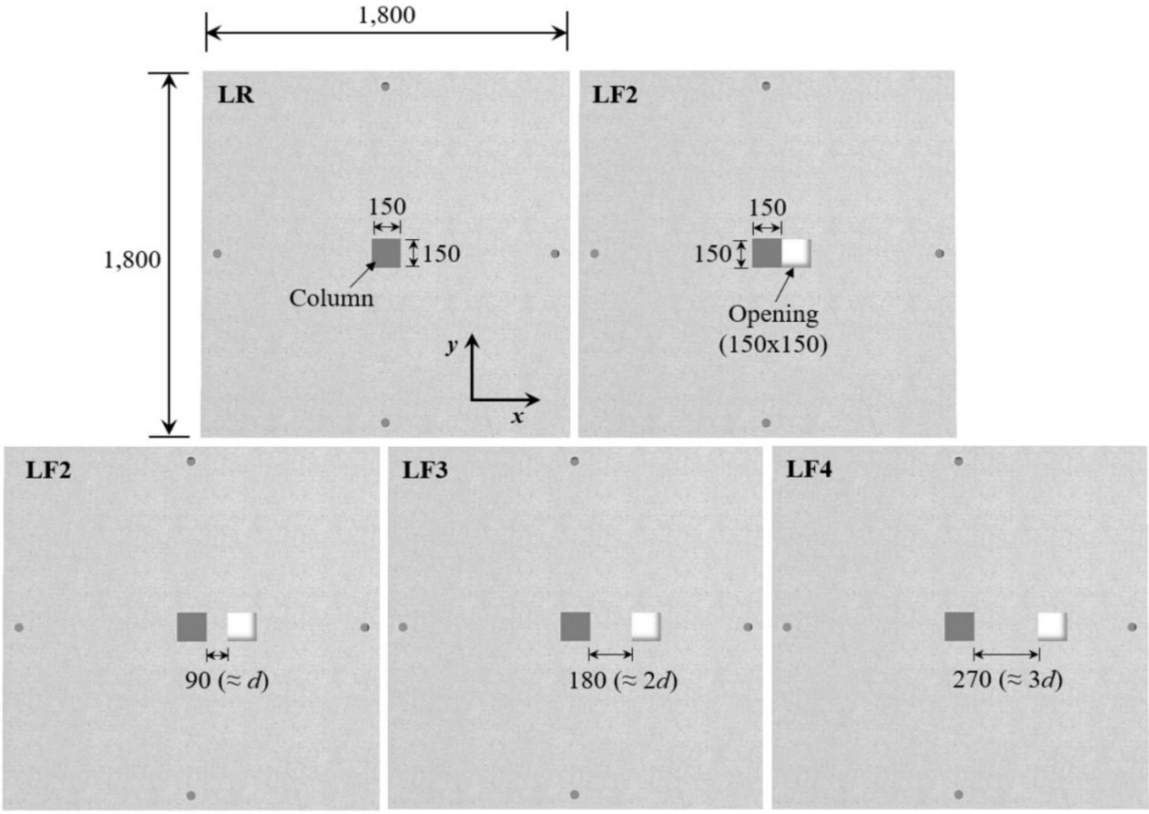


Figure 15. Slab characteristics (units in mm) [9].

The [9] examined the structural performance of flat slabs (1,800 mm x 1,800 mm x 130 mm) featuring openings positioned at varying distances from the column. The research indicated that all slabs experienced failure via punching, a brittle failure characteristic of flat slabs lacking shear reinforcement. The specimens were categorized into reference slabs without openings (LR) and slabs with openings (LF1, LF2, LF3, and LF4). All slabs from the LF group had a singular square aperture measuring 150 mm x 150 mm, located either adjacent to the column (LF1) or at specified distances (s) from the column face: LF2 with s = 90 mm

(≈ d); LF3 with s = 180 mm (≈ 2d); and LF4 with s = 270 mm (≈ 3d). Notably, slabs featuring openings, such as LF2 and LF4, demonstrated greater failure loads than the reference slab (LR), with an opening positioned 3d (d is the average effective height of a two-way slab in two directions) from the column having no substantial effect on the failure load. The slabs, including apertures, often exhibited more rigid behavior, resulting in reduced displacements relative to the reference slab, with the exception of LF3, which incurred greater displacements following a 150 kN load, Figure 15 shows the details of the slabs.

