



## A review of experimental results on fiber-reinforcement in punching shear resistance of reinforced concrete flat slabs

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Flat slab  
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### ABSTRACT

Punching shear resistance is crucial in structural design, particularly for flat slab systems. Numerous studies have demonstrated that the use of steel fibers or synthetic fibers in concrete structures is an effective method to enhance punching shear strength. Each fiber type has different mechanisms of action and varying degrees of influence on the structure's load-bearing capacity. The authors evaluate experimental data from 273 fiber-reinforced slabs and 84 control slabs to assess the impact of fibers on improving the strength and durability of flat slabs. The research indicates that integrating multiple fiber types enhances the mechanical performance of concrete in flat slab systems, underscoring the necessity for optimizing fiber combinations. However, knowledge gaps remain regarding the influence of fiber properties on punching shear resistance, which constrains the optimization of design parameters. Further investigation is required to refine predictive models and evaluate fiber combinations to improve structural performance in high-durability, safety-critical applications.

## 1. Introduction

The Flat reinforced concrete slabs emerged in the late 19th and early 20th centuries, developed and refined by Turner [1] and Maillart [2]. Flat slabs without beams offer significant advantages, including material and labor savings, reduced construction time, optimized space usage, and simplified construction processes. Flat slabs also improve living and working environments by enabling uniform distribution of light and air while

providing greater architectural design flexibility. To enhance punching shear resistance, reinforcement can be applied at the slab-column connection through mushroom slabs, column heads, or a combination of various solutions, as illustrated in Figure 1.

Flat slabs are often vulnerable to punching shear at the slab-column connection, leading to brittle failure and increasing the risk of structural instability. As shown in Figure 1a, pure flat slab connections are commonly used

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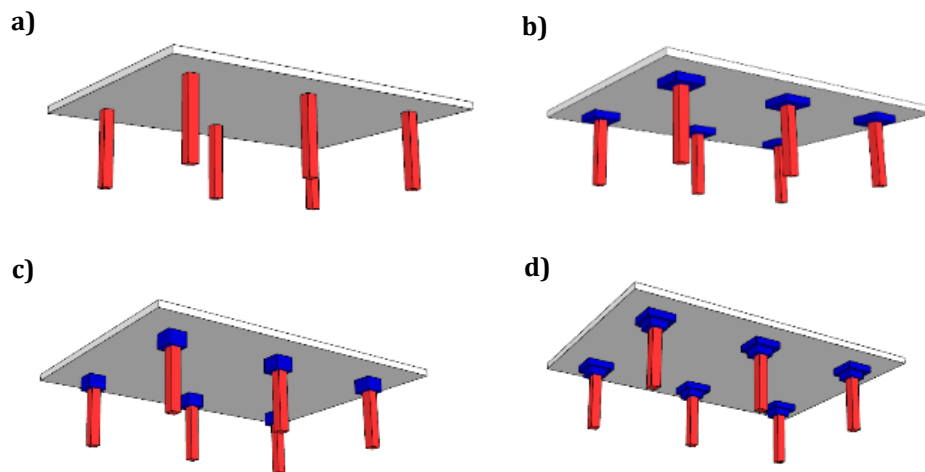
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in unique structures, particularly in shell structures, such as the shell structure at Terminal 2E of Roissy Charles de Gaulle Airport. A significant failure occurred at this facility just eleven months after its commissioning in 2004, resulting in the loss of four lives. Following this incident, Daou et al. [3] determined that steel tie rods were the primary cause of concentrated shear stresses, leading to punching shear failure in the concrete shell. The increased shear force led to the failure of the concrete shell, causing the entire structure to collapse (Figure 2).

Fiber reinforced concrete exhibits several notable advantages over conventional concrete. Incorporating fibers improves tensile strength, crack resistance, and impact resistance, extending the structures' lifespan and reducing maintenance costs. Studies have shown that fiber reinforcement enhances crack resistance, which mitigates the risk of premature failure and improves the overall durability of structures, particularly in applications requiring high strength and safety standards [4].



**Figure 1.** Various flat slab structures. (a) Flat plate, (b) Flat slab with drop panels, (c) Flat slab with column capitals, (d) Flat slab with combined drop panels and column capitals.

The development and application of fiber-reinforced concrete have evolved through various stages. The first patent for this material was filed in 1874; however, it was not until 1962, when Romualdi [5] conducted experiments with steel fiber-reinforced concrete, that the addition of steel fibers was found to effectively arrest the propagation of micro-cracks, significantly enhancing both the tensile and compressive strength of the concrete. This discovery marked a pivotal advancement for using fiber-reinforced concrete in construction.

With the significant advancements in and growing adoption of High-Performance

Concrete (HPC), the combination of steel fibers with HPC has led to the development of High-Performance Fiber Reinforced Concrete (HPFRC), a material with considerable potential for structures requiring enhanced flexibility and durability. HPFRC not only exhibits superior impact resistance but also significantly enhances tensile strength, improving the load-bearing capacity and service life of structural elements [6], [7].

In addition to steel fibers, other types of fibers play an essential role in reinforcing concrete, providing different mechanical properties and performance characteristics.

These fibers can be classified into three main categories: (i) Artificial inorganic fibers, (ii) synthetic organic fibers, and (iii) natural fibers, as depicted in Figure 3.

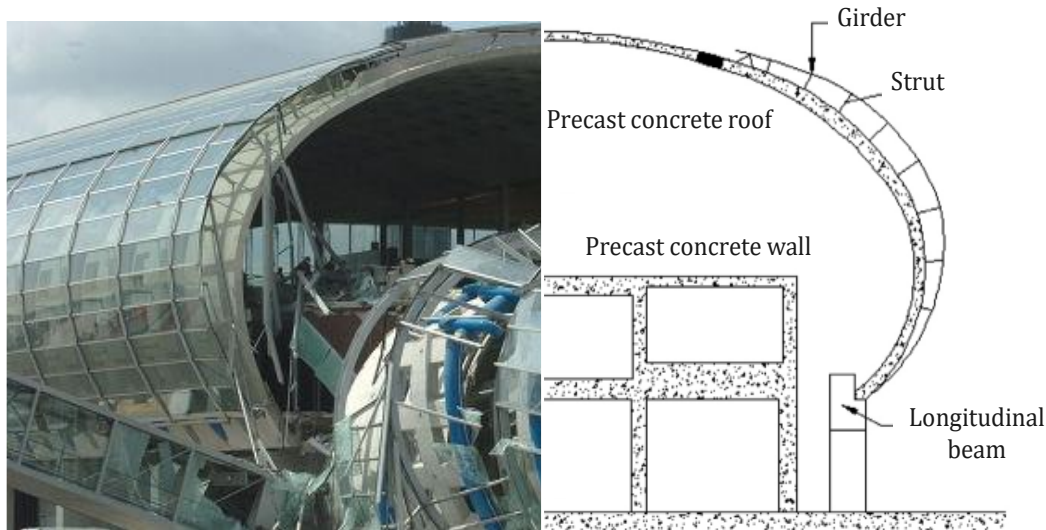


Figure 2. The collapse of Terminal 2E at Roissy Charles de Gaulle Airport.

