

## RESEARCH ARTICLE

# Effect of Ultra-High-Performance Fibre-Reinforced Concrete Strip Thickness on the Punching Shear Performance of Reinforced Concrete Flat Slabs

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## ABSTRACT

Design and construction errors or building function changes need strengthening concrete slab-column connections in flat slab systems. Increased flexural and shear capabilities enhance these connections' ultimate shear capacity. Due to its strength and longevity, ultra-high-performance fiber-reinforced Concrete (UHPFRC) reinforces structural sections. This study examines the punching behavior of column-slab connections of reinforced concrete flat slabs enhanced with externally bonded ultra-high-performance fiber-reinforced concrete strips. At the critical sections, UHPFRC strips of various thicknesses strengthened ten two-way slab specimens of three concrete types with compressive strengths of 20.8, 32.6, and 43.3 MPa. Before supporting the slabs on four opposing corners and shear-punching, the strips were pre-cast and attached to the tensile slab surface using epoxy. After strengthening reinforced concrete slabs with UHPFRC strips, the stiffness of the slab specimens at critical sections increased to resist punching shear load up to 26%, and the slab failure mode changed from brittle to ductile. Normal-strength concrete (NSC) slabs benefit from externally bonded UHPFRC strips' punching shear resistance. The strengthening method enhanced ductility, leading to a more robust structural performance and a change from a brittle to a ductile failure mode.

**Keywords:** Flat Slab, Punching Shear, UHPFRC, Concrete, Strengthening Strips

## INTRODUCTION

Since 1900, flat slabs have been extensively used in multi-story buildings due to their economic and functional benefits, such as the structure's overcapacity, aging, and various destructive changes in environmental conditions over an extended service period [1-3]. Therefore, it is necessary to reinforce reinforced concrete flat slab system structures to restore their functionality and extend their service life without incurring the expense of demolition and reconstruction [4-5].

Before the early 1980s, the most common method for repairing or reinforcing deteriorated structures was to attach steel plates to the tensile surface of concrete using adhesives and fasteners. After the mid-1980s, due to their high strength, lightweight, and resistance to environmental effects, new materials, such as fiber-reinforced polymers, became popular in strengthening structures [1,6].

Currently, strengthening techniques against punching reinforced concrete flat slabs that are externally applied to increase the ultimate shear capacity of column-slab connections can be expressed practically as four technique categories, including the shear strengthening, such as installing anchored or head bolts, grids of fans, and stirrups; and flexural strengthening, which is typically achieved by adding longitudinal reinforcement on the top of slabs, such as stirrups; and the third is shear strengthening as well, which is generally achieved by installing the enlargement of the support, which can be accomplished by widening the column, casting concrete capital, or post installing steel capital. In addition, post-tensioning systems, in which various pre-stressing systems are utilized to reinforce existing slabs, are also used. However, each technique has significant drawbacks for strengthening reinforced concrete slabs, such as high cost, the need for experienced and trained personnel, and the inability to produce ductile material [7-8].

In some instances, the benefits of strengthening flat surfaces may be outweighed by the expense and complexity of previous techniques. In addition, the performance of the bond between the external reinforcing material and the concrete element of the structure remains a weakness in the structure's strengthening mechanism. Consequently, punching shear in flat slabs requires enhanced techniques [9].

As an innovative cement-based composite material, ultra-high-performance concrete (UHPC) has been developed in various countries. This concrete has high tensile strength, greater than 7 MPa, compressive strength greater than 150 MPa, and high-energy dissipation capacity with ductile failure due to the addition of steel fibers. Recent studies on ultra-high-performance fiber-reinforced Concrete (UHPFRC) have demonstrated its tremendous potential for increasing the punching shear capacity of flat slabs, increasing their deformation capacity, and preventing brittle failures that can occur under high load stress and moment [10-11]. Recent research has revealed that concrete containing steel fibers subjected to cyclic loading exhibited greater load-bearing capacities, fracture resistance, energy dissipation values, and deformation capacity than non-fibrous Concrete [12]. Consequently, the strength of the UHPFRCs can be increased more rapidly through heat curing, in which shrinkage and creep coefficients are modest [13].

In addition, the strength of UHPFRC is superior to that of conventional concrete reinforced with steel or fiber due to its low air content and low water permeability, which ensures a long service life [14]. Overall, owing to these superior mechanical properties, UHPFRC is suitable for reinforcing deteriorated reinforced concrete structure elements and enhancing flexural or shear capacity

and ductility, as well as the permeability and durability of the particular strengthened structural element. Although tests have shown that UHPFRC flat slabs have much better shear strength than their normal strength concrete (NSC) equivalents, it may not be economically possible to construct an entire slab from UHPFRC. Consequently, the researchers anticipate identifying the appropriate application of UHPFRC inside the critical section shear zone [15].

Much study is being done right now on how to strengthen RC flat slabs with a UHPFRC layer [16-21]. For that reason, looking into this new method combines the benefits of strengthening with lower costs, faster application, and easier preparation. This work contrasts with making RC flat slabs stiffer via using pre-cast, epoxy-bonded UHPFRC strips. First, the RC base surfaces were sanded. Next, the UHPFRC was poured on top of them. Second, an epoxy glue was used to attach a pre-made UHPFRC element to the RC element. Through tests, Al-Osta et al. (2017) found that both methods ensured a connection between the RC and UHPFRC layers [22].