The research indicated that the apertures influenced the energy dissipation capability of the slabs. The LF1 slab, including an aperture adjacent to the column, exhibited a 23.6% decrease in energy dissipation, but LF3 and LF4, which featured openings at distances of 2d and 3d, demonstrated enhancements of 8% and 9%, respectively. The reinforcement behavior indicated that bars situated near openings exhibited reduced deformations relative to the reference slab, but greater deformations were noted for bars positioned between the column and the opening as the distance from the column increased. The study evaluated punching resistance predictions according to various design codes. The ACI 318 code overestimated the failure load by 41%, whereas Eurocode 2 yielded the most precise estimations, forecasting failure loads approximately 22% lower than the actual results. The NBR 6118 code overestimated the failure load since the specimen thickness was less than the minimum requirement, whereas the Fib Model Code projected failure loads that were 26% more than the experimental values.

Crack patterns in reinforced concrete slabs with apertures are substantially influenced by the location and dimensions of the openings. Diagonal openings augment the shear perimeter and generate elongated shear fractures between the column and the corners of the openings. Increased apertures, particularly those adjacent to the column, diminish punching shear capacity, stiffness, and energy dissipation. Deformation patterns are increasingly confined near the apertures, with symmetry reestablished when the openings are farther from the column.

In their 2014 research, [4] studied the punching shear behavior of reinforced concrete (RC) slabs by evaluating eight specimens with different opening sizes and placements, in addition to a reference slab devoid of openings. Two-way square slabs (2000 x 2000 x 120 mm), as illustrated in Figure 16, were subjected to axial force via a centrally positioned square column (200 x 200 mm). The openings measured 300 × 300 mm and 500 x 500 mm, located either near to the column or 300 mm away, and aligned parallel or diagonally to it.