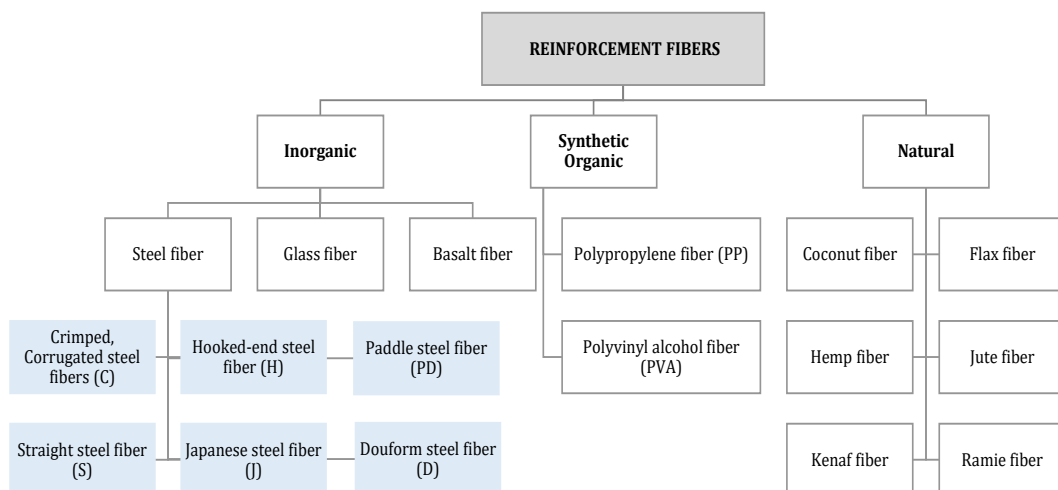


Figure 3. Fiber classification.

As illustrated in Figure 4, inorganic fibers include steel, glass, and basalt fibers, which are widely used due to their superior mechanical properties, such as high tensile strength, corrosion resistance, and excellent thermal stability.

Among these, steel fibers are the most widely used, offering a range of geometric shapes that are designed to optimize the load-bearing capacity and flexibility of fiber-reinforced concrete. Different steel fiber geometries are engineered to enhance the

mechanical properties of the concrete, including [8], [9], and [10]:

(i) Crimped and Corrugated Steel Fibers (C): These fibers feature distinctive crimped or corrugated shapes that improve the bond between the fiber and the concrete matrix, enhancing load-bearing capacity and reducing the risk of fiber slippage.

(ii) Hooked-End Steel Fibers (H): These fibers have characteristic hooked ends that significantly improve anchorage within the concrete, reducing the likelihood of

delamination and enhancing overall structural integrity.

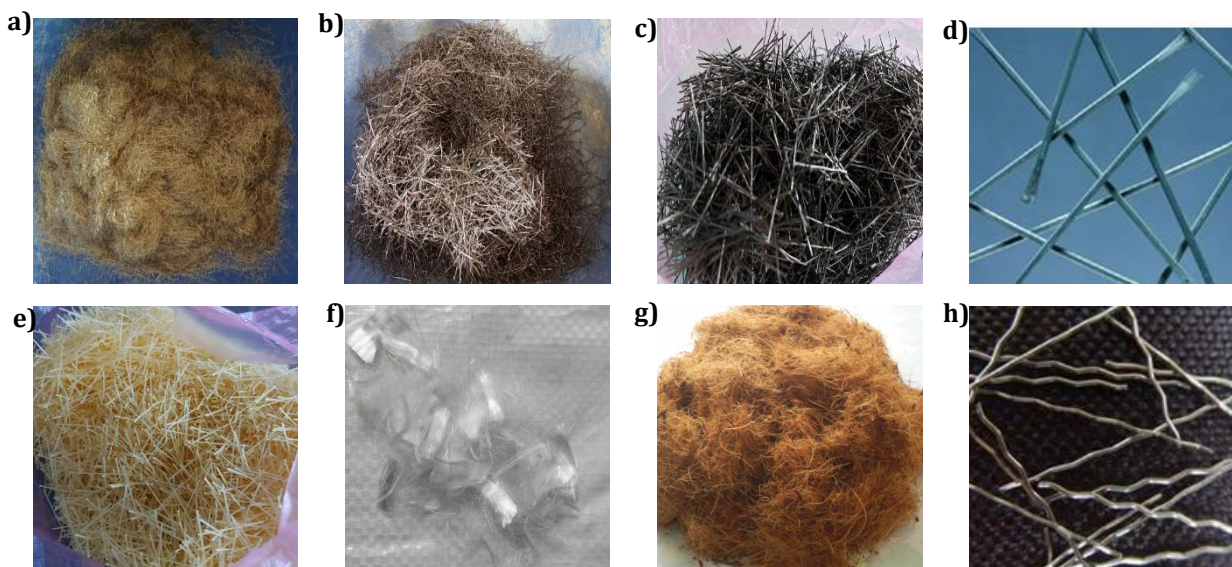
(iii) Straight Steel Fibers (S): While these fibers have a more straightforward design, they still provide effective reinforcement and are commonly used in structures subjected to moderate loads.

(iv) Japanese Steel Fibers (J): Produced with advanced manufacturing technologies, Japanese steel fibers are renowned for their high quality and durability, making them suitable for complex engineering applications.

(v) Paddle Steel Fibers (PD): These fibers have a unique shape that enhances the fiber-

concrete bond, improving both tensile and flexural strength.

(vi) Douform Steel Fibers (D): Specifically developed to increase tensile and flexural strength, these fibers are used in applications requiring specialized performance and high efficiency. Synthetic organic fibers (Figure 4e and Figure 4f), including polypropylene (PP) and polyvinyl alcohol (PVA) fibers, offer crack resistance and shrinkage reduction. During the curing phase, polypropylene fibers help to minimize shrinkage cracking, while PVA fibers not only enhance the ductility of the concrete but also improve its ability to bear heavy loads [11].



**Figure 4.** Various types of fibers. (a) Straight steel fiber - S, (b) Hooked-end steel fiber - H, (c) Basalt fiber - B, (d) Paddle-shaped steel fiber - PD, (e) Polyvinyl Alcohol fiber - PVA, (f) Polypropylene fiber - PP, (g) Coconut fiber, (h) Crimped or corrugated steel fiber - C.

Natural fibers such as coconut fibers, flax fibers, hemp fibers, jute fibers, kenaf fibers, ramie fibers, areca fibers, and banana fibers, which are gaining attention for sustainable construction, are environmentally friendly alternatives [12], [13]. Although they do not possess the high strength of synthetic or inorganic fibers, they offer advantages such as low production costs and eco-friendliness, making them suitable for small-scale

construction projects or green building initiatives. It is evident that the wide variety of fibers available for reinforcing concrete structures today, each with its unique size and mechanical properties, leads to different mechanisms of influence and varying effects on the load-bearing capacity of structures. In this paper, the authors will delve into an evaluation and analysis of experimental studies on various fiber types to assess the

effectiveness of each in enhancing the quality and durability of flat reinforced concrete slabs. This translation maintains technical accuracy and is suitable for academic and professional use in construction engineering.