In strengthening procedures, the bonding properties and quality of ordinary concrete and strengthening materials are among the most crucial factors. Numerous codes, such as ASTM, provide multiple evaluations to ensure a desirable strong bond [23]. In this context, several tests have been conducted, including the slant-shear test with the inclined bond interface at 55°, 60°, and 70° and the pull-off and fracturing tensile tests for two distinct bond mechanism methods, epoxy-bonded and sandblasted. According to the results, normal concrete specimens with sandblasted surfaces exhibited greater oblique shear strength than epoxy-bonded specimens [24]. Al-Osta et al. [22] reported that the results of fracturing tensile strength indicated a perfect bond between conventional Concrete and UHPFRC.

Similarly, split tensile strength and slant-shear experiments determined the bond strength between the host concrete and the UHPFRC. Nursyamsi et al. [25] found that UHPFRC provides perfect bonding during early strengthening and functions well with normal concrete surfaces. It was observed that the UHPFRC exhibited a high level of bonding and cohesion with the regular concrete and adhesive material, resulting in a practically seamless integration.

Re-reinforcing existing normal-strength reinforced concrete flat slabs is necessary to restore or increase their initial designed capacity. However, strengthening the application of flat slab slab-column connections is considered the most challenging form of enhancing practice. This study set out to answer the question, "How does adhesive epoxy resin strengthen different grades of reinforced NSC slab substrates?" by testing different thicknesses of UHPFRC strips linked at key punching portions. To further enhance the substrates of slab specimens of varying grades for punching at fractures and ultimate loads, the impact of various UHPFRC strip thicknesses was quantified.

## **METHODOLOGY**

The work is an extension of our previous study of Ali et al [35]. The current experimental program was designed to strengthen different grades of NSC flat

slabs against punching shear using varying thicknesses of UHPFRC strips. The methodology is outlined as follows:

**CONCRETE GRADES AND UHPFRC STRIPS**

The NSC mixing design used in this study allowed the production of three concrete classes at 28 days: 21 MPa, 31 MPa, and 41 MPa. Similarly, the UHPFRC mix design was used to create strips for reinforcement with thicknesses of 10, 15, and 20 mm and widths of 20 mm. Ten slabs with (1:4) scale were erected using the planned flat plate concrete slab construction with 5400 mm grid column lines in both directions; the column dimension was 300x300 mm, and the slab thickness was 200 mm, and the model size of flat reinforced concrete slabs was selected from contra flexural points of moment from negative to positive, as shown in Table 1.

**Table 1.** Specifics of the strips’ characteristics and slab specimens

Parameters	Grade of concrete slabs		
	Concrete specimens with grade 21 MPa	Concrete specimens with a grade 31 MPa	Concrete specimens with a grade 41 MPa
Control specimens	G21C0	G31C0	G41C0
Strip thickness 10 mm, placed at the critical section d/2	G21T10W20	G31T10W20	G41T10W20
Strip thickness 15 mm, placed at the critical section d/2	G21T15W20	G31T15W20	G41T15W20
Strip thickness 20 mm, fixed at the critical section d/2	G21T20W20	G31T20W20	G41T20W20

**MATERIALS**

**INTERNAL CURED REINFORCED NORMAL-STRENGTH CONCRETE FLAT SLAB SPECIMENS**

The three kinds of NSC employed in this study for substrate slab specimens were 21, 31, and 41 MPa. Depending on the needed concrete grades, various water-cement ratios were in each combination, along with standard Portland cement, river sand with a fineness modulus of 2.4, and coarse aggregate with a maximum size of 9.5 mm. The slump measurement of newly mixed concrete varied between 150 and 180 millimeters. Table 2 presents the ratio of regular-strength concrete used to create slab specimens. Over 28 days, standard cylinders were obtained from the NSC mixes to achieve the targeted compression strength.

**Table 2.** Mix proportions for different grades of normal-strength concrete

Concrete type	Target strength (MPa)	w/b	Mix proportion		The volume fraction of micro steel fiber* (%)	Superplasticizer (%)
NSC	21	0.67	Cement: fine	1:2.1:2.32	-	-
NSC	31	0.56	Aggregate: coarse aggregate	1:1.6:1.93		
NSC	41	0.49	Cement: Silica	1:1.23:1.6 1		
UHPFRC strips	>150	0.24	Fume: Silica sand	1:0.25:0.45	2	1.87%

\*Aspect ratio 40, and tensile strength above 2859 MPa.

### **ULTRA-HIGH-PERFORMANCE FIBER-REINFORCED CONCRETE STRIPS**

Copper-coated micro steel fibers, regular Portland cement, densified silica fume, well-graded sieved and dried fine sand, and a superplasticizer based on poly-carboxylate were the components that were included in the mix design for UHPFRC strips. Forty was the aspect ratio of the steel fiber that was coated with copper and was linear. According to Wille et al. [26], a 2% by-volume addition of copper-coated micro-steel fiber was made to absorb tensile stresses, hence preventing the development and interconnection of microcracks by preventing their propagation. The standard cylinder was removed from the UHPFRC mixture to ensure mechanical qualities after 28 days. Table 2 indicates the mixed proportions of the UHPFRC strengthening material.

### **BONDING MATERIAL**

Polymers, composites, grouts, mortars, and glues are popular adhesives. According to the literature, the bond strength between a substrate (reinforced NSC slab specimens) and strengthening material (UHPFRC strips) is the most important property for concrete strengthening [27]. The experiment used TYTAN FIX JET 20 glue to join NSC slab specimens with UHPFRC strips. Table 3 shows its properties [28]. Pull-off test equipment was used to check the bond between the substrate and the strips [29].

