International Journal of Advances in Engineering and Management (IJAEM)
Volume 7, Issue 08 Aug. 2025, pp: 793-801 www.ijaem.net ISSN: 2395-5252

# Punching Shear in RC Flat Slabs: A Comprehensive Review on Mechanics, Design Challenges, and Progressive Collapse Resistance

Sanni Ridwan Olawale[1,2]
[1]Postgraduate Student, Department of Civil Engineering,Kwara State University, Malete, Nigeria
[2]Lecturer, Department of Civil Engineering, Kwara State Polytechnic, Ilorin, Nigeria.
Corresponding Author: Saadu Abubakar Olayide[2], Mansur Abdulrasheed Wopa[2], Garuba Mustapha[2]

---

Date of Submission: 15-08-2025 Date of Acceptance: 25-08-2025

---

**ABSTRACT**: Reinforced concrete (RC) flat slab systems are a preferred choice in modern construction due to their architectural and economic advantages. However, their structural integrity is critically challenged by punching shear, a brittle failure mechanism at slab-column connections that can precipitate catastrophic progressive collapses. This review synthesizes recent research to provide a comprehensive overview of the factors influencing punching shear, the efficacy of predictive models, the evolution of shear reinforcement, and innovative strengthening techniques. The analysis consolidates findings on failure mechanics, highlighting the dominant role of concrete's tensile properties and the complex influence of time-dependent phenomena like creep and shrinkage. It examines a wide array of parameters, including slab depth (size effect), flexural reinforcement ratios, the presence of openings, load eccentricity, complex geometries like edge and re-entrant corners, column rectangularity, non-rectangular column grids, and the use of post-tensioning and non-traditional materials like Glass Fiber-Reinforced Polymer (GFRP) bars. A critical assessment of design code provisions (e.g., ACI 318, Eurocode 2) against advanced numerical methods and new proposed standards (FprEN 1992, MC 2010) reveals significant limitations in current codes, particularly for slabs with low reinforcement ratios (flexure-driven punching), significant depth, or non-standard geometries. The review delves into the nuances of shear reinforcement, emphasizing how stirrup detailing—anchorage, inclination, and configuration—profoundly impacts structural performance. A significant focus is placed on the role of Nonlinear Finite Element Analysis (NLFEA), detailing the importance of model calibration and the capabilities of tools like the Concrete Damaged Plasticity (CDP) model, with particular attention to the influence of the dilatancy angle. Lessons from real-world building collapses underscore the imperative of integrating construction-phase analysis and robust design to prevent progressive collapse. Finally, the paper outlines key challenges and charts a course for future research to enhance the safety and resilience of flat slab structures.

**KEYWORDS:** Punching Shear; Flat Slabs, Reinforced Concrete; Nonlinear Finite Element Analysis (NLFEA); Progressive Collapse

## I. INTRODUCTION

Reinforced concrete (RC) flat slabs, characterized by their direct support on columns without beams, are a staple of modern construction, especially in commercial buildings, parking structures, and residential towers. Their popularity is rooted in tangible benefits like simplified formwork, accelerated construction schedules, reduced story heights, and enhanced architectural freedom [1], [2].

Despite these advantages, the direct load transfer from the slab to the column creates a significant structural vulnerability: punching shear. This brittle failure is marked by the formation of a cone-shaped crack around the column, causing the slab to "punch" through its support [1]. The failure is typically sudden and catastrophic, with minimal warning. Crucially, the failure of a single slab-column connection can trigger a progressive collapse, where the initial local damage propagates, leading to a disproportionately large-scale failure of the entire structure [3]. This was tragically demonstrated by incidents like the Sampoong department store collapse in 1995 and the Skyline Plaza collapse in 1973 [3], [4].

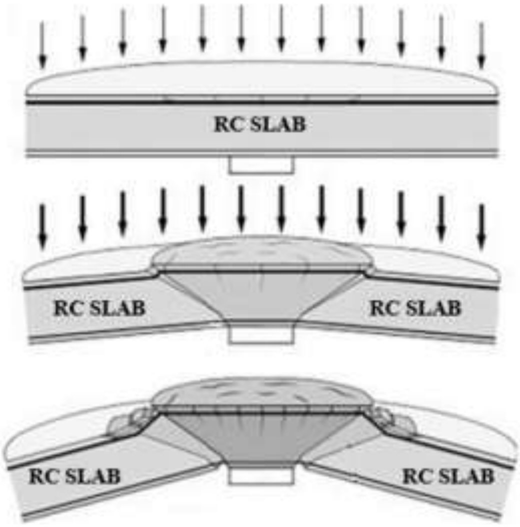


Figure 1: Schematic view of punching in a flat slab supported by only a column[1]

