Al-Rafidain Journal of Engineering Sciences

Journal homepage https://rjes.iq/index.php/rjes

ISSN 3005-3153 (Online)

Punching Shear Behaviour of Reinforced Concrete Flat Slabs with Openings: Mechanisms, Failures, and Strengthening Strategies: A Review

Hala S. Salami[*], Ali Sabah AL-Amili[2]

[1,2]Civil Engineering Department, Mustansiriyah University, Baghdad, 10064, Iraq.

ARTICLE INFO

Article history:

Received	28 March 2026
Revised	28 March 2026,
Accepted	22 April 2026,
Available online	3 May 2026

Keywords:
Punching shear
Flat slabs
Openings
Strengthening techniques
Fiber-reinforced polymer (FRP)

ABSTRACT

Reinforced concrete flat slabs are widely used for their architectural flexibility and construction efficiency, but they are vulnerable to punching shear failure—a sudden collapse at slab-column connections. Openings for stairs, elevators, and utility ducts worsen this vulnerability by removing concrete and reinforcement from critical regions.

This review synthesized studies from 2007 to 2025 to evaluate punching shear behavior in slabs with openings and the effectiveness of strengthening techniques. Findings showed that openings adjacent to columns reduced punching shear capacity by 29% to 65%, with circular openings causing less damage than rectangular ones. Openings beyond four times the slab thickness had minimal effect.

Strengthening methods proved highly effective. Externally bonded CFRP sheets restored or enhanced capacity by 22% to 77%. ECC applied around columns increased punching capacity by 34% to 38% and transformed failure from brittle to ductile. Super elastic Shape Memory Alloy (SMA) stirrups improved energy absorption by over 100%. Sustainable alternatives like geopolymer concrete with CFRP strengthening achieved up to 77% capacity improvement, while basalt-FRP bars reached 89% of steel-reinforced slab strength.

Traditional design codes like ACI 318 were overly conservative, whereas Artificial Neural Network models provided more accurate predictions with only 9% average error.

This review confirms that while openings severely weaken flat slabs, modern strengthening techniques effectively restore performance.

1. Introduction

Flat slabs are reinforced concrete floors supported directly by columns without beams, drop panels, or capitals. These systems enhance space utilization, offer aesthetic appeal, and help lower construction costs. Flat plates ease formwork, simplify flexural reinforcement placement, and reduce story heights, providing more usable space within the total height. They also decrease dead loads transferred to columns and foundations [1].

Punching, or two-way shear, produces truncated pyramid-shaped cracks that spread from the column into the flat slab. This failure mode leads to a complete loss of shear resistance at the connection, causing the slab to collapse and separate from the supporting column [2]. When loads are redistributed, nearby structural members experience excessive stress since they were not designed to bear the additional forces. This type of failure occurs abruptly and without warning, leading to a sudden collapse of the entire structure; hence, punching shear failure is

Corresponding author E-mail address: hlaslami2025@uomustansiriyah.edu.iq

https://doi.org/10.61268/v3jb7m22

regarded as catastrophic. Under uniform loading, flat slabs develop flexural cracks around the column zones at peak moments. As the load continues to increase, fan-shaped cracks gradually form and propagate [3]. The combined behavior of flexural and punching shear failures indicates that the slab retains notable ductility under flexural failure, as shown in Figure (1-1). However, the presence of openings close to columns reduces the punching resistance of flat slabs because such openings eliminate portions of the critical perimeter, removing concrete and reinforcement, and consequently diminishing the slab's overall shear capacity [4].

Therefore, accurately evaluating the punching shear strength of flat slabs containing openings is essential. Recent studies have concentrated on the analysis and design of reinforced concrete slabs [5] .

1.2 Types of Slabs

Slabs constitute a fundamental component of building structures, serving as the primary horizontal elements that transfer loads to supporting members. They may be supported by beams resting on columns or, alternatively, directly by columns without the use of intermediate beams. The chosen support configuration greatly influences the distribution of bending moments and the overall structural response[6]. There are several types of reinforced concrete slabs based on the geometry, loading and supports conditions as shown in Figures 1 and 2. below are several types of slabs:

1. Slabs with beams, according to support conditions and dimension:
    - One -way slab: This type of slab is supported on two opposed edges. The load is distributed to the beams in one direction, hence the name one-way span. It can be defined when the longer span length twice short direction (LL ≥ 2LS)
    - Two-way slab: this type of slab is guided load distribution where the load transferred and distributed to supported across two directions and the long direction is smaller than short direction (LL < 2LS).
2. Ribbed slab: This type of slab has ribs that run in one direction. These slabs can achieve significant material savings compared to solid slabs, with studies reporting up to 40–67% less concrete usage and substantial reductions in dead load [7].
3. Waffle slab as shown in Figure 1, slab has ribs that run in two directions similar to ribbed slabs. The ribs create a waffle-like pattern, which helps to reduce the self-weight of the slab and increase its stiffness.
4. Slab without beams (flat slabs and flat plates): these types are widely used RC floor systems, valued for their architectural flexibility, reduced floor heights, and construction efficiency. Both systems involve slabs supported directly by columns, but flat slabs may include drop panels or column capitals, while flat plates do not. Despite their advantages, these systems are particularly vulnerable to punching shear failures and progressive collapse [8].

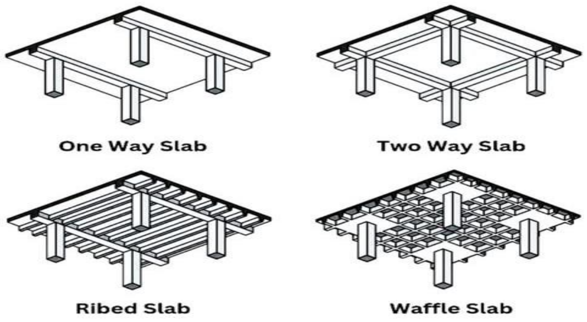


Figure 1. Types of the Reinforced Concrete Slabs with beams [9]

Flat slabs and flat plates as shown in Figure 2 distinguished by their smooth, beamless undersides represent one of the most widely adopted structural systems in residential, commercial, and office buildings. Their popularity stems from several advantages, such as simplified construction procedures, cost-effectiveness, and ease of integrating mechanical and electrical services within the structural depth. Moreover, the high degree of flexibility in accommodating openings and defining slab boundaries allows architects and engineers to adapt the system to diverse design requirements [10].

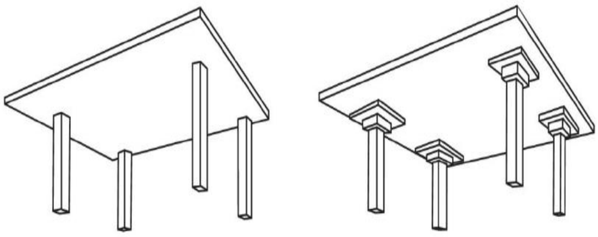


Figure 2. Slabs without beams (Flat Slab and Flat Plate) [9]

1.3 Punching Shear

In flat slab systems where are no beams between supporting columns, the transfer of loads occurs over relatively small areas, resulting in highly concentrated stresses at the slab–column connections. This region is of critical structural importance due to the intense shear forces acting within it. Excessive concentration of these stresses can lead to a specific type of failure known as punching shear [10].

Punching shear describes the localized failure of a slab in the vicinity of a column or concentrated load, where high shear stresses exceed the material's capacity. This phenomenon typically manifests as a truncated cone or pyramid-shaped failure surface surrounding the column, as illustrated in Figure 3 [11].

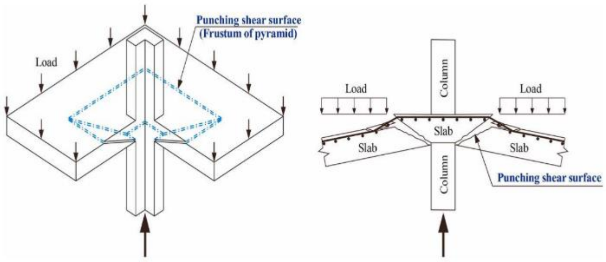


Figure 3. Punching failure in the slab columns connection area [11]

Punching shear failure occurs when a slab separates from its supporting column, disrupting the structural stability that depends on their interaction. This failure causes an abrupt load redistribution, overloading nearby members and potentially leading to progressive collapse. Because concrete fails suddenly and without warning, punching shear is especially dangerous. Engineers must therefore carefully evaluate factors like load distribution, material strength, and slab-column connection details. Proper design and reinforcement strategies are essential to prevent such failures and ensure the safety and durability of reinforced concrete structures [10].

Figure 4 shows the failure of a car park built since 1965 in UK and failed in punching shear in 1997 because the excessive load and the degradation for the structure.