## **2. Strengthening capacity**

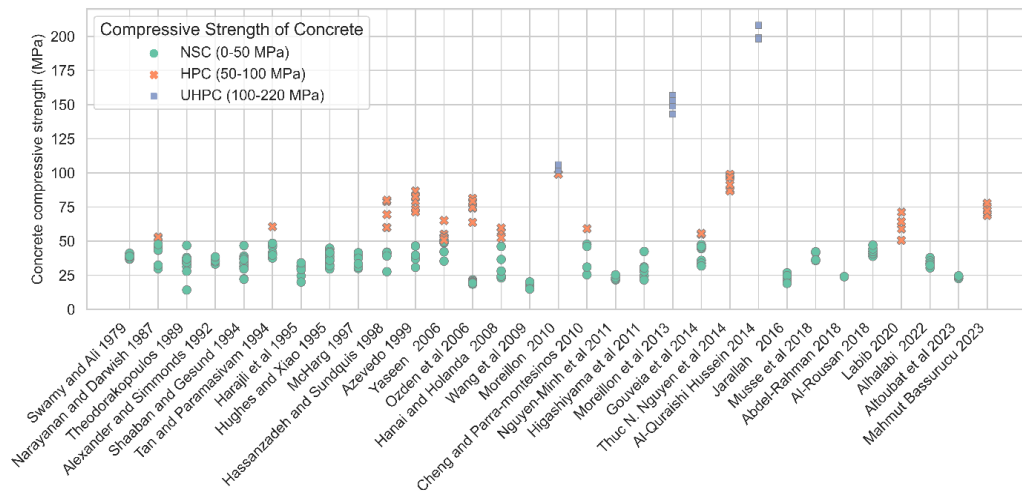
Initial studies on the shear-punching resistance of fiber-reinforced concrete flat slabs concentrated on evaluating the effectiveness of the concrete slabs in the slab-column connections by incorporating various fiber types. In the research by Theodorakopoulos [14], Rankin and Long [15], Narayanan and Darwish [16], Tan and Paramasivam [17], Harajli [18], Maalouf and Khatib [19], Hughes and Xiao [20], McHarg [21], and other studies, important contributions were made in understanding the impact of steel and other fibers on the load-bearing capacity of concrete flat slabs [22], [23], [24], [25], [26].

Experiments utilizing concrete with compressive strengths ranging from 20 MPa to 66 MPa, as shown in Figure 5, involved slab samples sized from 650 mm x 650 mm to 860 mm x 860 mm subjected to centrally concentrated loading, supported on four edges [22], [23], [24], [25], [26]. Comparing the results based on load-displacement curves reveals that slabs reinforced with fibers significantly improved load-bearing capacity compared to conventional slabs. The use of fibers has a substantial effect on the shear-punching resistance of concrete.

Theodorakopoulos's 1980 study [14] showed that steel fibers enhanced the shear-punching resistance by approximately 40%, and the post-punching capacity of concrete was also significantly improved due to the steel fibers. In conventional concrete, after

punching occurs, the structure suddenly loses its load-bearing ability, leading to a high risk of collapse. However, with steel fiber reinforcement, the broken concrete parts remain held together, creating a continuous structure despite damage, enhancing post-punching resistance by 150% to 400%. Narayanan and Darwish's 1987 study [16] also demonstrated that a higher fiber volume ratio increased the maximum load-bearing capacity of the slab by 42%. Tan and Paramasivam [17], as well as Harajli and colleagues [18], concluded that increasing the steel fiber ratio significantly boosted shear-punching resistance, with increases ranging from 22% to 36%, depending on the fiber type and ratio. Most studies using steel fibers, including those by Narayanan and Darwish, Tan and Paramasivam, and Harajli and Maalouf, focused on hooked steel fibers, while the studies by Theodorakopoulos and Hughes and Y. Xiao examined a broader range of fibers [16], [17], [18], [19].

Theodorakopoulos [14] researched four fiber types—S, H, PD, and J—to compare their reinforcement capabilities in lightweight concrete. Straight steel fibers (S) and hooked steel fibers (H) showed the best results, with corrugated steel fibers enhancing flexural and shear strength by up to 107.4%, while hooked fibers significantly improved ductility and load-bearing capacity. Paddle-shaped steel fibers (PD) also improved shear and flexural strength but reduced compressive strength. Japanese steel fibers (J) were less effective due to their shorter length, increasing strength by only 31.5% to 54.3%. This study demonstrated that corrugated or hooked steel fibers are the best options for enhancing the strength of flat slabs [14].



**Figure 5.** Summary of experimental studies based on concrete compressive strength.

Hughes and Xiao's experiments [19] revealed that Duoform steel fibers provided superior performance, increasing shear resistance by up to 40% and significantly enhancing the ductility of the concrete. Round steel fibers also showed significant improvements in load-bearing capacity, though they did not perform as well as Duoform fibers. Polypropylene fibers increased shear resistance by about 20% and effectively controlled cracking, though this effectiveness tended to diminish if the fiber ratio exceeded the optimal level. Polypropylene fibers also reduced crack width and enhanced the concrete's shear resistance. Specifically, with 1% polypropylene fibers, the crack width decreased to 1.2 mm compared to 2 mm with conventional reinforcement. While polypropylene fibers improve crack control and ductility, they have minimal impact on

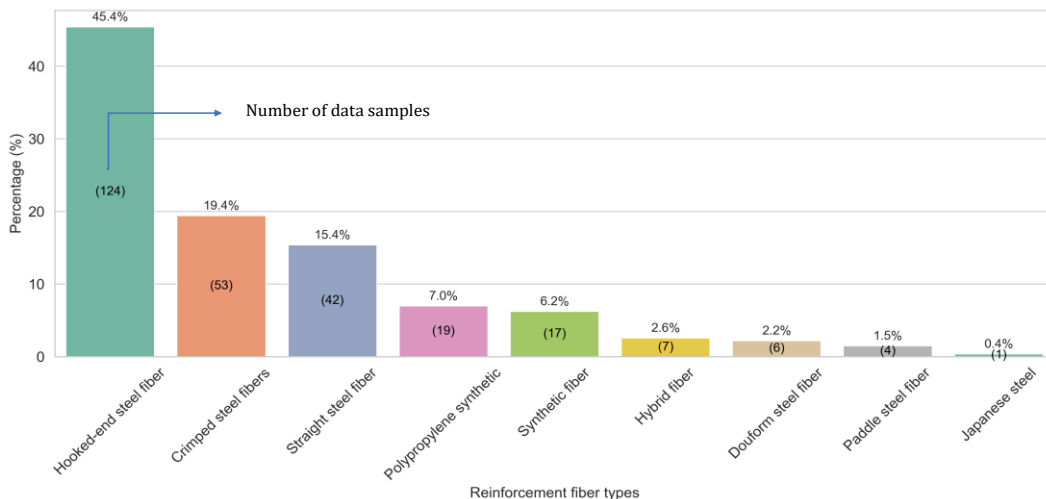
the flexural and compressive strength of concrete. Compared to steel fibers, concrete with polypropylene fibers may have lower load-bearing capacity, highlighting the distinct differences between fiber types in enhancing the mechanical properties of concrete [19]. Over the past two decades, High-Performance Concrete (HPC) and Ultra-High-Performance Concrete (UHPC) have achieved significant breakthroughs through research and technical innovations, contributing greatly to modern construction. With notable characteristics such as high compressive strength, durability, and excellent corrosion resistance, HPC and UHPC have become top choices for structures requiring durability and longevity. These materials not only increase load-bearing capacity but also help reduce structural thickness, thus saving materials and construction costs [27].