The complexity of punching shear stems from the interplay of numerous factors, including material properties, reinforcement details, slab geometry, and loading conditions. Consequently, accurately predicting punching shear capacity remains a formidable challenge. While design codes like ACI 318-19 and Eurocode 2 (EC2) offer predictive formulas, studies consistently show they can be unconservative or inaccurate under specific conditions, such as for slabs with low reinforcement ratios, significant depth, or complex loading scenarios [4], [5]. Recent proposals for the next generation of codes, like FprEN 1992 and MC 2010, aim to address these shortcomings by adopting more mechanics-based models like the Critical Shear Crack Theory (CSCT), but their efficacy across all conditions is still under evaluation [6].

This review synthesizes findings from a broad range of recent experimental and numerical studies to present a holistic overview of the current state of knowledge on punching shear. It examines the fundamental failure mechanics, critically assesses the key factors influencing shear resistance—with a new focus on the crucial role of shear reinforcement detailing—evaluates the predictive accuracy of existing and proposed design codes versus advanced numerical models, and explores innovative strengthening techniques. By integrating insights from case studies of real-world collapses, this paper aims to bridge the gap between theoretical understanding, design practice, and construction reality, highlighting pathways for future research to improve the safety and reliability of flat slab systems against both punching shear and progressive collapse.

## II. THE MECHANICS OF PUNCHING SHEAR FAILURE

Understanding the fundamental mechanics of punching shear is crucial for effective analysis and design. The failure is a complex three-dimensional stress problem involving multiple, interacting resistance mechanisms that evolve from initial cracking to ultimate collapse.

### 2.1. Failure Process and Resistance Mechanisms

The punching shear failure sequence begins with the formation of flexural cracks on the slab's tension face (typically the top surface around an interior column). As the load increases, these cracks propagate and incline towards the column, eventually coalescing to form a distinct failure surface, often idealized as a truncated cone or pyramid [7]. The resistance to this failure is primarily provided by a combination of three mechanisms [8]:

1. Shear strength of the uncracked concrete in the compression zone above the main crack.
2. Aggregate interlock across the cracked concrete surface, which provides frictional resistance to sliding.
3. Dowel action from the flexural reinforcement bars that cross the shear crack.

Advanced mechanical models like the Critical Shear Crack Theory (CSCT) are built upon this understanding. CSCT posits that punching strength is directly related to the slab's rotation and the resulting width of the critical shear crack. A wider crack diminishes the effectiveness of aggregate interlock, thereby reducing the overall shear capacity [9].

### 2.2. Failure Modes in Slabs with Shear Reinforcement

The introduction of shear reinforcement (e.g., stirrups, headed studs) makes the structural behaviour more ductile and complex, leading to several possible failure modes [10], [11]:

- **Crushing of Concrete Struts:** This failure occurs due to the crushing of concrete struts near the column, representing the maximum possible punching resistance ($V_{R,max}$).
- **Punching within the Shear-Reinforced Zone:** This mode involves the yielding or failure of the shear reinforcement itself, with the critical crack forming inside the reinforced perimeter.
- **Punching outside the Shear-Reinforced Zone:** The punching cone forms entirely beyond the reinforced area, indicating that the shear reinforcement was effective in moving the

International Journal of Advances in Engineering and Management (IJAEM)
Volume 7, Issue 08 Aug. 2025, pp: 793-801 www.ijaem.net ISSN: 2395-5252

failure surface outwards but was not sufficiently extended.

- **Delamination:** A failure mode related to poor anchorage of shear reinforcement, where horizontal cracks develop, separating the top and bottom layers of the slab. This is not explicitly covered by most design codes but has been observed in tests, particularly with prefabricated truss-type stirrups [11].

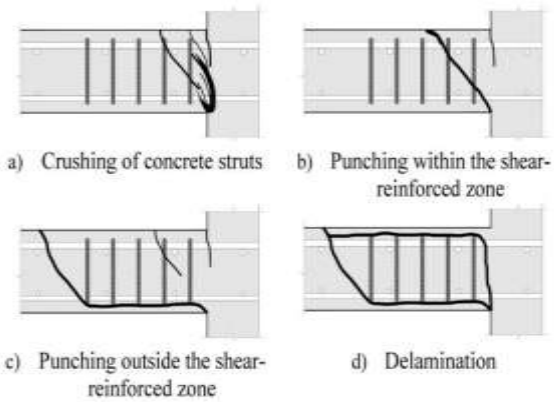


Figure 2: Shear failure mode of slab-column connection with stirrups [11].