**Table 3.** Properties of TYTAN JET FIX adhesive

Property	Value
Appearance color	White
Working time	5-10 minutes
Pre-curing time	30 minutes
Full hardening time	3 hours
Final bonding strength	400 kg /10 cm <sup>2</sup>
Temperature resistance after curing	-40°C to + 90°C

### **SPECIMENS PREPARATION**

#### **PREPARATION OF NSC SPECIMENS**

For the three grades of concrete, a 620-by-620-by-50-millimeter plywood mold was produced for the reinforced concrete slabs [35]. Four specimens were made for each grade, such as 21 MPa, with one classified as G21C0 and used as a control. The remaining three specimens were designated G21T10W20 for strengthening strip pattern one, G21T15W20 for strengthening strip pattern two, and G21T20W20 for strengthening strip pattern three (Table 1). The NSC specimens were then de-moulded and allowed to cure for 28 days. After which, surface preparations were made for the UHPFRC strip strengthening procedure.

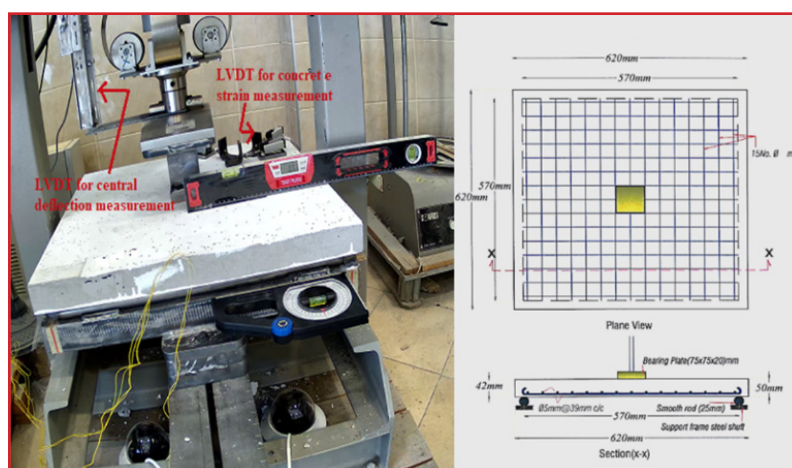
#### **PREPARATION OF UHPFRC STRIPS**

The plywood molds for the strip had thicknesses of 10, 15, and 20 mm, a width of 20 mm, and varied lengths based on the critical location  $d/2$  from the column's face. The fresh UHPFRC mixture was deposited in the strip molds and set for 16 hours. Subsequently, the UHPFRC strip specimens were removed from

the molds and cured for five days at 55°C inside a steam chamber. They were then transferred from the steam chamber to a water tank for 28 days of curing, after which the specimens were removed from the water vessel and surface-prepared. After 28 days of curing, the NSC specimen slabs and the UHPFRC strips were dried at laboratory temperature for one day, and their surfaces were cleaned by removing detritus and dust from the substrate. The following day, the bonding process was initiated by applying one layer of adhesive epoxy.

### TESTING PROCEDURE

The vertical load was progressively applied by bearing the flexure test machine's head column juke at 0.05 MPa/s. At each loading stage, fractures were observed by recording the deflection at the center of the slabs, rotation at the supports, Linear variable differential transformer's (LVDTs) measurement of concrete Strain on the compression face, and strains of reinforced steel bars. The positions and lengths of the first visible and subsequent fractures were marked during loading. When a failure occurred, the failure load was recorded and halted, demonstrating a decrease in load reading in conjunction with an increase in LVDT reading, as shown in Figure 1.



**Figure 1.** Loading set-up of reinforced concrete flat slabs and details of specimens

### RESULTS

The tests yielded a large amount of data. The load applied to the specimens is regarded as the most appropriate relationship between the experimental measurements. As a result, the experimental load-support rotation, load-mid span deflection, load-reinforcements strain, and load-concretes strain connections were organized for each test. The experimental relationships are provided and studied to determine the effects of factors and specimen behavior in the crucial area of punching shear underloading.

### MECHANICAL PROPERTIES OF CONCRETES

The mix proportions intended to make three grades of concrete (21, 31, and 41 MPa) were used to strengthen ten slab specimens with UHPFRC strips. These slab specimens were cast in three groups, with four in each group. For all groups, the mechanical features of NSC were figured out, as shown in Table 4 [30].

**Table 4.** Mechanical properties of concretes

Slab group	Compressive strength, MPa	Split tensile strength, MPa	Flexural tensile strength, MPa	Modulus of elasticity, GPA
G21C0	20.8	2.07	3.8	21.44
G31C0	32.6	2.31	4.35	26.84
G41C0	43.3	3.02	5.18	30.93
UHPFRC Strips	173.24	13.77	13.83	51.23

### **STRENGTHENING OF FLAT SLABS FOR PUNCHING LOADS WITH UHPFRC STRIPS**

#### **PUNCHING RESISTANCE BEFORE AND AFTER CRACKING**

The fracture load obtained from tested slab specimens reinforced with varied thicknesses of UHPFRC strips under punching shear demonstrates that strip thickness enhances crack load in all concrete grades compared to control specimens. Specifically, the slab specimens with concrete grade 20.8 MPa show a 105% increase in fracture load due to strengthening strips with a thickness of 20 mm. While the grade of slabs concrete slabs grows to 32.6 and 43.3 MPa, there is a minor increase. The ultimate punching shear resistance load obtained from strengthened slab specimens tested with various thicknesses of UHPFRC strips demonstrates that strip thickness impacts the ultimate resistance load of slab specimens in all concrete grades. When compared to the control specimens, the ultimate shear capacity of slabs concrete grade 20.8, 32.6, and 43.3 MPa improved by approximately 48.1%, 7.4%, and 7.2%, respectively, due to high shear resistance of higher grade of concrete. Table 5 shows significant improvements in slab specimens strengthened with 20 mm strip thicknesses in concrete grades as low as 20.8 MPa.