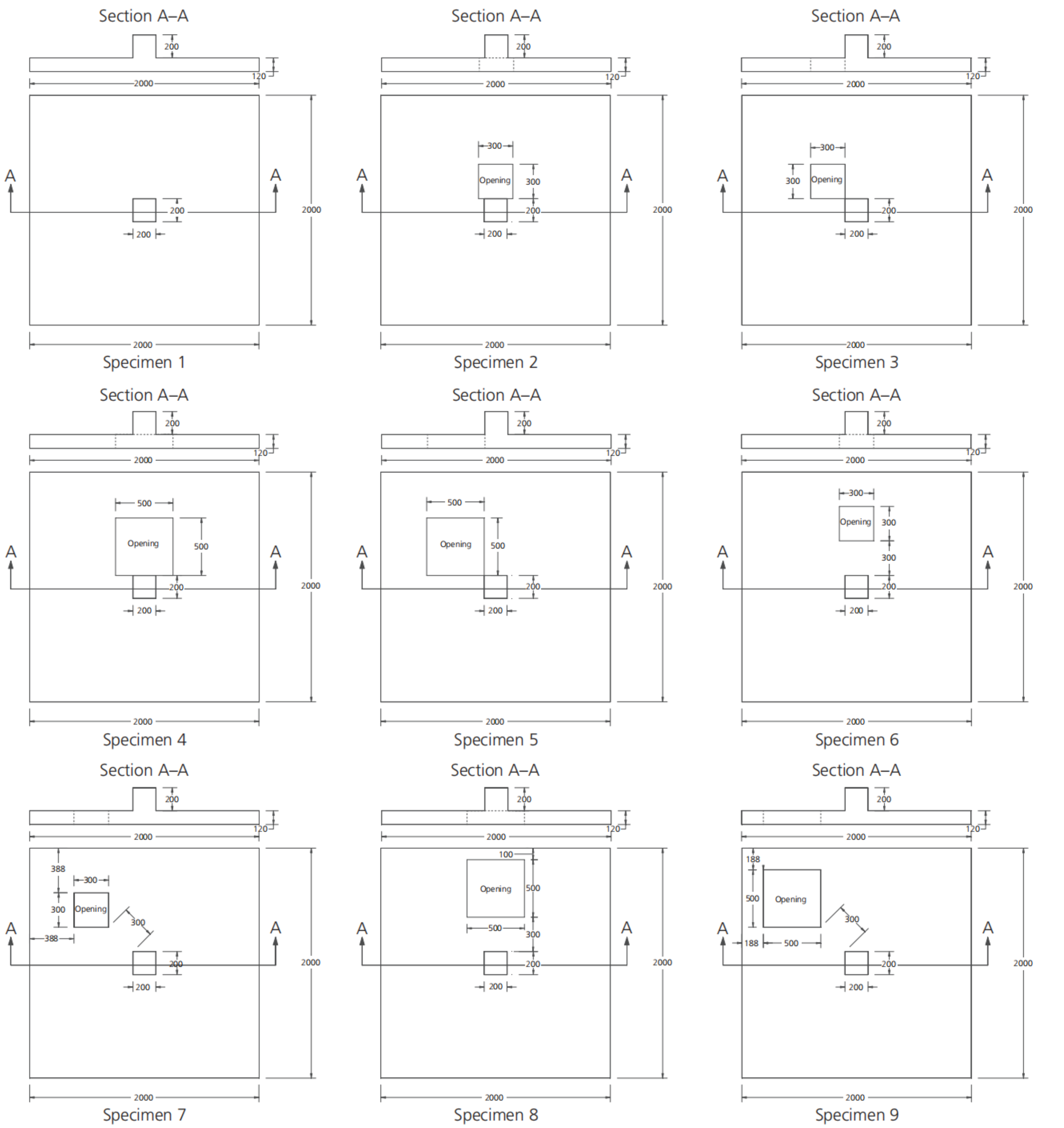


Figure 16. Specimen opening layouts (Dimensions are in mm) [4].

Augmenting the aperture dimensions and their proximity to the column markedly diminished punching shear capacity, initial stiffness, and energy dissipation. Openings situated 300 mm from the column exhibited a 1.42-fold increase in punching shear capacity, a 36% enhancement in initial stiffness, and a 1.85-fold augmentation in energy dissipation capacity relative to openings near the column. Deformation patterns were localized around openings, and symmetry was reinstated as the aperture distanced from the column. Crack patterns indicated that diagonally positioned apertures, located 300 mm apart, increased the punching shear perimeter and produced elongated shear cracks between the column and the corners of the openings.

In comparing code predictions, ACI 318, Eurocode 2, and (Turk Standartları Enstitusu) TS 500 effectively estimated the punched shear capacity of the reference specimen but overestimated the capacities for slabs with openings, particularly for wide diagonal openings in proximity to the column. Eurocode 2 yielded the most accurate forecasts; however, discrepancies reached 39% for bigger, contiguous openings.

Diagonal apertures improve energy dissipation efficiency, although parallel apertures typically offer superior load-bearing capability. Openings situated near the column adversely affect performance, diminishing load capacity, stiffness, and energy dissipation. The closeness of openings to the column, whether diagonal or parallel, affects the slab's punching shear performance, with neighboring openings resulting in the most adverse effects.

According to the [20] examined the impact of various opening positions on the punching performance of two-way reinforced concrete slabs. Ten slabs, each measuring 2000 × 2000 × 120 mm, as demonstrated in Figure 17, were subjected to punching loads from a centrally positioned 200 × 200 mm square column. The examined variables included opening dimensions (300 × 300 mm, 500 × 500 mm, and 700 × 700 mm) and opening orientations (parallel, diagonal, and adjacent). The maximum load capabilities of the slabs were ascertained by analytical equations from TS 500, ACI 318, and Eurocode 2. The research revealed that with larger aperture diameters, the ultimate load capacity, initial stiffness, and energy dissipation capacity of the slabs markedly diminished. The least favorable outcomes were noted for specimens with neighboring openings, succeeded by those with parallel openings, whilst slabs featuring diagonal apertures exhibited superior performance for maximum bearing capacity and energy consumption efficiency.