An effective design must ensure that the shear reinforcement is detailed and distributed to force the failure outside the reinforced zone, which typically corresponds to a more ductile response.

### 2.3. Post-Punching Behaviour and Progressive Collapse

After the initial punching failure, the slab detaches from the column, and its load must be carried by an alternative mechanism to prevent total collapse. This post-punching resistance is primarily provided by integrity reinforcement—typically bottom bars that are continuous through the column [7]. These bars act as suspenders, catching the failed slab section and transferring its weight to the column through catenary or membrane action. The mobilization of this resistance is a key defence against progressive collapse, where the failure of one connection leads to the overloading and subsequent failure of adjacent connections in a chain reaction [3].

## III. KEY FACTORS INFLUENCING PUNCHING SHEAR RESISTANCE

The capacity of a slab-column connection is governed by a complex synergy of material, geometric, and loading parameters. Recent research has refined our understanding of these factors, revealing nuances that are not always captured by current design codes.

### 3.1. Concrete and Reinforcement Properties

While the compressive strength of concrete ($f_c'$)is a primary parameter in all design codes, advanced numerical studies suggest its role may be secondary. Edri and Yankelevsky [7] demonstrated that the concrete tensile strength ($f_{ct}$) is a more dominant factor, influencing both the initial punching strength and the post-punching behaviours. This implies that concrete mixes optimized for tensile performance could significantly enhance punching resistance.

The flexural reinforcement ratio ($\rho_l$) is another critical factor. Higher ratios generally increase punching capacity by enhancing dowel action and controlling crack widths. However, as shown by Zufarihsan et al. [4], very low reinforcement ratios can lead to a flexure-dominated failure (flexural punching), where extensive yielding precedes punching, potentially masking the true shear capacity. The grade of reinforcement also has an impact; high-strength steel can increase capacity but may lead to wider cracks at service loads if not properly detailed, affecting serviceability [12].

Long-term effects such as creep and shrinkage are also significant, particularly for serviceability. These time-dependent phenomena cause stress redistribution, leading to increased deflections and wider cracks over time, which can indirectly reduce the ultimate punching strength by degrading the effectiveness of aggregate interlock [9].

### 3.2. Shear Reinforcement Detailing

The effectiveness of shear reinforcement is not solely dependent on its quantity but is profoundly influenced by its detailing and anchorage. A comprehensive review by Ferreira et al. [11] on various stirrup types highlights several key principles:

- **Anchorage is Paramount:** The efficiency of stirrups depends significantly on their anchorage, which is typically achieved through mechanical engagement via bends or hooks. The best performance is achieved when stirrups embrace the main longitudinal flexural reinforcement at both the top and bottom. Stirrups that do not embrace the flexural bars risk premature failure due to delamination.
- **Stirrup Type Matters:** Different stirrup configurations (single-leg, closed, open, multiple-leg, and truss-shaped) exhibit varying levels of efficiency. Closed stirrups that properly engage the flexural bars at their corners perform well. Open stirrups are most

effective when their legs are inclined at approximately 60° to the slab plane.

- **Prefabricated Systems:** Truss-shaped stirrups, often prefabricated, can be highly effective but require careful detailing. To prevent delamination, they may need supplementary reinforcement (like U-hooks) if they are not directly anchored around the main flexural bars.

Figure 3: types of single leg stirrups or links tested as punching shear reinforcement[11]

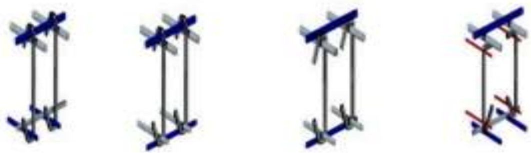

Figure 4: Types of closed Stirrups used as punching shear reinforcement[11]

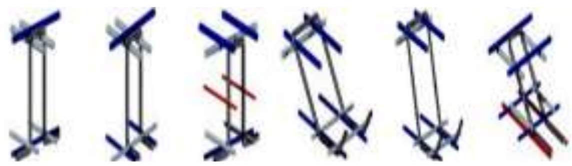

Figure 5: Types of open stirrups used as Punching shear reinforcement[11]

Figure 6: Types of multiple-leg stirrups used as Punching shear reinforcement[11]

### 3.3. Alternative Reinforcement and Systems

**GFRP Bars:** Glass Fiber-Reinforced Polymer (GFRP) bars are an attractive alternative to steel in corrosive environments. However, their distinct mechanical properties—lower modulus of elasticity and brittle nature—pose challenges for punching shear. Studies show that GFRP-reinforced slabs have lower punching shear capacity, larger deflections, and wider cracks compared to steel-reinforced slabs [8]. The lower stiffness of GFRP leads to wider cracks at lower loads, reducing the contribution of aggregate interlock and concentrating stress in the concrete compression zone.