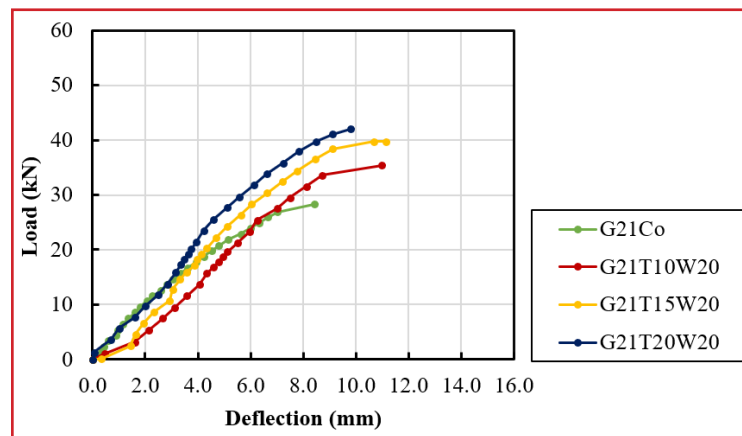
**Table 5.** Punching shear resistance and Strain in reinforcement at different locations from the critical section

Specimen	At the crack, loads				At the ultimate loads			
	Crack load, kN	Strain in reinforcements, mm/mm, $\times 10^{-3}$			Ultimate load, kN	Strain in reinforcements, mm/mm, $\times 10^{-3}$		
		0.5 d	1 d	1.5 d		0.5 d	1 d	1.5 d
G21Co	3.36	0.055	0.029	0.007	28.35	4.11	3.68	2.75
G21T10W20	6.77	0.028	0.005	0.0	35.37	2.57	1.17	0.0
G21T15W20	6.61	0.133	0.026	0.015	39.71	2.29	2.54	1.81
G21T20W20	6.90	0.013	0.006	0.004	42.00	2.58	2.15	2.44
G31Co	7.95	0.044	0.016	0.009	39.44	2.72	1.81	0.91
G31T10W20	8.50	0.017	0.01	0.006	41.40	2.17	2.49	2.48
G31T15W20	8.02	0.002	0.001	0.001	39.60	3.49	3.33	3.86
G31T20W20	8.19	0.034	0.024	0.012	42.37	3.98	3.49	2.37
G41Co	9.16	0.062	0.051	0.011	41.62	3.96	3.24	2.77
G41T10W20	10.15	0.061	0.018	0.019	47.77	2.62	3.93	2.53
G41T15W20	9.58	0.015	0.01	0.008	47.03	2.74	2.68	3.1
G41T20W20	9.50	0.019	0.016	0.011	44.62	3.66	3.79	3.07

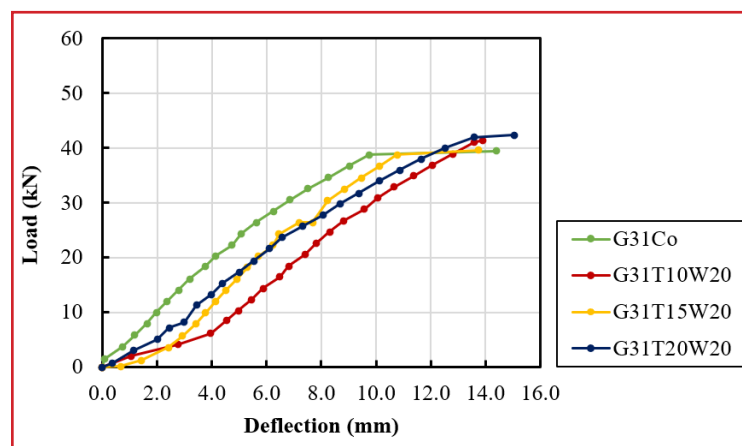
### LOAD-DEFLECTION CHARACTERISTICS

Deflection at the center of the tested slab specimens was measured experimentally using an LVDT. Following the appearance of the first crack, the load-deflection relationship was substantially determined by the reinforcing and strip distribution pattern used to strengthen the punching shear.

As shown in Figure 2, the first group curves with the concrete compressive strength slab 20.8 MPa represent a significant improvement in deflection at the point load compared to the control specimen. Specimen G21T20W20, with a strip thickness of 20 mm, exhibits a considerable deflection at ultimate load rather than the amount of ultimate load augmentation. While specimens G21T10W20 and G21T15W20 with 10 mm and 15 mm strip thickness show the lowest enhancement of ultimate load compared to the G21T20W20 specimen with great deflection, this indicates a strong influence effect of strip thickness on ductility behavior of slab specimens and their capacity against punching shear resistance.