**Table 1.** Fiber type statistics based on concrete compressive strength.

Fiber type	NSC	HSC	UHPC
Crimped, corrugated steel fiber (C)	n=50	n=3	n=0
Straight steel fibers (S)	n=13	n=7	n=22
Hooked steel fibers (H)	n=85	n=25	n=14
Japanese steel fibers (J)	n=1	n=0	n=0
Paddle-shaped steel fibers (PD)	n=4	n=0	n=0

However, research on flat slabs made of this type of concrete still presents limitations, as comprehensive studies need to be improved, and the number of experimental flat slab samples using high-strength concrete remains limited (Figure 5). Regarding high-performance concrete (HPC), many studies on the impact of fiber content have been conducted by authors such as Yaseen [26], S. Ozden [28], Minh [29], Moreillon [30], Nguyen [31], Hussein [32], Gouveia [33], AlHamaydeh [34], and Lampropoulos [35], along with numerous other studies [36], [37], [38], [39], [40], [41],

[42]. The combined results of concrete strength by fiber type are summarized in Table 1. These studies mainly used steel fibers at various ratios, ranging from 0.5% to 2%. The results demonstrate that adding fibers to concrete significantly improves the shear-punching resistance of slabs. The load-bearing capacity of the slabs increased by up to 48% when the fiber content was raised from 0% to 1.0%. Several parameters, such as fiber ratio, concrete compressive strength, and reinforcement ratio, were also studied, showing that these factors determine the overall effectiveness of steel fiber used in concrete [28].



**Figure 6.** Statistics of flat slab samples by fiber type based on collected experimental data from 273 samples.

Figure 6 classifies flat slab samples by fiber types used. Most research uses steel fibers, with hooked steel fibers being the most popular due to their ability to enhance ductility and improve the post-cracking load-bearing capacity of concrete. Besides improving load-bearing capacity, Ozden [29], Minh [30], Gouveia [34], and other authors noted that steel fibers also increase the slab's ductility and durability, contributing to preventing brittle failure and maintaining structural integrity under load. In particular, Lampropoulos [36] found that adding steel fibers significantly improves the

stiffness and load-bearing capacity of UHPC slabs. Additionally, Nguyen [32] pointed out that the orientation of the fibers during concrete pouring can significantly affect the slab's load-bearing capacity.

Recent studies have expanded the scope of reinforcement by using macro polyolefin synthetic fibers. AlHamaydeh [35] used this fiber type to study the shear-punching resistance and energy absorption of Self-Compacting Concrete (SCC) slabs. The results show that the concrete's load-bearing capacity increased, especially in crack resistance.

It is clear that the experimental methods in these studies primarily focused on assessing shear-punching resistance. Parameters such as concrete compressive strength, column size, reinforcement ratio, and steel fiber content were adjusted to evaluate their impacts. Most studies also point out that further research is needed to better understand the effects of fiber types, sizes, and orientations, and the impact of environmental factors on the performance of fiber-reinforced flat concrete slabs.

This study collected data from experiments on 273 fiber-reinforced slabs and 84 control slabs (without fibers). Figure 7 shows several studies on regular strength

concrete (NSC) flat slabs that include various fiber types for reinforcement. In these experiments, NSC was tested with many fiber types, including corrugated or crimped steel fibers (C), straight steel fibers (S), hooked steel fibers (H), paddle-shaped steel fibers (PD), polypropylene fibers (PP), and synthetic fibers (SN). For high-strength concrete (HSC), the focus has mainly been on certain fiber types, such as hooked steel fibers (H), straight steel fibers (S), Duoform steel fibers (D), and synthetic fibers (SN). For ultra-high-performance concrete (UHPC), research remains limited, focusing on a few fiber types, such as straight steel fibers (S) and hooked steel fibers (H).

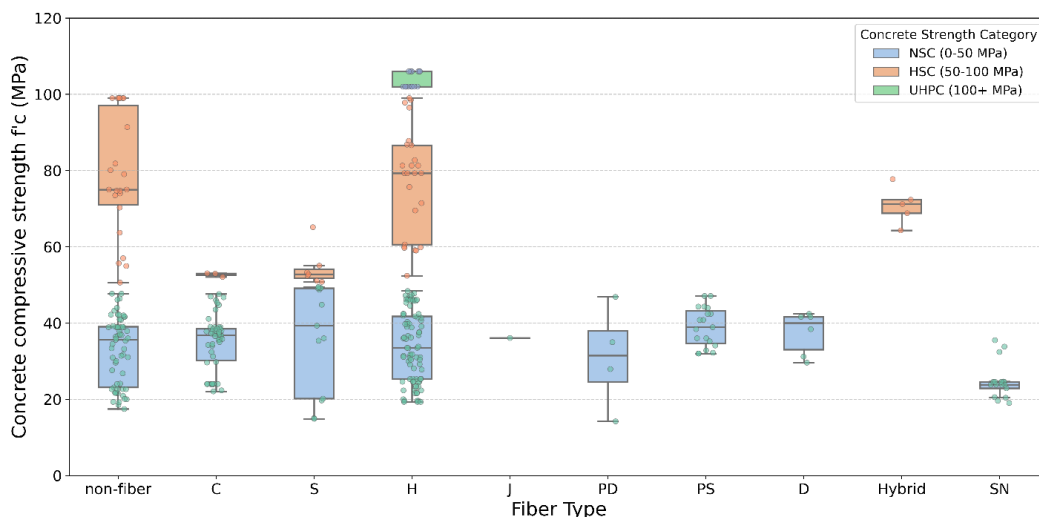


Figure 7. Experimental fibers by concrete compressive strength.

Figure 8 presents frequency distribution charts for the experimental data samples' span, height, column size, fiber volume, experimental load, and compressive strength ( $f'_c$ ). The span distribution predominantly ranges from 1500-1600 mm, with a secondary peak at 1000 mm. This right-skewed distribution indicates that longer spans have been less frequently tested. Height and column size show similar distributions, with the highest peak between 75-125 mm (height) and 100-150 mm