**Post-Tensioned Slabs:** The use of unbonded post-tensioning is common in flat slabs to control deflections and cracking over long spans. The prestressing force introduces a favourable state of pre-compression in the concrete, which generally enhances punching shear capacity. However, the behaviour, especially at edge columns where unbalanced moments are significant, is complex. Barbán et al. [13] tested post-tensioned slabs at edge columns and found that increasing the eccentricity of the load (the ratio of moment to shear, $M_u/V_u$) changed the failure mode from pure punching to a more ductile combination of flexure, torsion, and punching.

**BubbleDeck Slabs:** BubbleDeck slabs incorporate recycled plastic hollow spheres within the concrete core to reduce the slab's self-weight. While this offers economic advantages, it can reduce the punching capacity. Nicácio et al. [14] found that BubbleDeck slabs had a punching capacity up to 14% lower than corresponding solid slabs, with a more pronounced reduction in deflection capacity. The failure surface in these slabs tended to propagate through the hollow spheres at a steeper angle (approx. 45°).

### 3.4. Geometric and Loading Conditions

**Slab and Column Dimensions:** The slab depth (h or d) is a primary parameter, but its influence is moderated by a well-documented size effect, where the nominal shear stress at failure decreases as member depth increases [4]. Increasing slab thickness is a direct way to improve punching resistance [15]. Similarly, increasing the column dimensions enlarges the critical perimeter and reduces shear stresses, thereby increasing capacity [16].

**Column Rectangularity and Shape:** The geometry of the supporting column significantly affects the distribution of shear stresses. For rectangular columns, a high aspect ratio ($C_{max}/C_{min}$) leads to a concentration of shear stresses at the corners and along the short faces, which can reduce the punching capacity compared to a square column with the same perimeter [17], [18]. Design codes often struggle to accurately capture this effect, with some becoming unconservative for high aspect ratios. The shape of the column also matters; [19] found through FEA that cruciform-shaped columns provided the highest shear resistance, followed by T-shape, L-shape, and finally square columns of the same cross-sectional area.

**Non-Symmetrical and Irregular Layouts:** In practice, slabs and column grids are often not symmetrical. Non-symmetrical punching can arise

International Journal of Advances in Engineering and Management (IJAEM)
Volume 7, Issue 08 Aug. 2025, pp: 793-801 www.ijaem.net ISSN: 2395-5252

from unequal slab spans in orthogonal directions. [20] showed through FEA that the slab aspect ratio ($l_x/l_y$) significantly affects crack development, stiffness, and failure mode, which can shift from symmetrical punching to a non-symmetrical or flexural-punching failure. The shear span ratio ($a/d$) also plays a critical role, with increasing ratios generally reducing punching capacity. Furthermore, irregular column grids, such as parallelogram layouts, introduce complex behaviours that are not well-covered by standard design methods. Baskaran and Morley [21] tested such slabs and demonstrated that yield-line analysis can be a valuable tool for predicting their flexural capacity, which often governs failure in these complex geometries.

**Openings and Eccentricity:** The presence of openings near columns can severely reduce punching shear strength by interrupting the critical perimeter [5]. Yooprasertchai et al. [22] found that circular openings have the least detrimental effect, followed by square and rectangular openings. Eccentric loading, which induces unbalanced moments, is a common condition that significantly reduces punching capacity, with edge slab-column connections being a particularly critical case [23].

**Impact Loading:** Under high strain-rate events like impact loading, the behaviour of flat slabs changes significantly. [24] showed that both punching shear strength and stiffness increase with the loading rate, while deformation capacity is reduced. This can cause a shift in the failure mode from ductile flexure to brittle punching. This behaviour is attributed to a combination of material strain-rate effects (increased concrete strength) and inertial effects, with the latter being more significant.