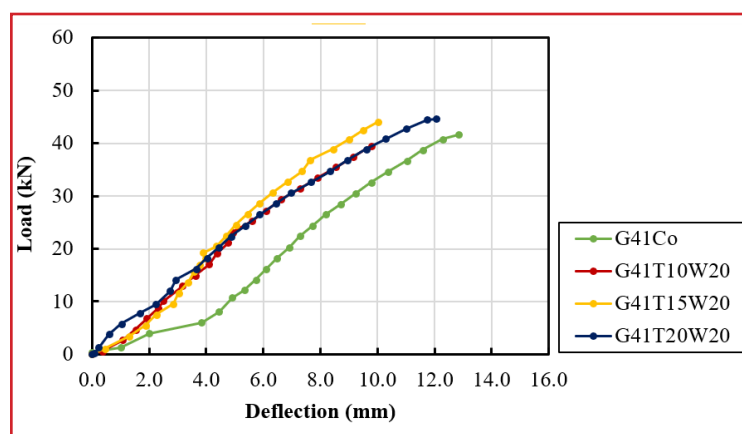
**Figure 2.** Load against deflection at mid-span for concrete slab specimens from the G21C0 group



**Figure 3.** Load against deflection observed at the midpoint of the span for concrete slab specimens belonging to the G31C0 group

Figure 3 shows the amount of deflection at various loading stages for concrete grade 32.6 MPa. Except for specimen G31T20W20 with 20 mm strip thickness, which has a slightly higher deflection than the control specimen, a minor rise in ultimate loads was identified with no changes in deflection compared to the control specimen. The effects of strip thickness on deflection and ductile behaviors are reduced as compressive strength increases from 20.8 MPa to 32.6 MPa; otherwise, the favorable impact on slab capacity against punching shear resistance is maintained.

Figure 4 shows the third set G41Co with a compressive strength of concrete slab of 43.3 MPa, demonstrating that increasing strip thicknesses for strengthening slab specimens reduces deflection in this scenario where the compressive strength of slab specimens rises to 43.3 MPa. Furthermore, as measured by the G41T20W20 slab specimen versus the control slab, the punching shear resistance load increases due to the increasing thickness of strengthening strips.



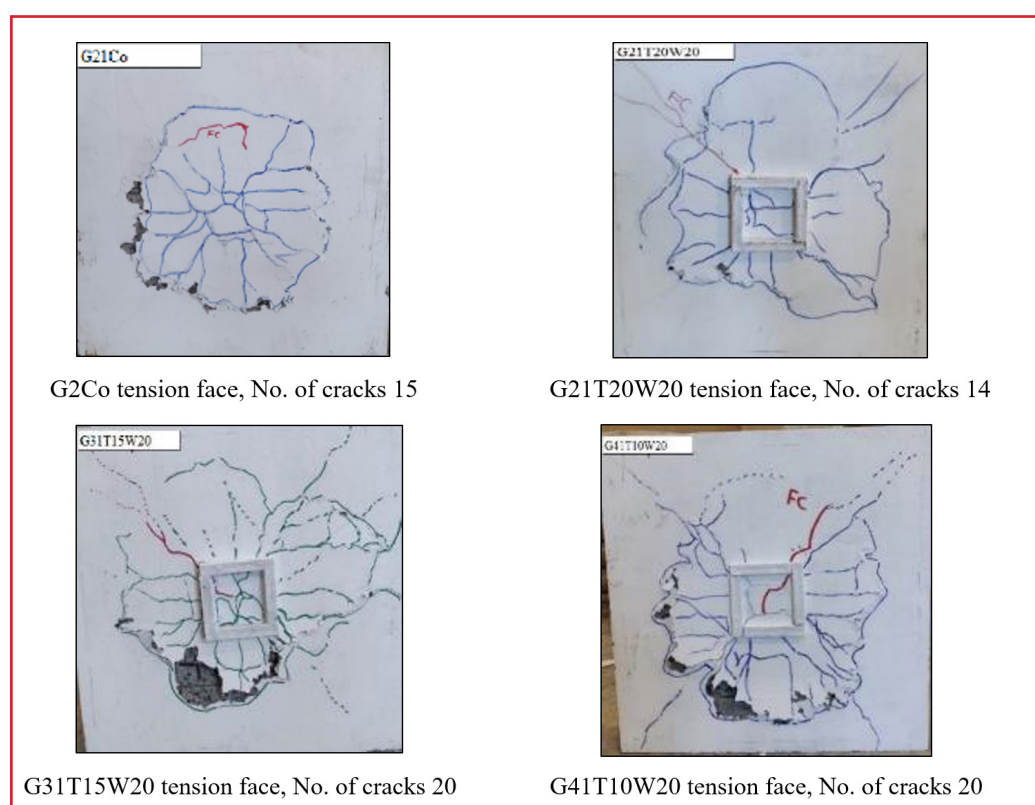
**Figure 4.** Load against mid-span deflection for G41C0 concrete slab specimen set

### **STRAIN IN THE STEEL REINFORCEMENT BARS**

Strain gauges were attached to the surface of the flexural reinforcement at three distinct distances from the face of the column, 0.5 d, 1 d, and 1.5 d, as indications for the magnitude of Strain in refinement at different positions in reinforced concrete slabs. Three representative cases for all sorts of concrete strengths (20.8 MPa, 32.6 MPa, and 43.3 MPa) were strengthened using varying thicknesses of UHPFRC strips. When the loading increases at the same pace as the Strain increases after the creation of the first crack. It is observed that when the compressive strength of the slab specimen rises, so does the Strain. The strain profile evolution of the slabs at various load levels demonstrates the benefits of using UHPFRC strips for strengthening over control slabs. In all circumstances, their role in transmitting the amount of Strain from the essential area for punching far away from the column is perceived in the strain relationships.

### ***THE PATTERN OF CRACKS AND MODES OF FAILURE***

Figure 5 shows the first crack formed around the perimeter of the column and extended in both directions towards the center of the column and radially towards the corner of the slab as the load increased. Various UHPFRC strip thicknesses significantly impacted the punching failure zone's expansion from the column's face to the exterior. In addition, increasing the number of fractures in the punching shear zone of the control specimen for slab specimens G21T20W20, G31T15W20, and G41T10W20 changes the failure mode from brittle to ductile.