The initial stiffness values of the slabs diminished as the aperture size increased, with the greatest stiffness recorded in specimens featuring diagonal openings and the least in those with parallel openings. The analytical capacity equations in TS 500, ACI 318, and Eurocode 2 were deemed insufficient for slabs with many apertures, as they did not yield accurate estimates of the ultimate load-carrying capacity in alignment with experimental findings. Nonetheless, the finite element analysis results, especially for the ultimate punching load, were shown to be notably congruent with the experimental outcomes. It was observed that as the opening size enlarged, the punching behavior of the slabs diverged from the anticipated pattern, particularly after attaining the ultimate punching force, owing to the degradation of the opening layout symmetry.

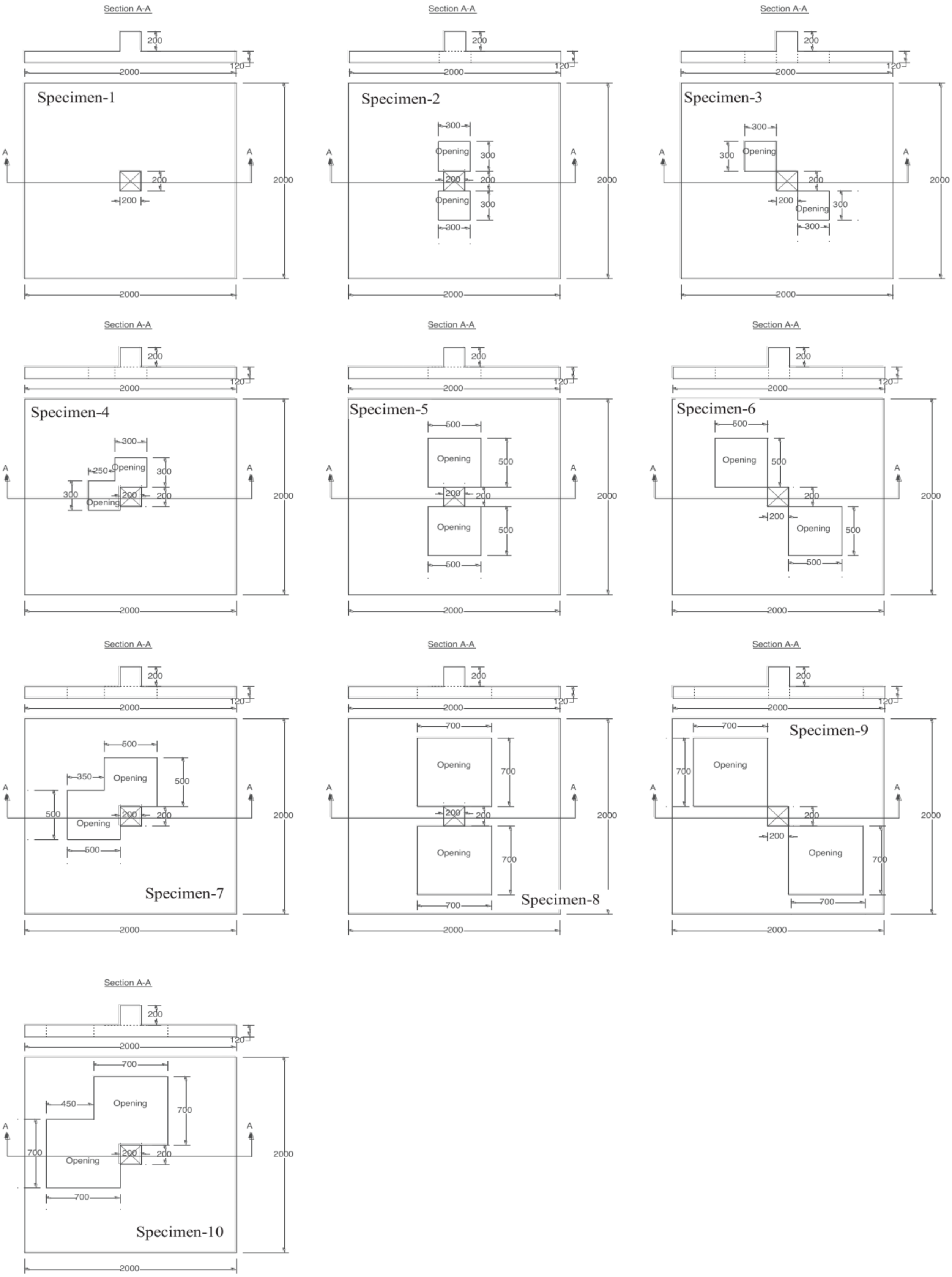


Figure 17. Opening Layouts of Test Specimens (Dimensions are in mm) [20].