## IV. PREDICTIVE MODELS: CODES VS. NUMERICAL ANALYSIS

### 4.1. Design Code Provisions

International design codes like ACI 318-19, Eurocode 2 (EC2), and the fib Model Code (MC2010) provide equations for predicting punching shear capacity, generally based on a critical perimeter at a specified distance from the column.

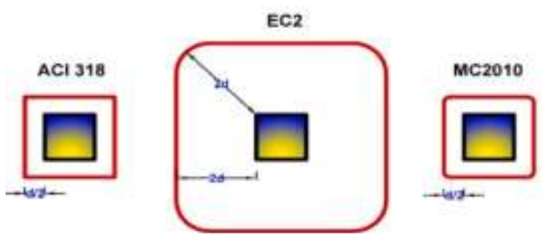


Figure 7: Critical Punching Perimeter [5]

However, numerous studies have identified their limitations:

- **Inaccuracy and Lack of Generality:** Codes can be overly conservative in some cases but dangerously unconservative in others, particularly for deep slabs with low reinforcement ratios or those with rectangular columns [4], [17].
- **Neglected Parameters:** The influence of flexural reinforcement ratio, slab aspect ratio, and complex interactions between eccentricity and openings are often inadequately addressed [5], [20].
- **New Code Proposals:** The final draft of the new Eurocode (FprEN 1992) and MC 2020 are shifting towards mechanics-based models like the CSCT. Lyčka & Štěpánek [6] compared these new provisions against a large database and found that while they represent an improvement, they can still produce a significant number of unsafe predictions and high variance, especially when detailing rules are not strictly followed.

### 4.2. Strut-and-Tie Models (STM)

As an alternative to empirical code equations, Strut-and-Tie Modelling (STM) offers a more mechanics-based approach for analysing disturbed regions (D-regions) in concrete structures, such as the area around a slab-column connection. STM idealizes the complex stress fields into a truss system of compression struts (concrete) and tension ties (reinforcement) connected at nodes. While primarily used for deep beams, the principles of STM are being adapted for punching shear. The method proposed by Lyčka & Štěpánek [6] is a recent example, using a simplified STM within the shear crack region to predict the resistance of slabs with shear reinforcement. Akinpelu et al. [25], in their study on deep beams, also highlighted the utility of STM and compared its predictions to FEM, demonstrating its potential as a robust analytical tool.

### 4.3. Nonlinear Finite Element Analysis (NLFEA)

NLFEA has emerged as a powerful and reliable tool for investigating punching shear, capable of overcoming the limitations of both physical experiments and simplified analytical models [8], [26]. By employing sophisticated material models, such as the Concrete Damaged Plasticity (CDP) model available in software like ABAQUS, NLFEA can provide deep insights into structural behaviour[23], [27].

Validated FE models have successfully predicted:

- The full load-deflection and load-rotation

International Journal of Advances in Engineering and Management (IJAEM)
Volume 7, Issue 08 Aug. 2025, pp: 793-801 www.ijaem.net ISSN: 2395-5252

responses.

- The initiation and propagation of complex crack patterns.
- Asymmetric damage evolution even in symmetric configurations.
- Stress distributions in both concrete and reinforcement [28].
- Localized failures, such as the rupture of individual reinforcement bars [7].

The accuracy of NLFEA is highly dependent on the proper calibration of the model. Key considerations include mesh sensitivity and the careful selection of material parameters for the CDP model, such as the dilation angle, viscosity parameter, and fracture energy, as these significantly influence the predicted response [20], [26]. Wosatko et al.[29] specifically highlighted the critical role of the dilatancy angle in pressure-dependent plasticity models, showing that its definition can significantly impact results.

## V. STRENGTHENING AND MITIGATION OF PUNCHING SHEAR

Given the need to upgrade existing structures, various methods for strengthening flat slabs against punching have been developed. A review by Koppitz et al. [30] provides a comprehensive classification of these techniques.

**Traditional Methods:** These include incorporating drop panels or column capitals to locally increase slab thickness [1].

**Post-Installed Reinforcement:** A common retrofit strategy involves installing shear reinforcement into the existing slab. Shear bolts, a type of headed stud designed for retrofitting, have been shown to significantly increase both strength and ductility [31].

**External Strengthening:**

- **Steel Plates:**Attaching column head steel plates to the slab soffit creates an external drop panel and has been shown to increase capacity by 1.5 to 2.15 times [2]. A similar technique involves using bolted steel angle plates [32].
- **UHPFRC Overlays:** A modern approach involves casting a thin layer of Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) on top of the slab. This not only increases the effective depth but also leverages the high tensile strength and strain-hardening properties of UHPFRC to enhance both strength and ductility [33].