**Figure 5.** Crack and failure pattern of reinforced slab specimens at tension face

### ***PREDICTION OF PUNCHING SHEAR RESISTANCE AT CRACK AND ULTIMATE LOADS USING DIMENSIONAL ANALYSIS***

Dimensional analysis is a tool that could be suitable to use for clarifying and representing the relationships between physical quantities. The fundamental relationships in dimensional analysis could always be represented as relationships between dimensionless groups [31]. Buckingham  $\Pi$ -theorem states that any expression which is a model for physical problem could be able to rearrange again and it could be simply by using a set of dimensionless variables. Consequently, the number of variables which were used to describe the physical problem might be reduced by the number of independent physical quantities which used in the model [32-34].

The following sections describe the conducting dimensional analysis with assistant of nonlinear multiple regression for predicting each of punching shear resistance of reinforced concrete flat slabs at crack, and ultimate loads.

**PREDICTION OF PUNCHING SHEAR RESISTANCE AT CRACK LOAD (Pcr)**

The expected variables that influence the punching shear resistance at crack load are compressive strength  $f'c$ , the effective depth of slab ( $d$ ), and critical perimeter ( $bo$ ) as in Equation 1. The set of variables, including the dependent variable, is ( $V$ ), and the total number of variables inside the set is ( $n$ ) and equal to 4. The primary dimensions are listed in Table 6.

$$\{Pcr\} = \{f'c, d, bo\} \tag{1}$$

**Table 6.** Primary dimensions in MLT and FLT systems of variables in  $\{Pcr\}$  influence the ultimate punching shear load of NSC slabs with strengthening

Variable No.	Parameters	Primary dimensions in MLT system	Primary dimensions in the FLT system
1	Pcr	[M1L1T-2]	[F1 L0 T0]
2	$f'c$	[M1L-1T-2]	[F1 L-2 T0]
3	$d$	[M0L1T0]	[F0 L1 T0]
4	$bo$	[M0L1T0]	[F0 L1 T0]
n=4		m=3	m=2

The number of primary dimensions is equal to 2 based on the FLT system, and the number of  $\pi$ -dimensionless group is equal to  $k=n-m=4-2=2$ . Consequently, the number of repeating variables is equal to two, and the variables selected include all possible primary dimensions [M], [L], and [T].

Therefore,  $f'c$  and  $d$  were selected as repeating variables. The  $\pi$ -dimensionless groups are as in Equation 2 and 3.

$$\pi_1 = (Pcr)(f'c)^a(d)^b \tag{2}$$

$$\pi_2 = (bo)(f'c)^a(d)^b \tag{3}$$

The dimensional form of Equation 2 can be stated as in Equation 4.

$$[M0L0T0] = [M1L1T-2] [M1L-1T-2]^a [M0L1T0]^b \tag{4}$$

Then, equating the powers for primary dimensions is carried out as follows:

Equating exponents of mass M:  $0 = (1). 1 + (1). a + (0). b \implies a = -1$

Equating exponents of length L:  $0 = (1). 1 + (-1). a + (1). b \implies b = -2$

Equating exponents of time T:  $0 = (-2). 1 + (-2). -1 + (0). -2 = 0$  satisfy

Thus, the first  $\pi$ -dimensionless group is as Equation 5.

$$\pi_1 = \frac{Pcr}{f'c*d^2} \tag{5}$$

The dimensional form of Equation 3 can be stated as in Equation 6.

$$[M^0L^0T^0] = [M^0L^1T^0] [M^1L^{-1}T^{-2}]^a [M^0L^1T^0]^b \quad (6)$$

Then, equating the powers for primary dimensions is carried out as follows:

Equating exponents of mass M:  $0 = (0). 1 + (1). a + (0). b \implies a = 0$

Equating exponents of length L:  $0 = (1). 1 + (-1). a + (1). b \implies b = -1$

Equating exponents of time T:  $0 = (0). 1 + (-2). 0 + (0). -1 = 0$  satisfy

Thus, the second  $\pi$ -dimensionless group is as Equation 7.

$$\pi_2 = \frac{b_o}{d} \quad (7)$$

The final form of  $\pi$ -dimensionless groups as in Equation 8.

$$\begin{aligned} \pi_1 &= \beta_1 \times \pi_2^{\beta_2} \times \pi_3^{\beta_3} \\ \frac{P_{cr}}{f'_c \times d^2} &= \beta_1 \times \left(\frac{b_o}{d}\right)^{\beta_2} \\ P_{cr} &= \beta_1 \times f'_c \times d^2 \times \left(\frac{b_o}{d}\right)^{\beta_2} \end{aligned} \quad (8)$$

Based on 27 tested strengthened slab data from this research, including data measured from NSC slab tests and the strips strengthening parameter, multiple nonlinear regression was used to predict the value of  $\beta_1$  and  $\beta_2$ . The proposed Equation 8 is for predicting punching shear crack load in NSC slabs, becomes in the form of Equation 9, with the coefficient of determination ( $R^2$ ) equal to 0.96 and root mean square error (RMSE) equal to 0.26 kN, as shown in Figure 6, and the value of  $\beta$  coefficient estimated from the IBM, SPSS software platform program that offers advanced statistical analysis as  $\beta_1 = 2.222$  and  $\beta_2 = -1.1$ .

$$P_{cr} = 2.222 \times f'_c \times d^2 \times \left(\frac{b_o}{d}\right)^{-1.1} \quad (9)$$

Where  $P_{cr}$  is Predicted ultimate punching shear load, kN,  $f'_c$  is Compressive concrete strength, kN,  $d$  is Effective depth of the slab, mm, and  $b_o$  is perimeter of critical section located at distance  $d/2$  from the face of column for the flat slab, mm.