Figure 4. Punching Shear Failure [12]

To mitigate the risk of punching shear failure, it is essential to strengthen the slab regions adjacent to columns using appropriate reinforcement configurations [12]. Design standards recommend placing either bent or straight reinforcing bars in the lower zones of the slab to improve its resistance against unexpected overloads and to prevent progressive collapse as longitudinal bars or stirrups with different techniques, even in cases where theoretical calculations indicate that punching shear reinforcement is not strictly required [13].

1.4 Openings in Slabs

Incorporating openings is often necessary to accommodate functional elements such as elevator shafts, staircases, and service ducts or any other purposes. In addition to these major penetrations, smaller openings are commonly introduced to allow the passage of mechanical and electrical systems, including plumbing, heating, and ventilation conduits.

While the influence of small openings is generally negligible since the structural system can effectively redistribute internal stresses without considerable adverse effects the presence of large openings can substantially alter the slab's structural behaviour. The removal of significant portions of concrete and reinforcing steel changes the internal force distribution, thereby reducing the slab's load-carrying capacity and overall stiffness. Such modifications may compromise the structural integrity of the system and its ability to meet design performance and safety requirements [14]. Openings reduce both the load capacity and punching shear strength of RC flat slabs, with larger and closer-to-column openings causing the most severe reductions up to 44% or more in some cases [15]. Also, Circular openings are less detrimental than rectangular or skewed shapes. Openings located further from columns (e.g., at least 3 times the slab depth) have minimal impact on failure load [16].

1.5 Fiber-Reinforced Polymer (FRP)

Fiber-Reinforced Polymer (FRP) is a lightweight, corrosion-resistant composite made of fibers (carbon, glass, or basalt) in a polymer matrix. It is widely used to strengthen concrete elements, including slabs with openings, improving punching shear resistance. FRP is easy to install and durable, though more expensive and brittle than steel [17][18].

Glass Fiber-Reinforced Polymers (GFRP) offer a practical and cost-effective method for strengthening reinforced concrete slabs, particularly those with openings, to improve punching shear performance. GFRP materials are lightweight, corrosion-resistant, and easy to handle, making them suitable for both cast-in-place and precast concrete applications.

Experimental studies have demonstrated that externally bonded GFRP sheets or strips can significantly enhance the load-carrying capacity of slabs with openings. By carefully selecting the reinforcement layout and fiber orientation, GFRP strengthening can restore slab performance to levels close to or exceeding those of unaltered slabs [19].

Carbon Fiber-Reinforced Polymers (CFRP) have emerged as a modern strengthening technique used to enhance the resistance of reinforced concrete slabs against punching shear, particularly by improving the interaction between the slab and the supporting column. FRP composites are increasingly utilized in precast and cast-in-place concrete systems due to their ease of installation, lightweight nature, corrosion resistance, high tensile strength, and availability in various practical forms [20].

Several studies have examined the structural behaviour of slabs containing openings and the effectiveness of externally bonded FRP systems in restoring or enhancing their load-carrying capacity. Researches had shown that selecting an appropriate FRP strengthen ratio can restore the load capacity of slabs with openings to a level comparable to slabs without openings. Moreover, [21]. Figure 5 illustrates the preparation and application process of the CFRP strengthening sheets to a casted slab.

Figure 5. Strengthening with CFRP Sheets [21]

Basalt Fibre-Reinforced Polymers (BFRP) present a sustainable and high-performance alternative to conventional FRPs for structural strengthening. Their application is particularly innovative for enhancing the punching shear capacity of slab column connections. This approach directly mitigates the prevalent durability and corrosion concerns inherent in traditional steel reinforcement systems [22]. In recent years, BFRP have gained attention as an efficient strengthening technique for precast and cast-in-place concrete slabs, offering advantages such as ease of installation, lightweight handling, and high mechanical performance. Several experimental investigations have examined the structural behavior of slabs incorporating openings when strengthened with externally bonded BFRP composites as shown Figure 6. For instance, researchers have demonstrated that applying BFRP strips externally to slabs with cutouts can restore or even enhance their original load-carrying capacity, similar to or greater than that of slabs without openings [23]. The researches confirmed that the opening size, shape, and location critically influence the performance of BFRP-strengthened slabs. Properly applied BFRP can significantly enhance both the load capacity and stiffness of these slabs. However, this effectiveness is contingent on preventing premature debonding failure. Achieving this requires meticulous surface preparation, a suitable adhesive, and optimal fiber orientation to fully mobilize the composite's tensile strength [24].

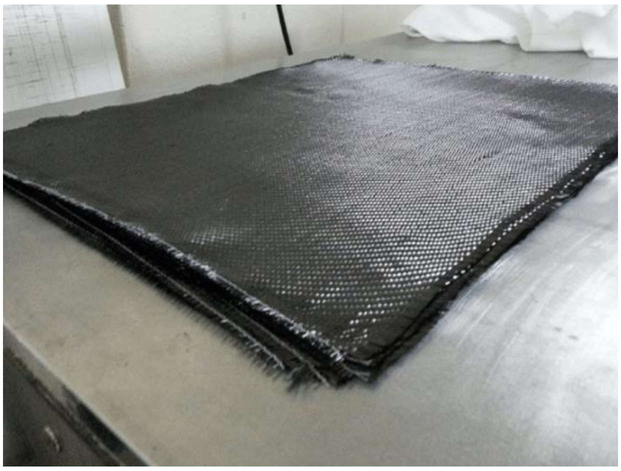


Figure 6. BFRP sheets [25]

1.6 Steel Plate Strengthening System

Steel plate strengthening has long been recognized as an effective technique for enhancing the load-carrying capacity and punching shear resistance of reinforced concrete (RC) slabs, particularly at slab–column connections where stress concentration is critical. The method involves attaching steel plates to the tension or compression zones of the slab using mechanical fasteners, epoxy adhesives, or a combination of both. This strengthening approach represents one of the earliest and most reliable techniques for upgrading existing concrete structures, offering significant improvements in both strength and stiffness [26]. The use of externally bonded steel plates has proven advantageous due to their high tensile strength, excellent ductility, and well-understood structural behavior. Unlike fiber-reinforced polymer (FRP) composites, steel plates possess isotropic mechanical properties and can sustain plastic deformation prior to failure, providing a visible warning before collapse. Furthermore, the availability and ease of fabrication of steel plates make this technique practical and economical, particularly for the rehabilitation of slabs, beams, and bridge decks [27]. Experimental studies have demonstrated the effectiveness of steel plate bonding in restoring the original load capacity of slabs weakened by openings or cutouts. For example, **Vasques and Karbhari** [27] investigated the structural response of reinforced concrete slabs with openings strengthened using externally bonded steel plates. Their findings revealed that steel plate strengthening could fully recover or even exceed the initial load-bearing capacity of the uncut slabs. Similarly, **Enochsson et al.** [28] analyzed the required steel reinforcement ratio and plate thickness to achieve comparable performance to that of solid slabs, emphasizing the importance of plate configuration and bonding quality in achieving optimal results. Other researchers, such as **Tan and Zhao** [29] studied the reinforcement of one-way slabs with central and edge openings using steel plate systems. Their results confirmed that externally bonded steel plates significantly enhanced the stiffness and load-carrying capacity of slabs with openings, provided that premature debonding and corrosion were prevented through proper surface preparation and protective coatings. The study also noted that the failure mode shifted from brittle shear failure to a more ductile flexural behaviour, reflecting improved structural resilience. Figure 7 illustrates a typical steel plate strengthening setup, showing the preparation and bonding process used in experimental investigations.

Figure 7. Steel Plate Strengthening [29]

The steel plate bonding technique continues to be an effective and reliable strengthening solution, offering a balance between high strength, ductility, and cost-efficiency, making it a suitable alternative for upgrading reinforced concrete slabs in both new and existing structures

2. Previous Researches

There are many researchers have studied the punching shear of RC slabs with various configuration (dimensions, concrete type, opening, and strengthening techniques). In this study, the researches reviewed in the time interval from 2000s to 2025.

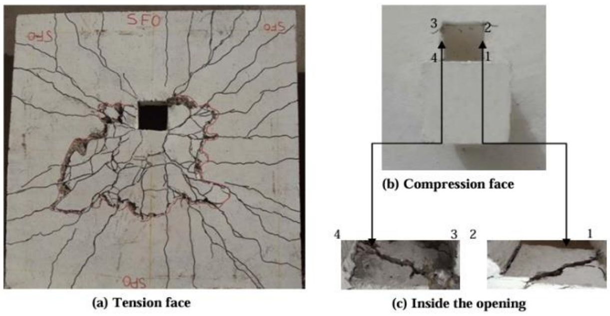
Al-Abasei et al. (2007) [30] conducted an experimental study on fourteen reinforced concrete flat slabs of dimensions 1000 x 1000 x 70 mm, with a central column of 150 x 150 x 200 mm, to evaluate the effectiveness of steel plate shear heads in enhancing punching shear resistance. The slabs were tested under axial loading through a central column, with steel plate dimensions varying from 250 x 250 mm to 450 x 450 mm, and thicknesses of 5 mm, 8 mm, and 12 mm, along with shear connectors arranged in 2 or 3 rows at 22.3 mm spacing. Results showed that initial cracking load increased from 12 kN in reference slabs to 30 kN in specimens with enhanced shear heads. Ductility index improved from 8.35 in reference slabs to 8.38 (0.19% increase) and 7.94 (55.38% increase) in optimized specimens. Ultimate load capacity increased by up to 54.33%, reaching 79.5 kN in slab P83R compared to 64.5 kN in reference slabs. All slabs failed in punching shear, with failure patterns mirroring the 450 x 450 mm plate shape. Increasing shear connectors did not enhance ultimate load, as cracks propagated around them. However, larger plate dimensions (450 x 450 mm) and greater thickness (8-12 mm) consistently improved ultimate deflection up to 19.85 mm. The study concluded that properly configured steel plate shear heads enhance ductility and strength, but design must ensure adequate rigidity and interaction with concrete.