Openings adjacent to columns markedly diminish the punching strength of flat slabs, with more pronounced reductions noted for apertures at the column face in contrast to those at the corner. Openings exceeding 1/10th of the span or column dimension influence the load-deflection curve, but those located more than 1.5 times the slab thickness from the column exert negligible effects. Positioning two apertures on opposite faces or corners mitigates strength reduction. Codes precisely forecast punching strength for apertures up to span/10, above recommended thresholds, as emphasized by [21], who conducted an experiment to know the influence of openings near columns on the punching strength of flat slabs. Seven big flat plate slabs (1,700 x 1,700 x 150 mm) were evaluated, featuring various opening positions: three with apertures positioned in front of the column face (Group I), three with openings at the column corner (Group II), and one control specimen devoid of openings as shown in Figure 18. The primary characteristics examined were the dimensions and positioning of the openings, while other variables such as slab thickness, steel reinforcement, and column dimensions remained unchanged.

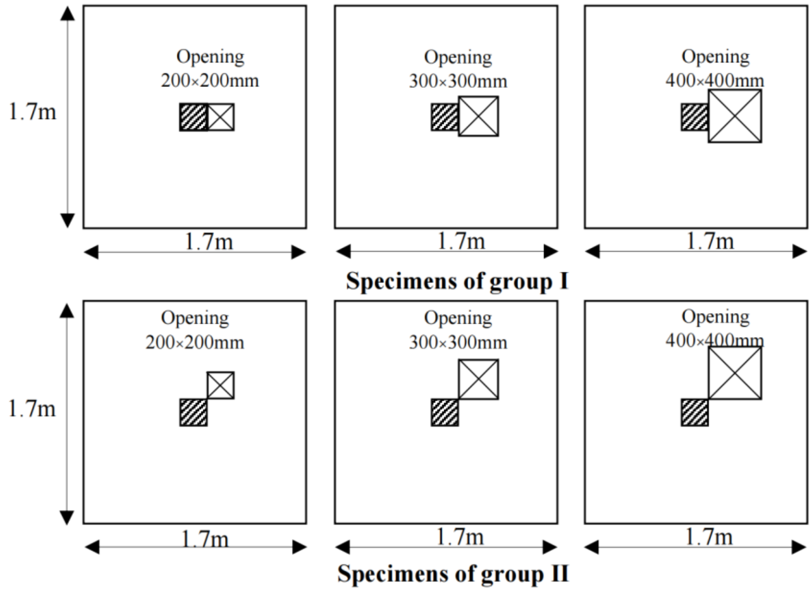


Figure 18. Details of tested slabs [21].

6. Conclusions

Two-way slabs are integral to modern construction due to their ability to sustain loads in multiple directions, offering flexibility and optimal space utilization. However, incorporating openings for architectural and utility functions, such as HVAC ducts and electrical conduits, introduces localized vulnerabilities that can significantly compromise structural integrity. These apertures reduce punching shear capacity, especially when located near column supports, leading to potential brittle failure modes. The presence of openings also disrupts normal stress distribution, causing stress concentrations that can lead to fractures, deformations, or early failures, particularly as aperture size increases. Strategic positioning of openings is crucial; apertures near high-stress zones, such as column strips, are especially detrimental, while locating them in less stressed areas mitigates their negative impact. Supplementary reinforcement, including rebar, stirrups, or fiber-reinforced polymers (FRP), helps alleviate adverse effects by enhancing ductility and load distribution. Current design codes, such as ACI 318-19 and Eurocode 2, provide general guidelines but lack specific provisions for handling openings, underscoring the need for refined norms and innovative strategies. Computational modeling, like finite element analysis (FEA), enables precise simulations to predict aperture impacts and optimize designs. Future research should focus on advanced prediction models, experimental validation, and hybrid reinforcement methods to enhance slab performance. Achieving a balance between architectural functionality and structural safety is imperative, ensuring design efficiency without compromising durability or aesthetics.

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