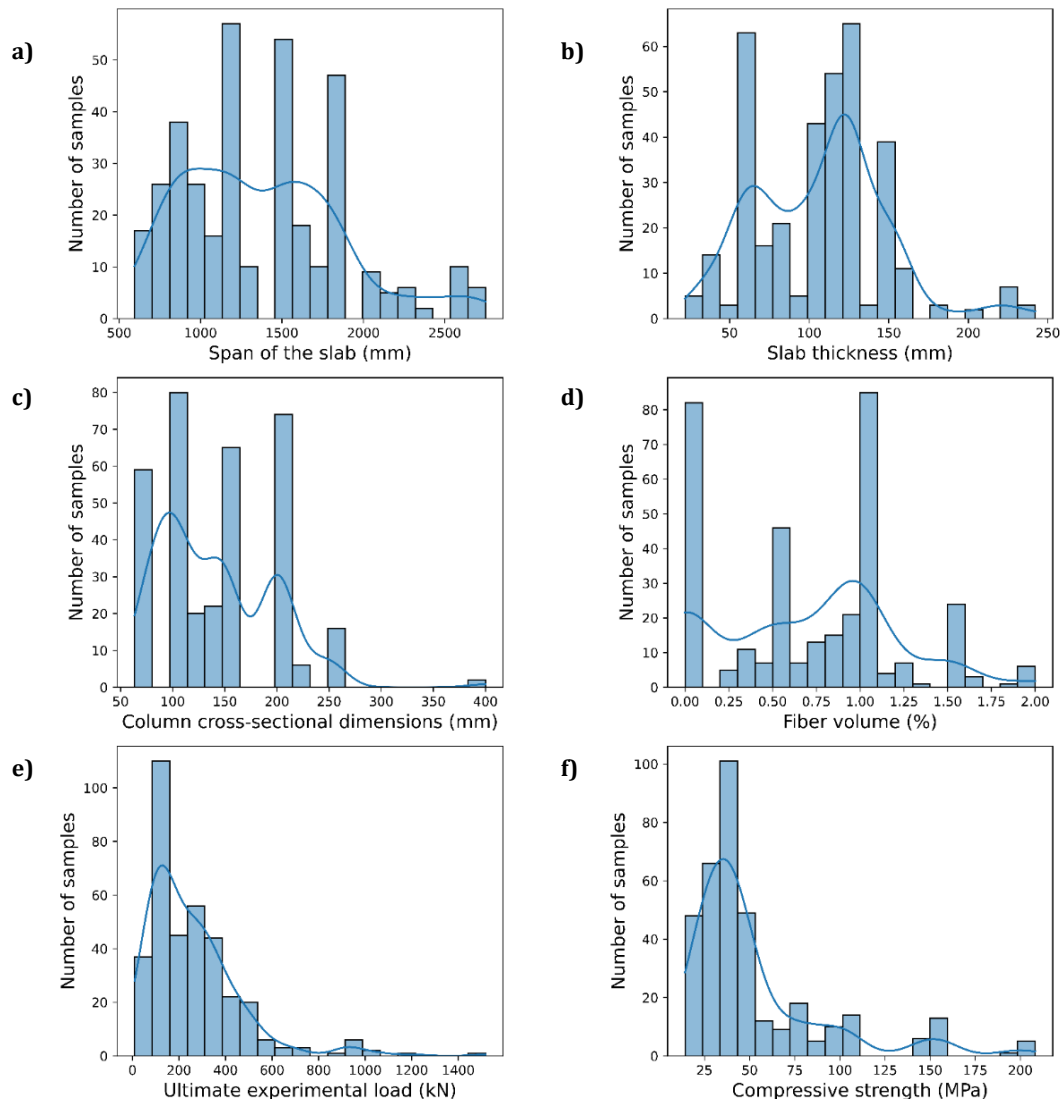
(column size), both right-skewed, reflecting the limitations of larger values.

Fiber volume distribution peaks at 0.5%, 1.0%, and 1.5%, with a few samples using more than 1.5%. Experimental load and compressive strength  $f'_c$  are also right-skewed, with most values falling within the range of 0-600 kN (load) and 25-50 MPa (compressive strength), showing that higher values have not been extensively studied.

Statistics indicate that material properties are distributed across various

values, reflecting randomness and parameter diversity. However, their distribution does not entirely match any specific pattern, tending to cluster around certain value ranges while other ranges are

less represented. Thus, although some properties have clear peaks, overall, the parameters do not follow a single distribution pattern (Table 2).



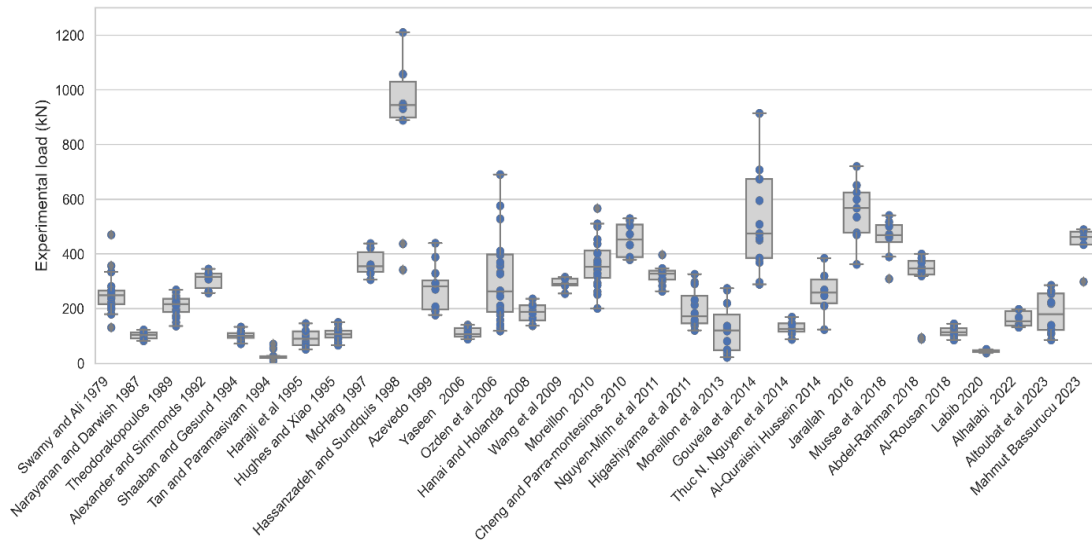
**Figure 8.** Distribution chart by parameters. (a) Span of the slab; (b) Slab thickness; (c) Column cross-sectional dimensions, (d) Fiber volume (%), (e) Ultimate experimental load, (f) Compressive strength.

Based on the experimental compression force chart from various studies (Figure 9), a general observation can be made that all studies indicate a significant increase in load-bearing capacity when adjusting parameters such as fiber composition, fiber type, vertical reinforcing steel, and flat slab thickness. Minh [30] and Lampropoulos [36], along with many other studies, noted that current formulas predicting shear-

punching capacity do not adequately consider factors such as fiber shape, the length-to-diameter ratio of steel fibers, and the contribution of tensile reinforcement. This leads to inaccurate results. Therefore, new formulas must be developed for more accurate predictions, and additional experimental studies should be conducted to verify results under real-world conditions.

**Table 2.** Statistical data from experimental tests.

	Length (mm)	f <sub>c</sub> (MPa)	Effective thickness (mm)	Fiber content (%)	Experimental load (kN)
Mean	1,374.3	52.4	84.8	0.7	257.8
STD	493.2	37.7	35.9	0.5	203.8
min	595.0	14.2	13.8	-	9.4
max	2,750.0	208.2	220.0	2.0	1,517.0



**Figure 9.** Ultimate experimental load from various studies.

### 3. Crack Resistance Capacity

#### 3.1. Crack Resistance by Fiber Type

Many studies provide images of concrete crack patterns during testing. These images reveal apparent differences between fiber-reinforced samples and those without fibers, clarifying the failure mechanism and evaluating the fibers' effectiveness in improving concrete's mechanical properties. Theodorakopoulos [14] demonstrated that adding steel fibers to concrete reduces slab deformation at all load stages while increasing first crack strength, shear-punching resistance, and post-punching capacity. Narayanan and Darwish [16] observed that cracks in samples with higher fiber volume ratios (from 0 to 0.94) were more minor and more evenly distributed, helping to maintain structural integrity after

reaching maximum load, with maximum load capacity increasing by 42%.