Said, Tian, and Hussein (2013) [31] conducted a study to evaluate the feasibility of using Artificial Neural Networks (ANNs) for predicting the punching shear strength of interior reinforced concrete slab-column connections without shear reinforcement, under monotonic concentric loading. The primary purpose was to develop a more accurate predictive model compared to existing empirical design code equations, such as those from ACI 318-08 [32], Eurocode 2 [33] , DIN 1045 [34], and BS 8110 [35]. Their methodology involved compiling and homogenizing an extensive experimental database from literature, initially consisting of 205 specimens, which was filtered to 153 tests based on strict criteria to ensure predominant shear failure, uniform flexural reinforcement, specific column shapes (square or circular), and controlled slab thickness (70–200 mm). The specimens varied in concrete compressive strength (9.6–102.3 MPa), effective depth (70–200 mm), flexural reinforcement ratio (0.4–6.9%), and other geometric parameters, with the dataset split into 122 samples for training and 31 for testing the ANN model. The ANN, a multilayer perceptron network with five input parameters, one hidden layer of eight neurons, and a tangent sigmoid transfer function, was trained using back-propagation.

The key finding was that the ANN model significantly outperformed all considered design codes, achieving an average absolute error of only 9.12%, compared to errors ranging from 16.10% to 51.20% for the code equations. The model demonstrated superior accuracy in capturing the complex relationships between input parameters and punching shear capacity, closely aligning predicted values with experimental results. A significant highlight was the identification of limitations in current code approaches, particularly their conservative and often inaccurate predictions for high-strength concrete and thicker slabs, suggesting a need for revised concrete strength and size-effect terms. Strengths of the research include the use of a large, carefully filtered database, a systematic comparison with multiple international codes, and the demonstration of ANN’s potential as a robust, data-driven tool for structural assessment. However, weaknesses involve the model’s reliance on the specific parameter ranges within the training data, limiting its extrapolation capability, and the exclusion of parameters like steel yield stress and compression reinforcement, which may affect generalizability to all practical scenarios.

Maya Duque et al. (2012) [36] conducted research with the purpose of developing a mechanical model to predict the punching shear strength and behavior of steel fiber reinforced concrete (SFRC) slabs, integrating both conventional reinforcement and fibre contributions. The methodology utilized the Critical Shear Crack Theory (CSCT) coupled with the Variable Engagement Model (VEM) for fiber action, validated against an extensive experimental database of 140 slab-column connections from 13 independent studies. The specimens varied in slab depth (55–180 mm), column size, concrete compressive strength (14–108 MPa), longitudinal reinforcement ratio (0.37–2.53%), and fiber volume (0–2%). The findings demonstrated that the proposed model accurately predicts punching strength, with an average experimental-to-predicted strength ratio of 1.08 and a low coefficient of variation. A key finding is the coupling of concrete and fiber contributions through the critical shear crack opening, which is proportional to slab rotation and effective depth, allowing the model to capture the enhanced strength and deformation capacity provided by fibers. The research strengths lie in its robust physical-mechanical basis, moving beyond empirical formulas, and its comprehensive validation across a wide range of parameters. However, a weakness is the inherent complexity of the full model, though the authors successfully derived a simplified, code-like design equation suitable for practical use, which maintains good accuracy with a reasonable safety margin.

Oukaili and Salman (2014) [37] investigated the influence of opening size and location on the punching shear behavior of RC flat plate. The study addressed the practical need for service openings near columns and their impact on brittle punching failure. Six specimens were tested under punching shear failure. All specimens measured 1000 × 1000 mm with a slab thickness of 70 mm and concrete strength of 30 MPa. Reinforcement consisted of a single layer of 6 mm diameter bars. Square openings of 100 × 100 mm, 150 × 150 mm, and 225 × 225 mm were introduced at different locations. Results showed a significant reduction in punching shear capacity due to openings. The maximum strength loss reached 29.25% for the largest opening adjacent to the column. Openings placed one slab thickness away caused a lower reduction of 13.47%. Corner openings were less detrimental than front-facing openings, with only an 11.43% reduction, Figure 8 shows the punching zone. Slab stiffness at service load decreased by up to 83%, accompanied by wider cracking. Despite limited specimens and lack of opening reinforcement, the study provides valuable experimental insight for design practice.



(a) Tension face

(b) Compression face

(c) Inside the opening

Figure 8. Punching zone [37]

Haidar (2016) [38] conducted an experimental study aimed at investigating the potential of externally bonded Aluminium sheets to enhance the punching shear strength of reinforced concrete slabs. The research sought to compare experimental results with predictions from major design codes, including ACI 318-11[39], BS8110-1997 [35], and Eurocode 2-2004 [33]. The methodology involved testing a total of 16 square slabs measuring 800×800×100 mm, divided into two groups based on concrete compressive strength: normal concrete (30 MPa) and high-strength concrete (65 MPa). Each slab was reinforced with a consistent steel ratio of 0.00859 using 10 mm diameter bars, and all specimens were designed to fail in punching shear under a central 80×80 mm column load. The variables examined included the plan area of aluminium sheets (0.16, 0.24, and 0.32 m²), sheet width (50 mm and 100 mm), and the distance of sheets from the column face (0.5d, 1.5d, and 2d).

The findings revealed that aluminium sheet strengthening significantly improved punching shear performance, with ultimate load increases ranging from 5% to 41% and first crack load improvements between 11.58% and 53.57%. Notably, the most effective sheet placement was at 0.5d from the column face, and increasing the plan area of aluminium consistently enhanced strength, while sheet width had negligible impact. The study also observed that normal concrete slabs benefited more from aluminium strengthening than high-strength concrete slabs. Comparisons with design codes indicated that all codes provided conservative predictions, with ACI 318-11[39] being the most conservative. Strengths of the research include a well-structured experimental program with clear variables and practical implications for retrofitting. However, weaknesses lie in the limited scale of specimens, the absence of long-term or cyclic load testing, and the need for further validation in real-world structural configurations.

Oukaili and Merie (2021) [40] conducted an experimental and numerical investigation aimed at evaluating the influence of openings near column areas on the punching shear resistance of reinforced concrete bubbled slabs, as well as assessing the effectiveness of strengthening such slabs with CFRP sheets. The primary purpose of the research was to understand how the presence, size, and location of openings, combined with the distribution pattern of void formers (plastic spheres), affect the structural performance of bubbled slabs, and to determine whether CFRP strengthening could mitigate the resulting reduction in load-carrying capacity.

The methodology involved testing fourteen large-scale slab specimens, each measuring 2000 × 2000 × 230 mm, designed as isolated interior slab-column connections. The specimens included solid and bubbled slabs, with spherical plastic voids of 180 mm diameter arranged in different patterns relative to the critical shear perimeter. Variables examined were opening dimensions (300 × 300 mm and 450 × 450 mm), opening position (in front of or at the column corner), distance from the column face (0 mm or 200 mm), and bubble distribution (inside or outside the critical shear zone) as shown in Figure 9. Four specimens were strengthened with unidirectional CFRP sheets applied around the openings. The concrete mix had an average compressive strength of approximately 27 MPa, and reinforcement consisted of two layers of steel bars with yield strengths around 568 MPa and 466 MPa, respectively. No shear reinforcement was used. Testing was performed under monotonic static loading until failure, with measurements taken for deflection, strain, and crack development. Numerical modelling was also conducted using ANSYS finite element software to validate experimental results.

The findings revealed several significant outcomes. The introduction of openings near the column significantly reduced punching shear capacity, with reductions reaching up to 65.8% compared to the solid slab. The distribution of voids played a critical role: when voids were placed outside the critical shear perimeter, the degradation was less severe, and the load capacity improved by 33.3–38.5% compared to slabs with voids distributed throughout. CFRP strengthening was effective, enhancing shear capacity by 22.2–30.8% compared to unstrengthened bubbled slabs with openings, though it did not fully restore the capacity to that of an unperforated bubbled slab. Deflection was more influenced by void distribution than by opening parameters, and strengthened slabs exhibited greater post-cracking stiffness. The finite element models showed acceptable agreement with experimental results, with failure load predictions generally within 5–16% of tested values.