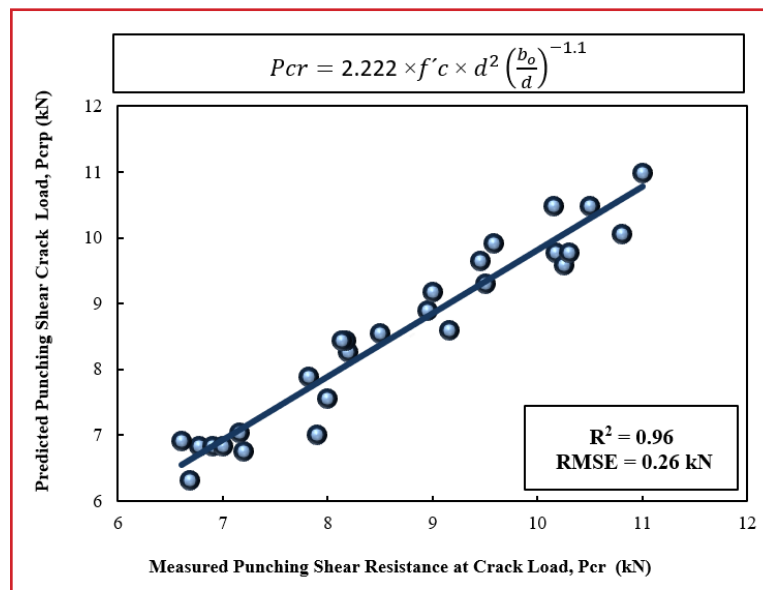
### **PREDICTION OF PUNCHING SHEAR RESISTANCE AT ULTIMATE LOAD ( $P_u$ )**

Based on both models for prediction punching shear resistance at crack load and punching shear after cracking, the punching shear resistance at ultimate load prediction could be produced as Equation 10. Then, after the summation of both models, the prediction model of punching shear resistance ultimate load

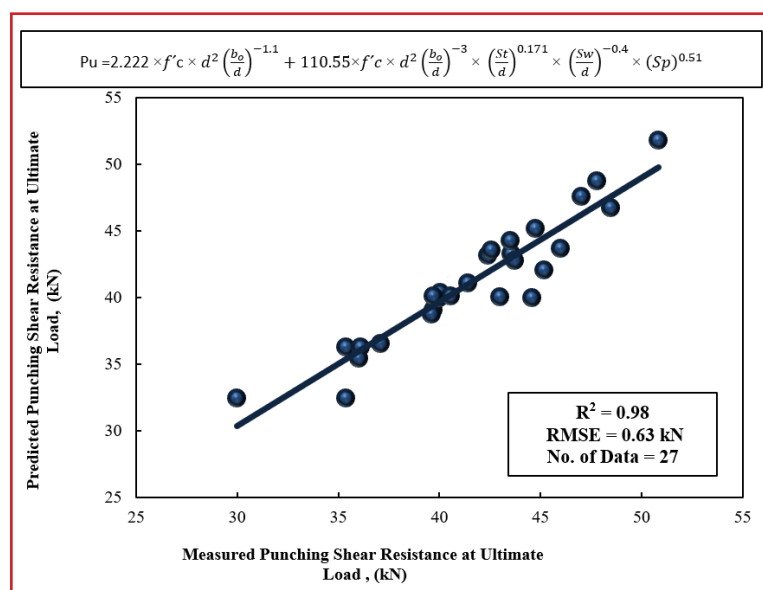
(Pu) is expressed as Equation 11. The prediction result is obtained from this model in Figure 7. The coefficient of determination ( $R^2$ ) equals 0.98, and RMSE equals 0.63 kN. As an output result from IBM, the SPSS software platform offers advanced static analysis.

$$P_u = P_{cr} + (P_u - P_{cr}) \tag{10}$$

$$P_u = 2.22 \times f'c \times d^2 \times (b_o/d)^{-1.1} + 110.55 \times f'c \times d^2 \times (b_o/d)^{-3} \times (St/d)^{0.171} \times (Sw/d)^{-0.4} \times (Sp)^{0.51} \tag{11}$$



**Figure 6.** Relation between experimental and predicted punching shear resistance at the crack load of tested slab specimens



**Figure 7.** Relation between experimental and predicted ultimate punching shear load (Pu) of tested slab specimens.

## DISCUSSION

### MECHANICAL PROPERTIES OF CONCRETE AND UHPFRC STRIPS

The mechanical parameters of the concrete utilized in this work are essential for understanding UHPFRC strip reinforcement. The three concrete grades 21, 31, and 41 MPa—met predicted compressive, tensile, and flexural strengths [30]. UHPFRC strips had higher mechanical qualities across all parameters, suggesting they might improve slab performance. The compressive strength of UHPFRC strips is 173.24 MPa, which is far higher than the highest grade of concrete utilized in the study (43.3 MPa). The experimental results confirm that UHPFRC strips might provide considerable reinforcement due to their high compressive strength, as shown in Table 4.