Figure 8: Attached column head steel plate to slab (red circles indicate buckling) [2]

For ensuring post-punching resilience and preventing progressive collapse, the inclusion of integrity reinforcement is paramount. These bottom bars, continuous through the column, are designed to suspend the slab after an initial punching failure, providing an essential "last line of defence" [3], [7].

## VI. PROGRESSIVE COLLAPSE AND CONSTRUCTION-PHASE FAILURES

The ultimate consequence of an unmitigated punching shear failure is progressive collapse. The review by [3] synthesizes research on this topic, outlining the primary resistance mechanisms: tension-compression membrane action, the joint's punching shear mechanism, and the post-punching mechanism provided by integrity reinforcement. Mobilizing all three is key to robust design.

The critical importance of a holistic approach that considers the construction sequence is highlighted by the case study of a building collapse presented by Ertürk Atmaca et al. [1]. The building was designed with an upstand beam system, which is not vulnerable to punching shear in its final state. However, the construction was staged: the first slab was cast directly on the columns, creating a temporary flat slab system. This temporary condition, which was not analyzed during design, could not support its own weight and collapsed due to punching shear. This case powerfully illustrates that punching shear failure can arise not only from deficiencies in the final design but critically from a

International Journal of Advances in Engineering and Management (IJAEM)
Volume 7, Issue 08 Aug. 2025, pp: 793-801 www.ijaem.net ISSN: 2395-5252

failure to account for the structural system's behaviour during intermediate construction stages.

Figure 9: Images of the collapsed part of the building due to the punching effect[1]

## VII. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

The body of research reviewed herein confirms that punching shear is a multifaceted phenomenon governed by a complex interplay of material, geometric, loading, and detailing factors. While significant progress has been made, several key conclusions and areas for future work emerge:

1. **Re-evaluation of Material and Detailing Parameters:** The finding that concrete tensile strength may be more critical than compressive strength warrants a re-evaluation of material specifications. More importantly, the profound impact of shear reinforcement detailing (anchorage, configuration, inclination) suggests that design codes need to move beyond simple quantity-based provisions to more prescriptive detailing rules to ensure reinforcement effectiveness.
2. **Modernizing Design Codes:** Current design codes exhibit weaknesses in handling lightly reinforced slabs, the size effect, load eccentricity, and complex geometries like rectangular columns and non-symmetrical slabs. The shift towards mechanics-based models like CSCT and STM in new proposals (FprEN 1992, MC 2020) is a positive step, but these models require further validation and refinement to improve their reliability and reduce variance.
3. **The Role of Numerical Modelling:** Validated NLFEA is an indispensable tool for understanding fundamental behaviours and accurately predicting the capacity of complex slab-column connections. Its reliability, however, is contingent on rigorous model calibration, including mesh sensitivity studies and careful selection of material parameters for constitutive models like CDP.
4. **Focus on Progressive Collapse:** The link between punching shear and progressive collapse must be a central focus of design. This requires greater emphasis on post-punching capacity and the mandatory inclusion of properly detailed integrity reinforcement.
5. **Holistic Design and Construction:** The case study of the building collapse is a stark reminder that structural design cannot be divorced from the construction process. Future design practices must explicitly address the stability and safety of structures at all intermediate stages.

Future research should focus on generating high-quality experimental data for complex cases, such as post-tensioned slabs, connections with combined openings and eccentric loading, and slabs with irregular column layouts. This data is essential for calibrating more sophisticated numerical models and for developing the next generation of more reliable and robust design codes that can ensure the safety and resilience of flat slab structures worldwide.

## REFERENCES

[1]. E. Ertürk Atmaca, A. C. Altunişik, M. Günaydin, and B. Atmaca, 'Collapse of an RC Building Under Construction with a Flat Slab System: Reasons, Calculations, and FE Simulations', Buildings, vol. 15, no. 1, Jan. 2025, doi: 10.3390/buildings15010020.

[2]. S. Lim et al., 'Punching shear strength of RC flat plate slab–column connections strengthened with column head steel plates', Journal of Building Engineering, vol. 111, Oct. 2025, doi: 10.1016/j.jobe.2025.113132.

[3]. X. Li, T. Dong, C. Wang, W. Zhang, R.