Among the strengths of this research are its comprehensive experimental design, which systematically varied multiple parameters, and the integration of finite element analysis for validation. The study provides practical insights into the behavior of bubbled slabs with openings a topic with limited prior research—and offers useful recommendations for strengthening techniques. However, weaknesses include the limited scale of the specimens relative to real-world applications and the assumption of perfect bond in the numerical model, which may overestimate stiffness. Additionally, the study did not explore the long-term durability of CFRP strengthening or the effects of cyclic loading, which are important for practical implementation. Despite these limitations, the research offers valuable data and analysis for engineers designing and rehabilitating bubbled slab systems with openings.

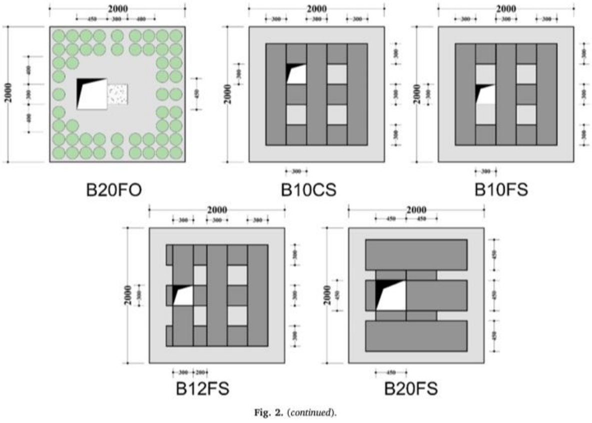


Figure 9. Fabrication of experimental bubbled slabs [40]

Yooprasertchai et al. (2021) [41] conducted experimental research with the purpose of investigating the influence of opening shape, number, and location on the punching shear capacity of reinforced concrete flat slabs. The methodology involved testing fourteen square slab specimens measuring 1000x1000x80 mm, constructed with two different concrete compressive strengths (20.18 MPa and 29.71 MPa) and reinforced with 10 mm bars at 175 mm spacing in both directions, achieving a flexural reinforcement ratio of 0.6%. The key variables were the opening shape (circular, square, and rectangular), the number of openings (2 or 4), and their distance from the column face (1h or 4h, where h is slab thickness). The findings demonstrated that openings significantly reduce punching capacity when placed close to the column, with a distance of 4h having minimal effect, thus validating code provisions. A significant highlight was that circular openings had the least detrimental impact on strength, followed by square and then rectangular openings, due to stress concentrations at corners, and increasing the number of openings from two to four substantially reduced capacity. The strength of this research is its novel and systematic examination of opening shape, a previously understudied factor, providing practical insights for design codes. A primary weakness is the use of only two concrete strength grades and the absence of shear reinforcement, which may limit the direct applicability of the results to all practical scenarios.

Abbas H. Mohammed (2022) [42] conducted experimental research with the purpose of investigating the influence of steel fiber volume ratio and column shape on the punching shear behavior of small-scale reinforced concrete flat slabs. The methodology involved testing ten slab specimens measuring 450x450x80 mm, cast from a concrete mix with a 28-day compressive strength ranging from approximately 48.8 MPa for plain concrete to 59.8 MPa for fiber-reinforced concrete. The key variables were the steel fiber volume fraction (0%, 0.5%, 1%, 1.5%, and 2%) and the stub column shape (square and circular), with all slabs lacking conventional shear reinforcement. The findings demonstrated that the addition of steel fibers significantly enhanced performance, with the slab containing 2% fibers and a square column (S5) exhibiting a 21.8% increase in punching shear capacity and a 42% increase in ultimate deflection compared to the plain concrete control. A significant highlight was that square columns provided an approximately 11% higher punching capacity than circular columns due to their larger bearing area. The strength of this research lies in its clear experimental demonstration of the dual benefits of fibers increased strength and ductility and its practical investigation of column shape. A primary weakness is the small scale of the specimens and the limited scope of parameters, such as testing only one fiber type and geometry, which may affect the direct scalability of the results to full-scale structural applications.

Ghayeb et al. (2023) [43] conducted research to experimentally and analytically investigate the effectiveness of externally bonded CFRP sheets as a strengthening technique for enhancing the punching shear capacity of two-way reinforced concrete flat slabs. The primary purpose of the study was to assess the performance of different CFRP sheet configurations in delaying crack formation, improving load-displacement behavior, increasing ductility, and ultimately boosting the punching shear strength of slab-column connections, while also developing and validating an analytical model for predicting the ultimate strength of such strengthened slabs.

The methodology involved testing four solid square slab specimens, each measuring 1000 mm x 1000 mm in plan with a 60 mm thickness. The concrete was designed for a target compressive strength of 30 MPa, and the slabs were reinforced with 6 mm diameter Grade 60 deformed steel bars. The experimental variables focused on the external strengthening scheme as shown in Figure 10 using unidirectional CFRP sheets bonded to the tension face (bottom) of the slabs with epoxy resin. Three strengthening schemes were evaluated: sample SS1 used two 150 mm wide CFRP strips in each direction; SS2 used three 150 mm wide strips in each direction; and SS3 used six 75 mm wide strips in each direction, resulting in a denser configuration. A fourth unstrengthened sample (CS) served as the control. The slabs were simply supported and subjected to a central static concentrated load through a steel section simulating a column, with instrumentation including LVDTs and strain gauges to monitor deflection, strain, and crack behavior.

The findings demonstrated that the CFRP strengthening significantly improved performance across all metrics. The most significant outcome was the progressive enhancement correlated with the amount and configuration of CFRP. Sample SS3, with the highest CFRP ratio and smallest spacing between strips, exhibited the best overall performance: it delayed the first crack, achieved the highest ultimate load (65.50 kN, a 16.96% increase over the control), showed the largest mid-span displacement (a 32.90% increase), and displayed the greatest ductility (a 73.15% enhancement). Furthermore, crack widths were substantially reduced in all strengthened specimens. The failure mode shifted from a brittle punching shear failure in the control to a more ductile failure involving CFRP debonding and concrete peeling in the strengthened slabs. The proposed analytical model, which incorporated factors for CFRP configuration and bond efficiency, showed good agreement with the experimental results and predictions from major design codes (ACI, CSA, JSCE), validating its utility for design purposes.

The research presents notable strengths, including a clear and incremental experimental design that effectively isolates the influence of CFRP amount and layout, a comprehensive performance assessment covering crack behavior, stiffness, ductility, and failure modes, and the valuable development and validation of a refined analytical model that accounts for practical CFRP application details. However, the study also has limitations. The use of small-scale slab specimens (60 mm thick) may not fully represent the behavior of full-scale, thicker slabs commonly used in practice. The research was conducted under static loading conditions only, leaving the performance under dynamic or cyclic (e.g., seismic) loads unexplored. Additionally, the study focused on a single concrete strength and a specific slab geometry with a central column, limiting the generalizability of the findings to other scenarios, such as edge columns or slabs with openings. The long-term durability of the epoxy-bonded CFRP under environmental exposure and the economic feasibility of the technique were also not addressed.

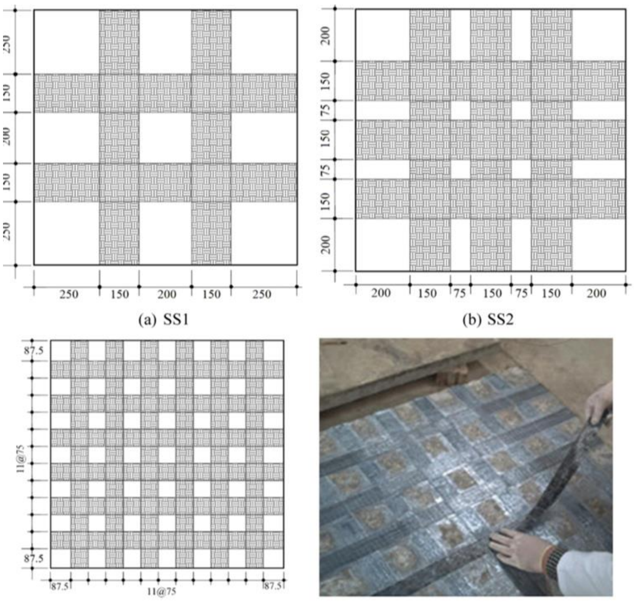


Figure 10. Strengthening scheme for the specimens [43]

Salihi and Hamad (2023) [44] experimentally investigated the punching shear resistance of two-way concrete slabs reinforced with basalt-FRP bars compared to conventional steel reinforcement. The purpose of their research was to fill a significant gap in the literature by evaluating the performance of this sustainable alternative under punching shear conditions, with implications for durable construction in bridges and high-rise buildings. Their methodology involved testing six large-scale square slabs (2000×2000 mm) representing interior slab-column connections. The variables included reinforcement type (steel vs. basalt-FRP), reinforcement ratio (0.88% to 1.77%), bar size (12 mm and 16 mm), and concrete compressive strength (approximately 21, 30, and 35 MPa). Key findings revealed that slabs with basalt-FRP bars achieved up to 89% of the punching shear capacity of steel-reinforced slabs when the equivalent axial stiffness was increased. The study also highlighted that reinforcement ratio and concrete strength significantly influenced ultimate load, deflection, and crack patterns. A major strength of the research is its comprehensive experimental approach and the proposal of a refined predictive model for enhanced accuracy. However, weaknesses include a limited number of specimens, the exclusion of long-term or cyclic loading effects, and logistical constraints in material sourcing, which may affect the generalizability of the results. Figure 11 shown the cracks patterns for the tested specimens.