Tan and Paramasivam [17] found that increasing the ratio of straight steel fibers (S) enhanced the samples' first crack load, yield load, and maximum load. Furthermore, the cracks were more minor and more evenly distributed with the addition of steel fibers. Harajli et al. [18] also concluded that hooked steel fibers (H) significantly improved slab-column connections' ductility and shear-punching resistance, with more minor and more evenly distributed cracks than samples without fibers. This study also showed that polypropylene fibers improved ductility, though they were less effective than steel fibers.

Hughes and Xiao [19] discovered that cracks were more minor and evenly distributed when using various fiber types,

including steel and polypropylene fibers. McHarg's study provided images showing enhanced shear-punching resistance and ductility of steel fiber-reinforced concrete compared to non-fiber-reinforced samples, with more minor and more evenly distributed cracks, maintaining structural integrity after reaching maximum load.

Ozden [29] pointed out that cracks in normal-strength concrete slab samples tended to develop quickly when the load reached a certain level. The crack pattern typically consisted of straight cracks extending from the load point to the slab edges, which is characteristic of brittle failure due to the lower tensile strength of normal-strength concrete. In contrast, in high-strength concrete samples, cracks appeared later due to the higher tensile strength of the concrete. The cracks were more minor and evenly distributed, though they could merge at higher loads and cause sudden failure. Nguyen et al. [30] also observed this phenomenon when testing high-strength concrete slabs reinforced with straight steel fibers of the Dramix type, showing more minor cracks but still resulting in brittle failure at high loads.

Hussein's study [33] revealed that ultra-high-performance concrete (UHPC) often exhibited small, barely visible cracks at low loads, thanks to the very high tensile and compressive strength of UHPC. When steel fibers were added, the crack pattern became more complex, with cracks developing in multiple directions but not spreading widely, allowing better control of slab failure. Moreillon [31] studied ultra-high-performance fiber-reinforced concrete (UHPFRC) slabs with short steel fibers and concluded that short steel fibers reduced crack width. The observed cracks were more

minor and more evenly distributed, improving the overall load-bearing capacity of the slab. Meanwhile, Lampropoulos [14] found that long steel fibers improved the tensile strength of UHPFRC slabs, producing larger cracks but fewer in number. The crack pattern with long steel fibers typically consisted of cracks running along the length of the steel fibers, allowing the slab to bear higher loads before failure occurred.

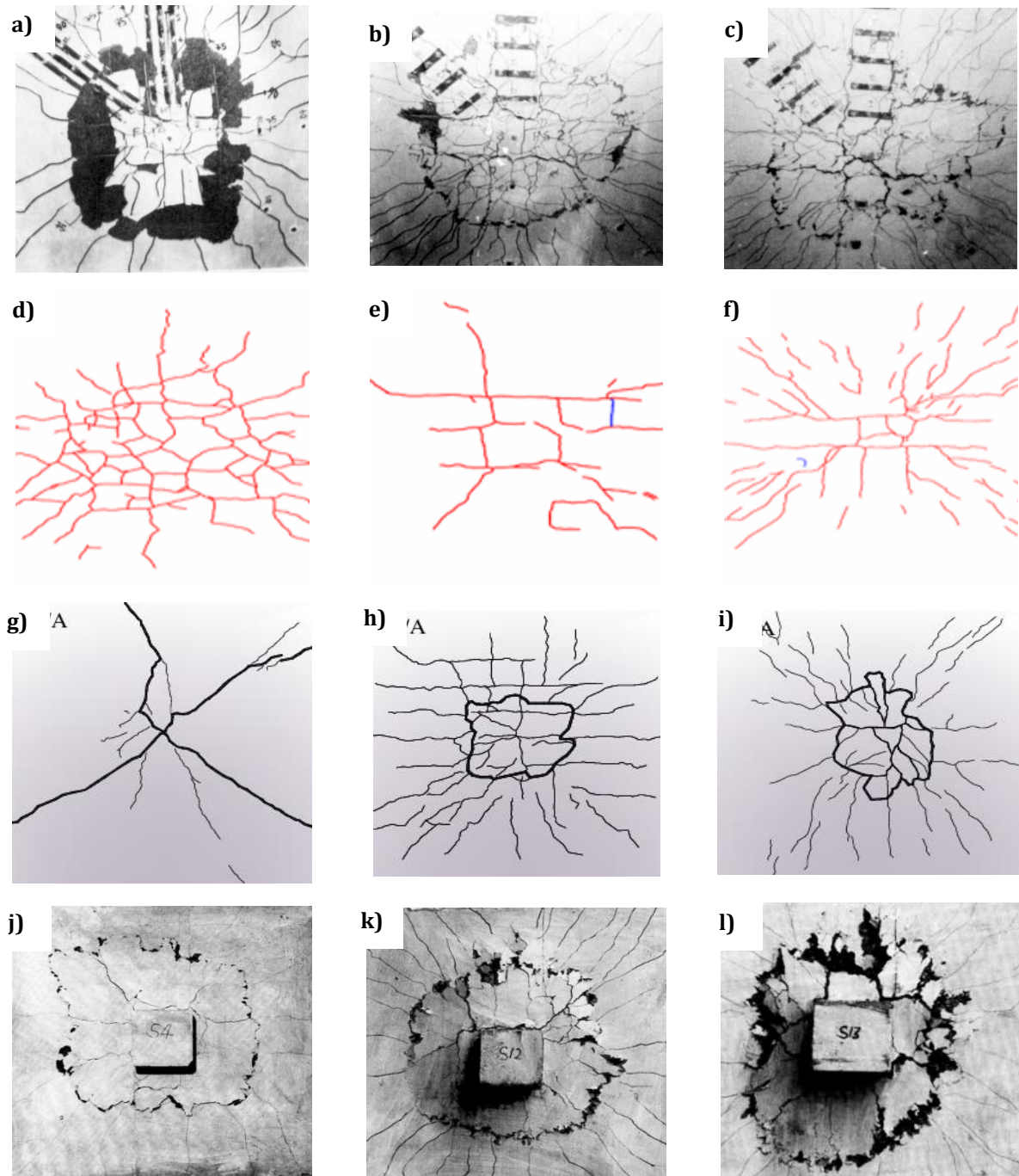
For other fiber types, AlHamaydeh's research [35] demonstrated that macro polyolefin synthetic fibers significantly reduced crack width in self-compacting concrete. Slabs using this synthetic fiber exhibited tiny, evenly distributed cracks, improving overall load-bearing capacity.

In conclusion, the studies indicate that adding fibers to concrete significantly improves crack resistance and enhances the overall durability of concrete slabs. Fiber reinforcement helps control the formation and propagation of cracks, improves ductility, and increases the load-bearing capacity of structures. However, the effectiveness of different fiber types, such as steel, glass, basalt, and synthetic organic fibers (polypropylene), varies significantly depending on the mechanical properties and interaction between the fibers and the concrete matrix. The specific effectiveness of each fiber type depends on several factors, including shape, size, content, and fiber distribution method in the concrete.