Liu, and J. Wang, 'A Review on the Progressive Collapse of Reinforced Concrete Flat Slab–Column Structures', May 01, 2025, Multidisciplinary Digital Publishing Institute (MDPI). doi: 10.3390/ma18092056.

[4]. R. Zufarihsan, A. Tambusay, B. Suryanto, and P. Suprobo, 'Predicting the punching failure of lightly reinforced concrete flat slabs without shear reinforcement', Structures, vol. 74, Apr. 2025, doi: 10.1016/j.istruc.2025.108473.

[5]. B. R. Alnemrawi and R. Z. Al-Rousan, 'Numerical and analytical study on the punching shear capacity prediction for eccentrically loaded flat slabs with openings', Results in Engineering, vol. 24, Dec. 2024, doi: 10.1016/j.rineng.2024.103315.

[6]. L. Lyčka and P. Štěpánek, 'New method for prediction of punching resistance of flat slabs with shear reinforcement and its comparison with recently proposed code provisions', Materials and Structures/Materiaux et Constructions, vol. 58, no. 4, May 2025, doi: 10.1617/s11527-025-02649-2.

[7]. I. E. Edri and D. Z. Yankelevsky, 'Numerical framework for assessing punching shear behavior in integrity-reinforced concrete flat slab specimens', Structures, vol. 76, Jun. 2025, doi: 10.1016/j.istruc.2025.108823.

[8]. A. Alateyat et al., 'Punching shear behavior of GFRP-reinforced concrete flat slabs using finite element analysis', Journal of Building Engineering, vol. 105, Jul. 2025, doi: 10.1016/j.jobe.2025.112507.

[9]. S. Ravasini, F. Vecchi, B. Belletti, and A. Muttoni, 'Verification of deflections and cracking of RC flat slabs with numerical and analytical approaches', Eng Struct, vol. 284, Jun. 2023, doi: 10.1016/j.engstruct.2023.115926.

[10]. J. P. de A. Siqueira, E. J. P. de Albuquerque, M. Fernández Ruiz, and G. S. Melo, 'Punching shear in flat slabs with re-entrant corner columns and shear reinforcement', Eng Struct, vol. 310, Jul. 2024, doi: 10.1016/j.engstruct.2024.118098.

[11]. M. P. Ferreira, M. G. Costa, M. J. M. Pereira Filho, M. F. Ruiz, and D. V. Faria, 'Influence of stirrup detailing on the punching resistance of reinforced concrete flat slabs', Eng Struct, vol. 336, p. 120220, Aug. 2025, doi: 10.1016/j.engstruct.2025.120220.

[12]. Y. Yu, C. Espanol, E. I. Saqan, and O. Bayrak, 'Behavior of Reinforced Concrete Beams with Large-Diameter High-Strength Tension-Spliced Bars', ACI Struct J, vol. 122, no. 3, pp. 119–132, May 2025, doi: 10.14359/51742243.

[13]. V. V. Barbán, G. S. Melo, and A. L. Carvalho, 'Punching shear tests of post-tensioned flat slabs supported on edge columns', Structural Concrete, vol. 21, no. 1, pp. 247–261, Feb. 2020, doi: 10.1002/suco.201900160.

[14]. W. G. Nicácio, J. A. O. Barros, and G. S. S. A. Melo, 'Punching behavior of BubbleDeck type reinforced concrete slabs', Structural Concrete, vol. 21, no. 1, pp. 262–277, Feb. 2020, doi: 10.1002/suco.201900176.

[15]. A. Zaib and S. Ahmad, 'Review on Columns Dimension and Slab Thickness Effect on Punching Shear Stress in Flat Plate Structures', International Journal of Civil Engineering, vol. 7, no. 7, pp. 118–122, Jul. 2020, doi: 10.14445/23488352/ijce-v7i7p114.

[16]. H. A. Faris and L. M. Abd, 'Effect of Column Dimensions on the Punching Shear of Flat Slab', Int J Sci Res Sci Eng Technol, pp. 378–393, Aug. 2019, doi: 10.32628/ijsrset196452.

[17]. O. S. PAIVA, M. P. FERREIRA, D. R. C. OLIVEIRA, A. F. LIMA NETO, and M. R. TEIXEIRA, 'Influence of the column rectangularity index and of the boundary conditions in the punching resistance of slab-column connections', Revista IBRACON de Estruturas e Materiais, vol. 8, no. 3, pp. 260–295, Jun. 2015, doi: 10.1590/s1983-41952015000300003.