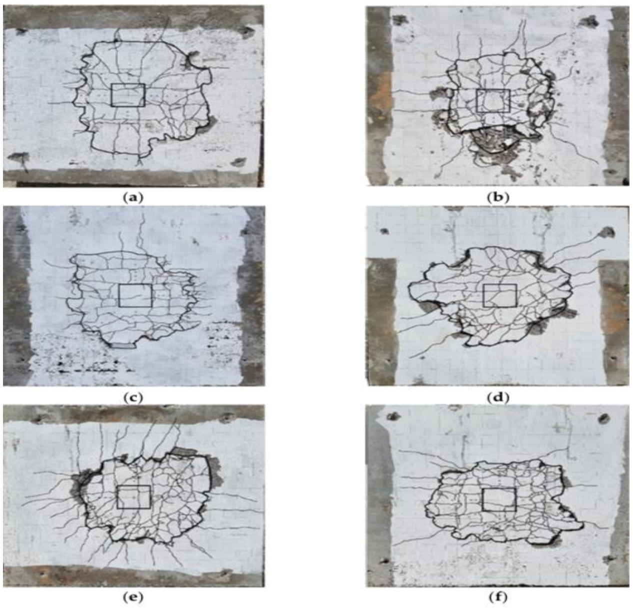


Figure11. Punching shear failure and cracks pattern [44]

Duan and Zhang (2023) [45] conducted an experimental study to compare the punching shear behaviour of two-way concrete slabs reinforced with a CFRP grid against those reinforced with traditional HRB400 steel bars. The purpose was to evaluate the potential of using CFRP grids as a non-corrosive, high-strength alternative in slab-column systems. Their methodology involved testing two full-scale slabs, each measuring 1800 x 1800 x120 mm and made with concrete having a mean compressive strength of 23.1 MPa. One slab (S1) was reinforced with a CFRP grid at a ratio of 0.33%, while the other (S2) used steel bars at 0.37%. The key findings revealed that the

CFRP-reinforced slab exhibited a 40% higher ultimate load capacity (281.3 kN vs. 200.1 kN) despite a lower reinforcement ratio, and it failed with a significantly smaller punching cone angle of 24.1° compared to 38° in the steel-reinforced slab, indicating a different failure mechanism. The most significant finding was the superior performance and two-way integrity provided by the CFRP grid as illustrated in Figure 12. A major strength of this research is its direct experimental comparison providing clear, quantifiable data on a relatively novel reinforcement material. However, a primary weakness is the very limited scope, with only one specimen per variable, which restricts the generalizability of the results and prevents a robust statistical analysis of the observed behavior.

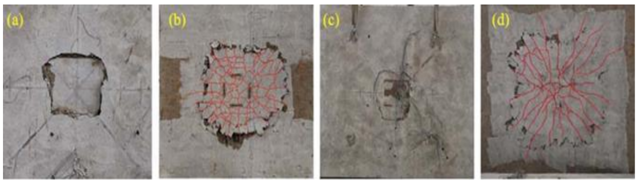


Figure 12. Distribution of cracks on the surface of the slab [45].

Abdul Sahib et al. (2024) [46] conducted an experimental and numerical investigation to explore the enhancement of using CFRP sheets to enhance the punching shear capacity of RC flat slabs. The primary purpose of the research was to evaluate the effectiveness of various CFRP strengthening configurations on interior, edge, and corner slab-column connections, addressing a gap in existing design codes, particularly for edge and corner conditions. The methodology involved testing nine small-scale slab specimens (1000 × 1000 × 100 mm) made of concrete with a compressive strength of 45 MPa and reinforced with 14 mm steel rebars. Three specimens served as controls, while the others were strengthened with different patterns of unidirectional CFRP strips, including multi-directional and orthogonal layouts.

The findings revealed that CFRP strengthening significantly improved punching shear resistance, with increases of up to 64% in some configurations, and also enhanced stiffness and energy absorption. However, this often resulted in reduced ductility. A key significant finding was that strengthening was more effective for edge and corner connections than for interior ones. The study also highlighted that moving the load closer to supports increased load capacity but reduced ductility, promoting brittle failure. Among the strengths of this research are the combination of experimental and finite element analysis, the practical slab dimensions, and the direct comparison with ACI code predictions, which showed improved accuracy when CFRP was used. A weakness, however, is the use of small-scale specimens, which may not fully represent full-scale structural behaviour, and limited discussion on the long-term durability or economic feasibility of the proposed strengthening techniques as shown in Figure 13.

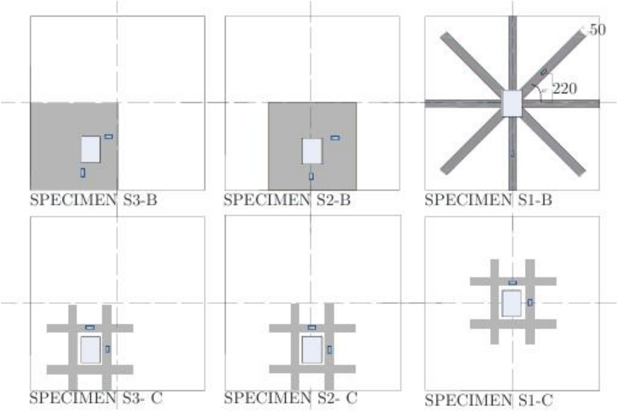


Figure 13. The strengthening technique, along with the location of the strain gauges [46]

Hamoda et al. (2024) [47] investigated the punching shear performance of reinforced concrete slab-to-steel column connections enhanced by partially replacing the critical shear zone with high-performance concretes specifically Engineered Cementitious Composite (ECC) and Ultra-High Performance ECC (UHPECC). The study aimed to evaluate the effectiveness of these materials in improving load capacity, ductility, and failure modes under both concentric and eccentric loading conditions. The experimental program involved testing eight square slabs as shown in Figure 14, each measuring 1000 × 1000 × 120 mm, with an effective depth of 100 mm and reinforced with

0.4% flexural steel. The slabs incorporated post-cast zones of ECC or UHPECC at varying distances (S = 1d, 1.5d, 2d) from the steel column flanges and were compared to control slabs made of normal concrete (MPa). Advanced instrumentation and nonlinear finite element modelling (Abaqus) were used to simulate and validate the structural behavior.

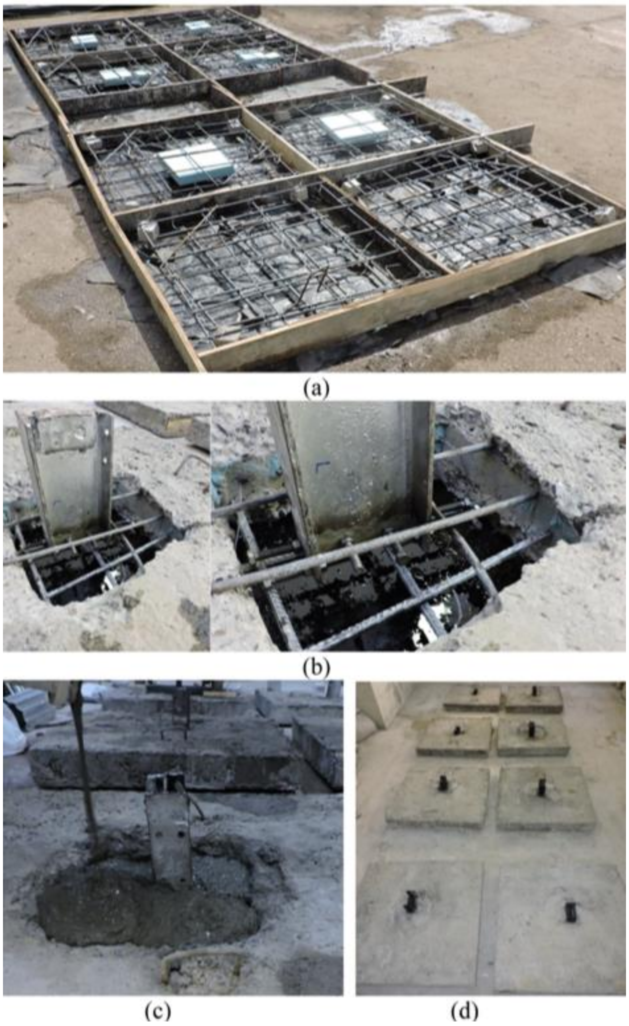


Figure 14. Casting and preparation of slabs [47]

The findings demonstrated significant improvements in performance, with the most notable results observed for slabs with UHPECC at S = 2d, which increased ultimate loads by 33% under concentric loading and 28% under eccentric loading compared to control slabs. Additionally, these configurations showed enhanced elastic stiffness (up to 84% increase) and energy absorption capacity (up to 218% improvement). A key insight from the parametric study was that increasing the S/d ratio beyond 3.5 yielded diminishing returns on punching shear capacity. The research strengths include a comprehensive experimental-numerical approach, clear validation of finite element models, and practical design equations proposed for engineers. However, weaknesses lie in the limited scale of specimens, the absence of long-term durability or fire resistance assessments for the hybrid connections, and the need for further validation in full-scale structural applications under dynamic loads.