### EFFECTIVENESS OF UHPFRC STRIPS ON PUNCHING RESISTANCE

The study found that UHPFRC strips significantly improved punching resistance. In particular, 20 mm thick strips increased fracture stress by 105% in slabs with 20.8 MPa concrete, as Equation 12.

$$\text{Percentage Increase} = \left( \frac{\text{Crack Load with UHPFRC} - \text{Crack Load without UHPFRC}}{\text{Crack Load without UHPFRC}} \right) \times 100 \quad (12)$$

Substituting the given values:

$$\text{Percentage Increase} = \left( \frac{6.90 - 3.36}{3.36} \right) \times 100$$

$$\text{Percentage Increase} = \left( \frac{3.54}{3.36} \right) \times 100$$

$$\text{Percentage Increase} = 1.054 \times 100 \approx 105.4\%$$

Previous research has shown that UHPFRC strips increase concrete slab punching shear capability [35-36]. Upper concrete grades had 48.1%, 7.4%, and 7.2% improvements in ultimate shear capacity for grades 20.8, 32.6, and 43.3 MPa (for 20mm), respectively, as in Equation 13.

$$\text{Improvement, \%} = \left( \frac{\text{Ultimate Load (Strengthened Specimen)} - \text{Ultimate Load (Control Specimen)}}{\text{Ultimate Load (Control Specimen)}} \right) \times 100 \quad (13)$$

$$\text{Percentage Improvement} = \left( \frac{42.00 - 28.35}{28.35} \right) \times 100 \approx 48.1\%$$

$$\text{Percentage Improvement} = \left( \frac{42.37 - 39.44}{39.44} \right) \times 100 \approx 7.4\%$$

$$\text{Percentage Improvement} = \left( \frac{44.62 - 41.62}{41.62} \right) \times 100 \approx 7.2\%$$

These values show that UHPFRC strips benefit all grades, although their influence decreases with concrete strength. Santos et al. [37] found that external reinforcing methods benefit lower-strength concrete substrates more.

### ***LOAD-DEFLECTION BEHAVIOR OF CONCRETE SLABS***

The study's load-deflection behaviour supports UHPFRC strips' efficacy. The 20.8 MPa concrete grade increased ultimate load deflection, especially for specimens reinforced with 20 mm thick strips (Figure 2). This increased ductility means the slab can absorb and disperse loads better, lowering the risk of rapid, brittle fracture. The load-deflection relationship improved less for 32.6 MPa and 43.3 MPa grades, although the strips still had an influence (Figures 3 and 4). Increased compressive strength and strip thickness reduce deflection, demonstrating the synergistic link between concrete strength and reinforcing, as supported by [38].

### ***STRAIN DISTRIBUTION AND LOAD TRANSFER WITH UHPFRC STRIPS***

Strain measurements at different distances from the column face reveal UHPFRC strip load distribution and efficacy. Data shows that the strips diffuse Strain from the column face, decreasing localized stress concentrations that cause punching shear failures. Visintin et al. [39] found comparable strain redistribution effects using high-performance fiber-reinforced concrete coverings. UHPFRC strips improve slab structural integrity by distributing Strain according to strain profile progression. This behaviour reduces the danger of progressive deterioration and failure in slabs subjected to intense cyclic loads.

### ***FRACTURE PATTERNS AND FAILURE MECHANISMS***

The fracture patterns and failure mechanisms (Figure 5) corroborate UHPFRC strips' advantages. With UHPFRC strips, brittle failure modes change to ductile failure modes, which are better for structural components since they warn before collapse. This transition supports Said et al. [40], who found that fiber-reinforced materials improve concrete ductility with increasing strip thickness, cracks and their propagation decrease, proving that UHPFRC strips reduce crack development and damage. This study suggests that UHPFRC strips may improve the durability of reinforced concrete slabs, especially under extreme stress.

### ***CONCLUSION***

The results obtained from the investigation on enhancing the structural integrity of flat slabs using different thicknesses of UHPFRC strips have yielded some significant conclusions. The experimental findings indicate that augmenting the thickness of the UHPFRC strips significantly improves the punching shear resistance of the flat slab specimens. More precisely, slabs including 10mm, 15mm, and 20mm strips exhibited corresponding improvements in punching shear resistance of approximately 24.8%, 40.0%, and 48.1% when using concrete grade 20.8 MPa. The concrete grades of 32.6 MPa and 43.3 MPa had increases of about 4.97%, 0.41%, 7.4%, 14.8%, 13.0%, and 7.2%, respectively. Significantly, a strip thickness of 20mm has shown superior effectiveness in enhancing the stiffness of concrete slabs and their resistance to punching shear. This was evident by the expansion of the punching area and an enhanced ability to withstand deformation before failure. Furthermore, the load-deflection and

support rotation data demonstrated a significant enhancement in the ability of the slabs to bend without breaking compared to the control slabs. This suggests a transition from a fragile to a more flexible failure mechanism. UHPFRC strips increase the mechanical properties, resistance to punching shear, and overall performance of concrete slabs. This offers essential information for engineers and designers who want to enhance the safety and longevity of concrete buildings using modern composite materials.

Results from this study suggest that ultra-high-performance fiber-reinforced concrete (UHPFRC) strips are a viable option for reinforcing flat concrete slabs, provided that their intended use is altered. These strips enhance punching shear resistance, ductility, and crack propagation.

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### **CONFLICTS OF INTEREST**

The author has no conflicts of interest to declare.

### **AUTHOR CONTRIBUTIONS**

**Ashti Sediq Ali:** formal analysis, investigation, methodology, software, writing-original draft preparation. **Ferhad Rahim Karim:** conceptualization, supervision, validation, writing-review & editing. **Serwan Khurshid Rafiq:** supervision.

### **DATA AVAILABILITY STATEMENT**

All the data is available in this article.

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