Therefore, more detailed studies are required to fully understand each fiber type's mechanisms and determine optimal conditions for their use to achieve maximum performance. Comparative studies on the effectiveness of different fiber types in improving crack resistance and tensile strength in concrete will provide critical

information, guiding practical applications and developing more sustainable and efficient structural solutions. Additionally, focusing on accurate experimental methods and modeling will help clarify failure mechanisms, assist in the optimization of fiber usage ratios, and improve efficiency

and reliability in construction projects. This will enhance the quality of concrete and open up broader application opportunities for fiber-reinforced concrete materials in projects demanding high crack resistance and long-term durability.



**Figure 10.** Crack patterns. (a) No fiber [14], (b) 0.5% Corrugated steel fiber [14], (c) 1.0% Corrugated steel fiber [14], (d) 0% Straight steel fiber [33], (e) 0.5% Straight steel fiber [33], (f) 1.1% Straight steel fiber [33], (g) 0% Straight steel fiber [30], (h) 0.8% Straight steel fiber [30], (i) 1.6% Straight steel fiber [30], (j) No fiber [19], (k) 0.5% Duoform fiber [19], (l) 1.5% Duoform fiber [19].



### 3.2. Crack Resistance of Hybrid Fibers

Although many studies have been on fiber types in flat slab structures, research on combining reinforcement fibers still needs to be done. However, several recent authors have highlighted fiber applications' significant potential and effectiveness in flat slabs. Notably, studies by Bassurucu [43], Labib [44], and Moreillon [31] demonstrated the considerable benefits of hybrid fiber reinforcement.

Bassurucu [43] assessed the effectiveness of single and hybrid fibers, showing remarkable results, especially in improving punching shear resistance and energy absorption in reinforced concrete flat slab systems. The study used three types of fibers: straight steel (S), hooked-end steel (H), and polypropylene (PS). In terms of punching shear resistance, Bassurucu [43] found that using a single fiber type, such as straight steel fibers (S), improved load-bearing capacity by approximately 45.66% compared to control samples without fiber reinforcement. Although effective, this improvement was relatively modest. Conversely, when combining multiple fiber types, especially hybrid fibers with two or three types, the results showed a significant increase in punching shear resistance. A combination of three fiber types (straight, hooked-end, and polypropylene) achieved the highest improvement, with an increase of 63.9%. Simultaneously, a two-fiber combination (straight and hooked-end) also showed a significant improvement of 61.45%. This combination demonstrated an optimal and effective reinforcement method due to the complementary properties of fibers with different sizes and mechanical characteristics [43]. The energy absorption capacity of structural elements also showed

apparent differences between single and hybrid fibers. When using only one fiber type, the energy absorption capacity improved moderately, with single straight steel fibers (S) achieving a 76.59% increase. In contrast, hybrid fibers, particularly the three-fiber combination, improved energy absorption by up to 213.39%, and the two-fiber combination reached 176.95%. Bassurucu concluded that the combination of straight and hooked-end steel fibers created a synergistic effect, helping to prevent the development of large and small cracks, thus enhancing the structure's resistance to loads (Figure 11) [43].

Furthermore, the cracks were more minor and more evenly distributed with hybrid fibers, particularly the combination of hooked-end steel fibers and straight steel or polypropylene fibers. This led to increased ductility and reduced the risk of sudden failure, allowing the structure to maintain load-bearing capacity for longer [43]. Similar findings by Labib and Moreillon indicated that combining multiple fiber types in reinforced concrete structures, especially hybrid fibers, significantly enhanced punching shear resistance [31], [44]. The results showed that using a single fiber type at 0.5% steel fiber improved the punching shear resistance of concrete compared to non-reinforced concrete. Specifically, this single-fiber-reinforced concrete increased punching shear resistance by 10.5%. Meanwhile, fiber-blended concrete exhibited superior performance. When blending 0.5% steel fiber with 0.2% polypropylene fiber (sample HFC1), punching shear resistance increased by 25%. Increasing the steel fiber content to 1.5% while maintaining the 0.2% polypropylene fiber content (sample HFC2) resulted in a 34% increase in punching shear

resistance compared to non-reinforced concrete. The authors concluded that combining steel and polypropylene fibers improved durability, enhanced crack resistance, and maintained the structure's ductility, yielding better results than using a single fiber type alone (Figure 12) [44]. However, further experimental studies are

needed to better understand the effects of combining different fiber types and the impact of varying fiber ratios on reinforcement efficiency. Future experimental research will help establish a foundation for applying hybrid fibers in construction, ensuring more sustainable and load-bearing structures.

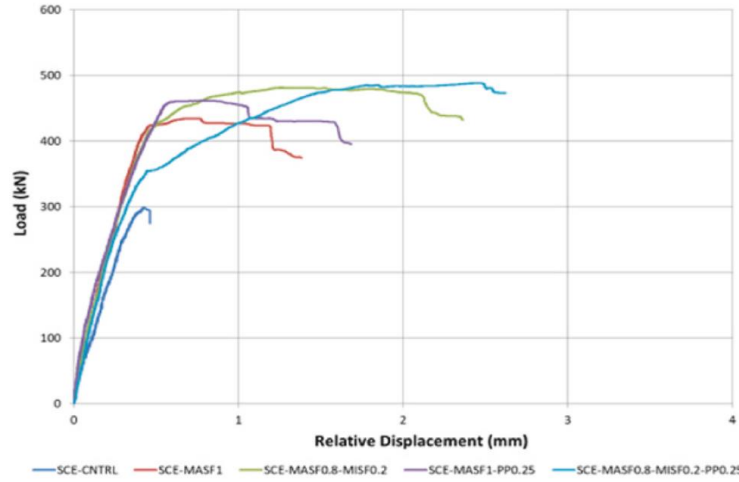


Figure 11. Load-displacement curve extracted from Bassurucu [43].

Table 3. Design equations for nominal punching shear capacity with fiber reinforcement.

Narayanan and Darwish [16]

$$V_{R-FRC} = \xi_s (0.24f_{spf} + 16\rho + 0.41\tau F) b_f d$$

$$F = \frac{L_f}{D_f} V_f d_r, f_{spf} = \frac{f_{cfu}}{20 - \sqrt{f_F}} + 0.7, \xi_s = 1.6 - 0.002h,$$

$$d_r = 1(\text{hooked end steel fibers}) \quad d_r = 0.75(\text{crimped steel fibers}) \quad d_r = 0.5(\text{straight steel fibers})$$

$$\text{Square loading pad: } b_r = (4(\alpha_{col} + 3\pi h))(1 - KF),$$

$$\text{Circular loading pad: } b_r = \pi(\alpha_{col} + 3h)(1 - KF), \quad \text{at } t = 1.5h$$

Higashiyama et al. [45]

$$V_{R-FRC} = \beta_d \beta_p \beta_f (f_{pcd} + V_b) u_p d$$

$$f_{pcd} = 0.2\sqrt{f'_c} \leq 1.2\text{MPa},$$

$$\beta_d = \sqrt{\frac{1000}{d}} \leq 1.5, \quad \beta_p = \sqrt{100\rho} \leq 1.5, \quad \beta_f = 1 + \frac{1}{1 + 0.25\frac{u_s}{d}},$$

$$V_b = 0.41\tau_F F, \quad F = \frac{L_f}{D_f} V_f d_f$$

$$d_r = 1(\text{hooked end steel fibers}) \quad d_r = 0.75(\text{crimped steel fibers}) \quad d_r = 0.5(\text{straight steel fibers})$$

$$\text{Square loading pad: } u_p = u_{p1}(1 - KF),$$

$$\text{Circular loading pad: } u_p = u_{p2}(1 - KF) \text{ at } \frac{d}{2}$$

Nomenclature

$V_{R-FRC}$ : Nominal punching shear capacity of the fiber-reinforced concrete slab (N or kN).