Selim et al. (2024) [48] investigated the punching shear capacity of reinforced concrete flat slabs utilizing both traditional steel and innovative superelastic Nickel-Titanium (Ni-Ti) shape memory alloy (SMA) bars as shear reinforcement under repeated vertical loading. The primary purpose of this research was to experimentally and numerically assess the effectiveness of SMA stirrups in enhancing the punching shear resistance, ductility, and energy absorption of slab-column connections, comparing their performance against conventional steel stirrups and an unreinforced control specimen.

The methodology involved testing nine half-scale slab-column specimens, each measuring 1100 mm x 1100 mm in plan with a 120 mm thickness and a 150 mm x 150 mm protruding column as shown in Figure 15. The experimental variables included the type of shear reinforcement (steel or SMA), the orientation of stirrups (vertical or inclined), and the spacing between stirrups (0.5d or d, where d is the effective depth of 100 mm). The concrete mix was designed for a target compressive strength of 30 MPa, and the reinforcement comprised high-tensile steel bars for flexural reinforcement, with closed stirrups made of either steel or Ni-Ti SMA for shear reinforcement. The SMA bars were surface-treated to improve bond with concrete. A complementary three-dimensional finite element model was developed using ABAQUS, incorporating the Concrete Damage Plasticity model for concrete and appropriate constitutive models for steel and super elastic

SMA, which was validated against the experimental results.

The findings demonstrated that the inclusion of shear reinforcement, particularly inclined stirrups, significantly improved the punching shear performance. Specimens with inclined SMA stirrups at 0.5d spacing exhibited the most substantial enhancements, showing increases in ultimate load capacity up to 51.38% and in cracking load up to 57.65% compared to the control slab. Notably, slabs reinforced with SMA stirrups displayed superior ductility and energy absorption capacity, with absorbed energy increasing by as much as 102.54%, alongside a remarkable deflection increase of 116.61% for one configuration. The SMA reinforcement also contributed to reduced crack widths and better crack distribution, with cracks forming farther from the column face. The finite element analysis closely mirrored the experimental outcomes, validating the numerical model's accuracy in predicting load-deflection behavior, crack patterns, and failure modes.

The research presents several strengths, including a well-designed comparative experimental program that systematically evaluates a novel smart material (SMA) against conventional steel, the successful integration of advanced numerical modeling for validation and deeper insight, and the clear demonstration of SMA's superior performance in enhancing ductility, energy dissipation, and deformation capacity—key attributes for seismic resilience. However, the study also has limitations. The use of half-scale specimens, while practical, may not fully capture the behavior of full-scale structural elements. The research focused on a single concrete grade (30 MPa) and a specific slab geometry, limiting the generalizability of the findings to other strengths or configurations. Furthermore, the experimental program was conducted under repeated vertical loading only; the performance under combined cyclic lateral and gravity loads, which is critical for seismic applications, was not investigated. Finally, the cost implications and practical construction challenges associated with implementing SMA reinforcement in real-world projects were not addressed, which is an important consideration for widespread adoption.

Figure 15. Casting curing, and testing of specimens [48]

Ali (2025) [49] conducted a research study to evaluate the performance of geopolymer concrete in circular slabs subjected to punching shear and the effect of external strengthening using CFRP sheets. Eleven circular specimens, each 750 mm in diameter and 70 mm thick, were cast and tested. The specimens included slabs with and without openings and were supported by either a central or edge column with a diameter of 150 mm. The geopolymer concrete, had compressive strength of about 35 MPa, and the reinforcement included 8 mm bars spaced at 75 mm centers and 6 mm column ties. The findings revealed that openings near the column significantly reduced the first cracking load (up to 32.9%) and ultimate load, whereas the use of CFRP increased the ultimate load by up to 28% in central-column specimens. Notably, CFRP sheets also improved shear stress resistance and decreased deflection values. The research's strength lies in its innovative use of sustainable materials and comprehensive experimental setup. However, a limitation is the relatively small number of specimens in each test group, which may affect the generalizability of the results. Figure 16 shows the crack pattern for the specimens.

Figure 16. Crack pattern for circular specimen [49]

Saad (2025) [50] conducted an experimental study to investigate the punching shear behavior of geopolymer concrete flat slabs with openings near columns and their strengthening using CFRP. The research aimed to explore the environmental and structural benefits of geopolymer concrete as an alternative to ordinary Portland cement, and to evaluate how openings adjacent to columns affect punching shear capacity, as well as the effectiveness of CFRP sheets in restoring or enhancing this capacity. The methodology involved testing 14 square slab specimens (700 × 700 × 70 mm) with centrally, edge-, and corner-located columns (150 × 150 × 150 mm). The geopolymer concrete, based on Ground Granulated Blast Furnace Slag (GGBS), achieved a compressive strength of 42 MPa, and all slabs were reinforced with 8 mm diameter steel bars at 110 mm spacing. The test variables included the presence of a 100 mm square opening near the column and the application of CFRP in different configurations (local strips or full wrapping). Key findings revealed that introducing an opening near the column significantly reduced the ultimate load capacity by 29% and lowered the first cracking load by 55%. However, the application of CFRP notably improved performance, with some configurations increasing the ultimate load by up to 77% and shear stress capacity by 80% compared to unrepaired slabs. Full wrapping of CFRP around the column proved most effective. Strengths of the research include its practical focus on a relevant structural problem, a clear experimental matrix, and valuable quantitative results on CFRP effectiveness. A limitation, however, is the use of a single, relatively small opening size and the limited exploration of other variables such as different CFRP layouts or long-term durability, which could be addressed in future studies.

Su et al. (2025) [51] conducted a comprehensive experimental and theoretical study to investigate the effectiveness of using ECC to strengthen reinforced concrete flat slab-column connections against brittle punching shear failure. The primary purpose of the research was to evaluate the improvement in punching shear behavior, load-bearing capacity, ductility, and failure mechanisms by incorporating ECC (with polyethylene/PE and hybrid steel/PE fibres) into the critical connection zone, and to develop a modified analytical approach for predicting the punching shear strength of such ECC-enhanced connections by accounting for the altered failure surface, Figure 17 shows the casting of specimens.

The methodology involved preparing and testing eight slab-column connection specimens. All slabs measured 1400 mm x 1400 mm in plan with a 120 mm thickness, connected to a 200 mm x 200 mm column. Two control specimens (NC-1.0 and NC-1.5) were cast entirely with normal concrete having a compressive strength of 40.81 MPa and reinforced with steel ratios of 1.0% and 1.5% using 12 mm diameter HRB400 bars. The six strengthened specimens featured a localized ECC zone cast around the column within the otherwise normal concrete slab. The experimental variables included the ECC zone side length (440, 560, 680 mm), steel reinforcement ratio (1.0%, 1.5%), and the type/dosage of fibres within the ECC: 1% PE fibres (PE1-ECC), 2% PE fibres (PE2-ECC), and a hybrid of 0.5% steel plus 1.5% PE fibres (SP2-ECC). The specimens were subjected to concentric static loading with instrumentation to measure deflection, steel strain, and crack development.

The findings demonstrated that the incorporation of ECC significantly enhanced the structural performance. The most significant outcomes were the transformation of the failure mode from a brittle punching shear in control specimens to a more ductile flexural-induced punching shear in ECC-enhanced connections, accompanied by a substantial increase in ductility and deformation capacity. ECC increased the first crack load by 18.58–33.31% and the peak load by 34.15–37.76% compared to the control. Specimens with a higher PE fibre dosage (2%) showed a 17.20% higher peak load and a 29.27% higher yield load than those with 1% PE fibres, while the hybrid fibres improved crack resistance and stiffness but did not significantly affect the ultimate punching capacity. Crucially, the punching shear failure surface consistently formed outside the ECC zone, enlarging the critical shear perimeter and increasing the crack angle from 21–29° in normal concrete to 30–50° in ECC specimens. This observation led to the development of a modified coefficient (k) for the critical shear perimeter, which, when applied to design codes like GB50010-2010 and DIN 1045-1, provided accurate predictions of the punching shear strength.