[18]. V. Filatov, 'Evaluation of punching shear strength of flat slabs supported on rectangular columns', in E3S Web of Conferences, EDP Sciences, Mar. 2018. doi: 10.1051/e3sconf/20183302007.

[19]. M. A. Akinpelu, D. S. Gabriel, A. M. Salman, and I. A. Raheem, 'Numerical study on the effect of different column shapes on punching shear behavior of flat slabs', Results in Engineering, vol. 19, Sep. 2023, doi: 10.1016/j.rineng.2023.101345.

[20]. B. Zheng, W. Zheng, B. Cao, and Y. Zhang, 'Nonlinear finite element analysis of non-symmetrical punching shear of rectangular flat slabs supported on square

columns', Eng Struct, vol. 277, Feb. 2023, doi: 10.1016/j.engstruct.2022.115451.

[21]. K. Baskaran and C. T. Morley, 'Strength assessment of flat slabs on non-rectangular column grid', Magazine of Concrete Research, vol. 59, no. 4, pp. 273–286, May 2007, doi: 10.1680/macr.2007.59.4.273.

[22]. E. Yooprasertchai, Y. Tiawilai, T. Wittayawanitchai, J. Angsumalee, P. Joyklad, and Q. Hussain, 'Effect of shape, number, and location of openings on punching shear capacity of flat slabs', Buildings, vol. 11, no. 10, Oct. 2021, doi: 10.3390/buildings11100484.

[23]. T. S. Viswanathan, V. Sairam, K. Srinivasan, and G. Mannayee, 'Study on Edge Slab-Column Connection in Flat Slab', International Journal of Civil Engineering and Technology, vol. 8, no. 9, pp. 53–60, 2017, [Online]. Available: http://iaeme.com/Home/journal/IJCIET53editor@iaeme.comhttp://http://iaeme.com/Home/issue/IJCIET?Volume=8&Issue=9http://iaeme.com

[24]. K. Micallef, J. Sagaseta, M. Fernández Ruiz, and A. Muttoni, 'Assessing punching shear failure in reinforced concrete flat slabs subjected to localised impact loading', 2014, Elsevier Ltd. doi: 10.1016/j.ijimpeng.2014.04.003.

[25]. M. A. Akinpelu, B. Adeoye Ibitoye, S. O. Odeyemi, and K. O. Olorede, 'Numerical Verification of Strut and Tie Models and Failure Modes of Reinforced Self-Compacting Concrete Deep Beams', 2021. [Online]. Available: www.scientific.net.

[26]. A. S. Genikomsou and M. A. Polak, 'Finite element analysis of punching shear of concrete slabs using damaged plasticity model in ABAQUS', Eng Struct, vol. 98, pp. 38–48, Sep. 2015, doi: 10.1016/j.engstruct.2015.04.016.

[27]. A. S. Genikomsou and M. A. Polak, 'Finite Element Analysis of a Reinforced Concrete Slab-Column Connection using ABAQUS', 2014.

[28]. Z. Qiang, L. Yaozhuang, and K. Kolozvari, 'Numerical modeling of steel–concrete composite structures', Structural Concrete, vol. 19, no. 6, pp. 1727–1739, Dec. 2018, doi: 10.1002/suco.201700094.

[29]. A. Wosatko, A. Winnicki, M. A. Polak, and J. Pamin, 'Role of dilatancy angle in plasticity-based models of concrete', Archives of Civil and Mechanical Engineering, vol. 19, no. 4, pp. 1268–1283, Aug. 2019, doi: 10.1016/j.acme.2019.07.003.

[30]. R. Koppitz, A. Kenel, and T. Keller, 'Punching shear of RC flat slabs - Review of analytical models for new and strengthening of existing slabs', Jul. 2013. doi: 10.1016/j.engstruct.2013.02.014.

[31]. M. A. Polak, 'Ductility of Reinforced Concrete Flat Slab-Column Connections', 2005.

[32]. H. R. Taresh, M. Y. M. Yatim, and M. R. Azmi, 'Punching shear behaviour of interior slab-column connections strengthened by steel angle plates', Eng Struct, vol. 238, Jul. 2021, doi: 10.1016/j.engstruct.2021.112246.

[33]. D. W. Menna and A. S. Genikomsou, 'Punching Shear Response of Concrete Slabs Strengthened with Ultrahigh-Performance Fiber-Reinforced Concrete Using Finite-Element Methods', Practice Periodical on Structural Design and Construction, vol. 26, no. 1, Feb. 2021, doi: 10.1061/(asce)sc.1943-5576.0000546.