$f_{spf}$ : Tensile strength of the fiber-reinforced concrete determined using the split-cylinder method (MPa).

$\rho$ : Average reinforcement ratio in both directions of the slab.

$\tau F$ : Bond strength between fibers and the concrete matrix (MPa).

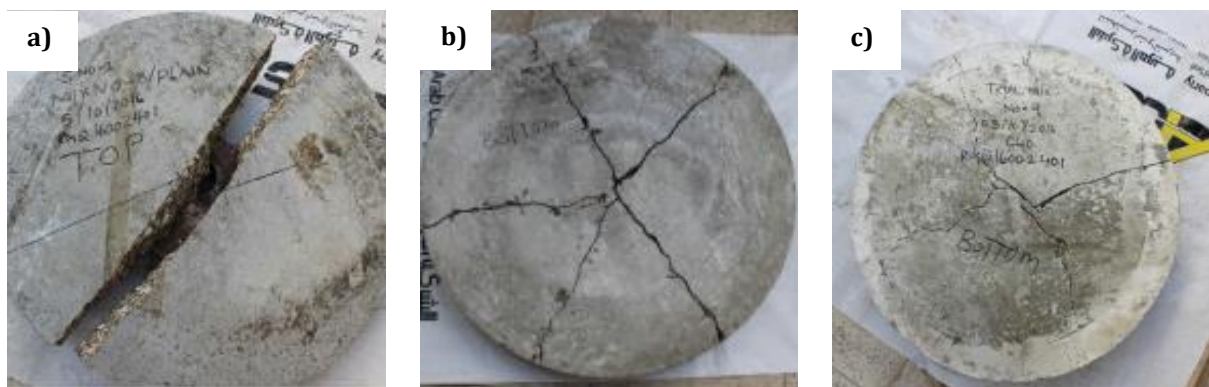
$F$ : Fiber factor, related to fiber length, diameter, volume fraction, and type.

$L_f$ : Fiber length (mm).

$D_f$ : Equivalent diameter of the fiber (mm).

$V_f$ : Volume fraction of fibers in the concrete mix, expressed as a percentage.

$d_r$ : Factor dependent on the type of fiber.



**Figure 12.** Experimental samples by W.A. Labib [44].

(a) No fiber, (b) Single fiber reinforcement, (c) Hybrid fiber reinforcement.

### 3.3. Formula for Predicting Punching Shear in Fiber-Reinforced Flat Slabs

Several predictive formulas for the punching shear capacity of reinforced concrete slabs have begun to incorporate the role of fibers. Notably, the formulations by Narayanan and Darwish, as well as Higashiyama et al., integrate fiber-related parameters into their analytical frameworks, thereby elucidating the influence of fiber geometry and mechanical properties on the load-carrying capacity of these structural elements (Table 3).

The method proposed by Narayanan and Darwish [16] considers fibers through parameters including the tensile strength of fiber-reinforced concrete ( $f_{spf}$ ), the bond strength between fibers and the concrete matrix ( $\tau F$ ), and a fiber factor ( $F$ ). The fiber factor ( $F$ ) is determined by the fiber volume

fraction ( $V_f$ ), the aspect ratio ( $L_f/D_f$ ), and the fiber type ( $d_r$ ), enabling an adequate representation of force transfer mechanisms within cracked concrete and facilitating the quantification of fiber contribution.

In contrast, the approach by Higashiyama et al. [45] incorporates fibers by adjusting the essential punching shear strength ( $f_{pcd}$ ), introducing a direct fiber contribution term ( $V_b$ ), and employing correction factors ( $\beta_d$ ,  $\beta_p$ ,  $\beta_f$ ,  $\beta_f$ ). This comprehensive framework captures the combined effects of fiber volume ( $V_f$ ), aspect ratio ( $L_f/D_f$ ), bond strength ( $\tau F$ ), and geometric as well as stress-related parameters, thereby offering a more intricate depiction of fiber influence on punching shear resistance.

Both methods predominantly focus on steel fibers (hooked, crimped, straight). The effects of alternative fiber types, such as

polymer, natural, or hybrid fibers, have yet to be thoroughly examined, underscoring the need for further research to broaden the applicability and accuracy of these predictive approaches.

#### **4. Conclusion**

Based on the evaluation of previous experimental studies, the authors conclude as follows:

The research group collected and analyzed data from 273 fiber-reinforced concrete and 84 control slabs, all tested under concentrated loading. This collection and processing of experimental data provide a rich database for assessing the effectiveness of reinforcement fibers in improving the mechanical properties of concrete slabs.

The collected dataset includes a wide range of key design parameters, such as concrete compressive strength, ranging from 25 MPa to 210 MPa, and various types of steel fibers and synthetic fibers (such as polypropylene, nylon, and carbon fibers), along with different ratios of tensile reinforcement. This diversity allows for a comprehensive evaluation of the impact of design factors on the overall performance of fiber-reinforced concrete slabs.

The research results show that reinforcement fibers not only enhance the overall durability of slabs but also improve crack resistance and maintain the structure's ductility. Steel fibers, synthetic fibers, and hybrid fiber systems effectively enhance load-bearing capacity and shear-punching resistance, reducing the formation and propagation of cracks under load.

Compared to using single fiber types, combining multiple fiber types optimizes the unique mechanical properties of each fiber,

creating a complementary effect that comprehensively improves concrete performance. The study and application of hybrid fibers hold great potential for optimizing structural performance, minimizing cracking, and increasing the load-bearing capacity of fiber-reinforced concrete.

However, there are still many limitations in studying the effects of fiber type, size, content, and orientation on the punching shear performance of flat slabs. This presents difficulties in optimizing designs and applying fibers in practice. To address this issue, further research is needed to explore these factors in greater depth, thereby developing accurate predictive models and specific design guidelines to enhance the efficiency of fiber reinforcement in construction.

In the future, further research on the combination of different fiber types will help maximize the potential of fiber-reinforced concrete while expanding its application in projects requiring high durability and structural safety.

#### **Contributions of authors in this article**

**Vu Hieu Phuong:** Methodology, Data management, Formal analysis, Investigation, Validation, Visualization, Feedback on peer review, Writing – original manuscript. **Nguyen Tien Thuy:** Data compilation, Methodology, Supervision, Grant Acquisition, Manuscript Editing. **Le Hoang An:** Methodology, Supervision, Grant Acquisition, Manuscript Editing.

#### **Declaration of competing interest and dedication to copyright**

The authors declare the absence of any potential conflicts of interest from this study

and affirm that the paper has not been previously published.

## Data available

Data will be provided upon request.

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