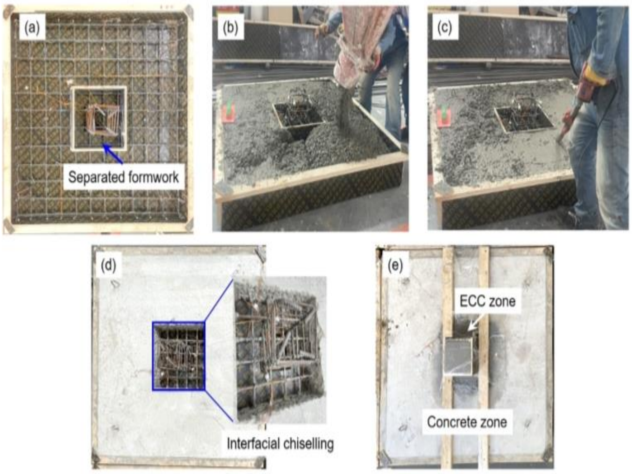


Figure 17. Specimens casting [51]

Ashteyat et al. (2025) [52] conducted a comprehensive review article aimed at synthesizing existing research on the influence of openings on the punching shear behavior of two-way RC slabs and evaluating the effectiveness of various strengthening techniques, alongside a critical assessment of the predictive accuracy of major international design codes. The purpose was to bridge the gap between isolated experimental findings, numerical simulations, and practical code provisions, providing a unified reference that integrates the effects of opening parameters, the performance of strengthening systems like FRP, Textile Reinforced Mortar (TRM), and shear studs, and the reliability of code-based predictions to guide safer and more efficient design practices for modern slab systems with service openings.

The methodology adopted a systematic PRISMA framework to ensure a transparent and objective literature review. The authors searched the Scopus database for peer-reviewed journal articles published between 2010 and 2025, using keyword combinations related to slab types, shear behavior, openings, strengthening techniques, and code evaluations. The review encompassed a wide array of experimental, numerical, and analytical studies, though it did not involve new specimen casting or testing itself; instead, it synthesized data from numerous referenced works. The included studies featured varied specimen geometries, with slabs typically being two-way flat plates of different dimensions and concrete compressive strengths often reported in the range of 25-40 MPa, reinforced with conventional steel bars, and in some cases strengthened with CFRP, TRM, or shear studs. The analysis focused on extracting key experimental outcomes, numerical validation results from finite element models (primarily using ABAQUS with Concrete Damaged Plasticity material models), and comparisons between experimental failure loads and code predictions from ACI 318-19 [53], Eurocode 2 [33], MC2010 [54], BS 8110 [35], TS 500 [55], and ECP 203 [56].

The findings highlighted several significant points. Openings near the column can reduce punching shear capacity by up to 45%, with circular openings causing less reduction than rectangular ones. Among strengthening techniques, FRP systems improved load capacity by up to 76%, while TRM composites showed superior gains in stiffness (up to 336%) and energy dissipation (118%), offering better fire resistance and bond compatibility. The review of design codes revealed that ACI 318 is consistently conservative, often underestimating capacity, whereas Eurocode 2 and Model Code

2010 provide more balanced and accurate predictions. Numerical simulations using nonlinear finite element analysis demonstrated good agreement with experimental results, effectively capturing failure mechanisms and enabling parametric studies beyond experimental limitations.

3. Conclusions

This review synthesized previous researches focused on punching shear in flat slabs with openings and associated strengthening techniques. The main conclusions are:

- Openings adjacent to columns can reduce punching shear capacity by up to 65%, with circular openings being less detrimental than rectangular ones.
- Openings within 1–2 times slab thickness cause severe degradation, while those beyond 4h have minimal effect.
- Externally bonded FRP (CFRP, GFRP, BFRP) can restore or enhance load capacity by up to 77%, though debonding must be prevented.
- ECC and UHPECC in critical zones transform brittle punching failure into ductile flexural failure, increasing capacity by up to 33%.
- Super elastic SMA stirrups improve energy absorption by over 100%, ideal for seismic applications.
- Geopolymer concrete and BFRP reinforcement offer comparable performance with lower environmental impact.

Traditional design codes underestimate capacity, whereas ANN and mechanics-based models provide more accurate predictions also, long-term durability, dynamic/seismic performance, and full-scale validation require further investigation.

References

[1] T. Ying, “Behavior and Modeling of Reinforced Concrete Slab-Column Connections,” The University of Texas at Austin, 2007.

[2] J. K. W. J.G. MacGregor, *Reinforced Concrete Mechanics and Design*, 6th editio. 2004.

[3] M. Rasheed, “Shear Behaviour in Reinforced Concrete Beams: Mechanisms, Failure Modes, and Predictive Models: A Review,” *Al-Rafidain J. Eng. Sci.*, pp. 210–227, 2024.

[4] A. Committee, “318M-19: Building Code Requirements for Concrete and Commentary,” *Aci 318-19M*, p. 628, 2019.

[5] S. B. of R. C. T.-W. S. with O. Buildings, “Peer-Reviewed Journal,” *Build. 2765*, 2025.

[6] Shital Borkar, I. Khedikar, and K. Dabhekar, “ANALYSIS OF FLAT SLAB STRUCTURE AND CONVENTIONAL SLAB STRUCTURE,” *J. Emerg. Technol. Innov. Res.*, vol. 10, p. 11, 2018.

[7] T. Huber, J. Burger, J. Mata-Falcón, and W. Kaufmann, “Structural design and testing of material optimized ribbed RC slabs with 3D printed formwork,” *Struct. Concr.*, vol. 24, no. 2, pp. 1932–1955, 2023, doi: 10.1002/suco.202200633.

[8] P. H. Thu Htun, N. Phone, and K. Zeyar Win, “Comparative Study on Analysis and Design between Flat Slab and Flat Plate System for RC Building,” *Int. J. Sci. Eng. Appl.*, vol. 7, no. 9, pp. 313–317, 2018, doi: 10.7753/ijsea0709.1013.

[9] Yonca Hurol, *The Tectonics of Structural Systems: An Architectural Approach*, First Edit. Northern Cyprus: Routledge (Taylor & Francis Group), London & New York, 2016.

[10] W. L. Park, Robert & Gamble, *Reinforced Concrete Slabs*, 2nd ed. New Jersey, USA: John Wiley & Sons, Inc, 1999. doi: Non.

[11] A. Al-, “Experimental Study of Flat Plate Construction with Special Embedded Shearhead,” Al-Mustansiriya University, Baghdad, Iraq, 2006.

[12] B. Regúlez, D. M. V Faria, L. Todisco, M. Fernández Ruiz, and H. Corres, “Sustainability in construction: The urgent need for a new ethics,” *Struct. Concr.*, vol. 24, no. 2, pp. 1893–1913, Apr. 2023, doi: https://doi.org/10.1002/suco.202200406.

[13] M. J. Awad and M. M. Rasheed, “Influence of compression reinforcement on shear strength and failure modes in reinforced concrete beams,” *J. Build. Pathol. Rehabil.*, vol. 10, no. 1, p. 65, 2025.

[14] O. Enochsson, J. Lundqvist, B. Täljsten, P. Rusinowski, and T. Olofsson, “CFRP strengthened openings in two-way concrete slabs – An experimental and numerical study,” *Constr. Build. Mater.*, vol. 21, no. 4, pp. 810–826, 2007, doi: https://doi.org/10.1016/j.conbuildmat.2006.06.009.

[15] A. Ashteyat, M. Shhabat, A. Al-Khreisat, and S. Aldawsari, “Shear Behavior of Reinforced Concrete Two-Way Slabs with Openings,” *Buildings*, 2025, doi: 10.3390/buildings15152765.

[16] T. El-Shafiey, A. Atta, A. Hassan, and M. Elnasharty, “Effect of opening shape, size and location on the punching shear behaviour of RC flat slabs,” *Structures*, 2022, doi: 10.1016/j.istruc.2022.08.076.

[17] Vasques & Karbhari, “Evaluation of efficiency of externally bonded FRP composite strips for strengthening RC slabs with openings,” *Compos. Part B Eng.*, vol. 40, no. 8, p. 724, 2009, doi: 10.1016/j.compositesb.2009.04.01.

[18] A. M. Imran and M. J. Awad, “Structural efficiency of non-prismatic reinforced concrete beams: a comprehensive review,” *Khwarizmia*, vol. 2024, pp. 57–62, 2024.

[19] A. Ibrahim and M. Sherif, “Strengthening of RC flat slabs against punching shear with GFRP laminates adopting a hybrid technique,” *Eng. Appl. Sci. Res.*, vol. 50, pp. 490–498, 2023, doi: 10.14456/easr.2023.51.

[20] ACI Committee 440.1R-06, “Guide for the design and construction of concrete reinforced with FRP bars,” *Am. Concr. Inst.*, p. 44, 2006, [Online]. Available: www.concrete.org

[21] H. Tan, K.H. & Zhao, “Strengthening of openings in one-way reinforced concrete slabs using CFRP systems,” *Cem. Concr. Compos.*, vol. 26, no. 7, p. 673, 2004, doi: j.cemconcomp.2003.09.009.

[22] J. Sim, C. Park, and D. Y. Moon, “Characteristics of basalt fiber as a strengthening material for concrete structures,” *Compos. Part B Eng.*, vol. 36, no. 6, pp. 504–512, 2005, doi: https://doi.org/10.1016/j.compositesb.2005.02.002.

[23] V. Fiore, T. Scalici, G. Di Bella, and A. Valenza, “A review on basalt fibre and its composites,” *Compos. Part B Eng.*, vol. 74, pp. 74–94, 2015, doi: https://doi.org/10.1016/j.compositesb.2014.12.034.

[24] S. S. Aman, B. S. Mohammed, M. A. Wahab, and A. Anwar, “Performance of reinforced concrete slab with opening strengthened using CFRP,” *Fibers*, vol. 8, no. 4, 2020, doi: 10.3390/fib8040025.

[25] F. Azimpour-Shishevan, H. Akbulut, and M. A. Mohtadi-Bonab, “Effect of thermal cycling on mechanical and thermal properties of basalt fibre-reinforced epoxy composites,” *Bull. Mater. Sci.*, vol. 43, no. 1, 2020, doi: 10.1007/s12034-020-2059-y.

[26] R. Pucinotti, A. D. Elia, and R. A. De Lorenzo, “Influence of Steel Reinforcement on,” vol. 3, no. 2, pp. 783–787, 2011.

[27] Jasim M.Al-Khafaji and A. H. Aziz, “EXPERMENTAL STUDY OF PUNCHING SHEAR FOR REINFORCED CONCRETE FLAT PLATE SLABS WITH COUPLED COLUMNS,” vol. 2, no. 4, 2009.

[28] M. A. Golham and A. H. A. Al-Ahmed, “Strengthening of GFRP Reinforced Concrete Slabs with Openings,” *J. Eng.*, vol. 30, no. 01, pp. 157–172, 2024, doi: 10.31026/j.eng.2024.01.10.

[29] M. Ayyad, M. Taha, and M. Zahran, “Strengthening of reinforced concrete voided slabs using steel,” *Res. Pap. Concr. Struct.*, no. July, pp. 0–7, 2021.

[30] J. S. Al-Abasei, A. N. Abbas, and H. I. Qassem, “Experimental Investigation of Steel Plate Shearheads in Reinforced Concrete Flat Slabs,” *J. Eng. Dev.*, vol. 11, no. 3, pp. 1–13, Dec. 2007.

[31] A. M. Said, Y. Tian, and A. Hussein, “Evaluating Punching Shear Strength of Slabs without Shear Reinforcement Using Artificial Neural Networks,” pp. 1–18.

[32] ACI Committee 318, “Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary,” Mar. 2008, *Farmington Hills, MI.*

[33] European Committee for Standardization, “Eurocode 2: Design of Concrete Structures - Part 1-1: General Rules and Rules for Buildings,” 2004, *Brussels, Belgium*.

[34] Deutsches Institut für Normung, “DIN 1045-1: Concrete and Reinforced Concrete, Design and Construction,” Aug. 2008, *Berlin, Germany*.

[35] British Standards Institution, “Structural Use of Concrete - Part 1: Code of Practice for Design and Construction,” 1997, *London, UK*.

[36] M. D. L. F *et al.*, “Punching shear strength of steel fibre reinforced concrete slabs,” vol. 40, pp. 93–94, 2012, doi: 10.1016/j.engstruct.2012.02.009.

[37] N. K. Oukaili, “Punching Shear Strength of Reinforced Concrete Flat Plates with Openings,” 2014.

[38] H. H. Haidar, “Improvement of punching shear strength of reinforced concrete slabs using aluminum sheet stiffeners,” 2016.

[39] ACI Committee 318, “Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary,” 2011, *Farmington Hills, MI.*

[40] N. K. Oukaili and H. D. Merie, “Case Studies in Construction Materials CFRP strengthening efficiency on enhancement punching shear resistance of RC bubbled slabs with openings,” *Case Stud. Constr. Mater.*, vol. 15, no. August, p. e00641, 2021, doi: 10.1016/j.cscm.2021.e00641.

[41] E. Yooprasertchai, Y. Tiawilai, T. Wittayawanitchai, and J. Angsumalee, “Effect of Shape , Number , and Location of Openings on Punching Shear Capacity of Flat Slabs,” 2021.

[42] A. H. Mohammed, H. M. Mubarak, A. K. Hussein, T. Z. Abulghafour, and D. E. Nassani, “HighTech and Innovation Punching Shear Characterization of Steel Fiber-Reinforced Concrete Flat Slabs,” vol. 3, no. 4, pp. 483–490, 2022.

[43] H. Hamad, R. Saeed, and M. A. Al-kannoon, “Case Studies in Construction Materials Performance of reinforced concrete flat slab strengthened with CFRP for punching shear,” *Case Stud. Constr. Mater.*, vol. 18, no. September 2022, p. e01801, 2023, doi: 10.1016/j.cscm.2022.e01801.

[44] B. Salihi and F. Hamad, “Two-Way Slab Punching Shear Resistance: Experimental Insights into Basalt-FRP Bar as Flexural Reinforcement,” *Sustain.*, vol. 15, no. 21, 2023, doi: 10.3390/su152115417.

[45] N. Duan and J. Zhang, “Comparison of Punching Shear Behaviour of Two-Way Concrete Slab Reinforced with CFRP Grid and Steel Bars,” *J. Phys. Conf. Ser.*, vol. 2463, no. 1, 2023, doi: 10.1088/1742-6596/2463/1/012013.

[46] M. Q. Abdul Sahib, R. Aghayari, M. J. Moradi, and M. Tahamouli Roudsari, “Experimental Investigation on the Rehabilitation of RC Flat Slabs Using CFRP Sheets to Enhance Punching Shear Capacity,” *Buildings*, vol. 14, no. 1, pp. 1–18, 2024, doi: 10.3390/buildings14010153.

[47] A. Hamoda, A. A. Abadel, M. Ahmed, V. Wang, and Z. Vrcelj, “Punching shear performance of reinforced concrete slab-to-steel column connections incorporating ECC and UHPECC,” *Eng. Struct.*, vol. 322, no. PB, p. 119145, 2025, doi: 10.1016/j.engstruct.2024.119145.

[48] M. Selim, K. Fawzy, H. Abdel, K. Mahmoud, K. Fawzy, and M. Zaghlal, “Results in Engineering Punching shear capacity of RC flat slabs with steel and superelastic Ni-Ti shape memory shear reinforcement under repeated loads,” *Results Eng.*, vol. 24, no. October, p. 103302, 2024, doi: 10.1016/j.rineng.2024.103302.

[49] Haider Raad Ali, “Punching Shear Behaviour of Geopolymer Concrete Circular Slab with and without Openings and Strengthening A,” Mustansiriyah University, 2025.

[50] Zahraa Maitham Saad, “Punching Shear Behavior Of Geopolymer Flat Slabs With Opening Strengthened By CFRP,” Mustansiriyah University, 2025.

[51] Y. Su, C. Wu, M. Xu, X. Wang, and C. Jin, “Case Studies in Construction Materials Strengthening of RC fl at slab-column connections against punching shear using engineered cementitious composites (ECC) with PE and hybrid steel / PE fibres : An experimental and theoretical study,” *Case Stud. Constr. Mater.*, vol. 23, no. September, p. e05473, 2025, doi: 10.1016/j.cscm.2025.e05473.

[52] A. Ashteyat *et al.*, “Results in Engineering Shear strengthening of two-way reinforced concrete slabs with openings : A review of strengthening techniques and code perspectives,” *Results Eng.*, vol. 28, no. October, p. 108059, 2025, doi: 10.1016/j.rineng.2025.108059.

[53] American Concrete Institute, “Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary,” 2019, *Farmington Hills, MI, USA*.

[54] International Federation for Structural Concrete, “fib Model Code for Concrete Structures 2010,” 2013, *Ernst \& Sohn, Lausanne, Switzerland*.

[55] Turkish Standards Institution, “Requirements for Design and Construction of Reinforced Concrete Structures,” 2000, *Ankara, Turkey*.

[56] Egyptian Code Committee, “Egyptian Code for Design and Construction of Reinforced Concrete Structures,” 2018, *Cairo, Egypt*.