Tikrit Journal of Engineering Sciences (2024); 31(3): 105-116
DOI: http://doi.org/10.25130/tjes.31.3.10

IRAQI Academic Scientific Journals

ISSN: 1813-162X (Print); 2312-7589 (Online)
Tikrit Journal of Engineering Sciences
available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

# Experimental Study of Punching Shear on Reinforced Concrete Waffle Slabs Strengthened by CFRP Sheets

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**Keywords:**
*Waffle slab; CFRP Sheets; Reinforced concrete; Punching shear; Retrofitting.*

**Highlights:**

- *Experimental verification of ultimate strength and failure mode of waffle flat slabs.*
- *Behavior of punching shear in waffle slabs strengthened by CFRP sheets.*
- *Create a practical methodology for enhancing the shearing capacity of waffle slabs.*

ARTICLE INFO
**Article history:**

| | | |
|---|---|---|
| Received | 17 July | 2023 |
| Received in revised form | 23 Oct. | 2023 |
| Accepted | 20 Nov. | 2023 |
| Final Proofreading | 01 Feb. | 2024 |
| Available online | 25 Sep. | 2024 |



**Citation:** Khamees RS, Ali MSA. **Experimental Study of Punching Shear on Reinforced Concrete Waffle Slabs Strengthened by CFRP Sheets**. *Tikrit Journal of Engineering Sciences* 2024; **31**(3): 105-116.
http://doi.org/10.25130/tjes.31.3.10

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**Abstract**: For the last five decades, researchers have been studying the punching shear of two-way reinforced slabs at column supports in structural testing laboratories. Limited tests are available on retrofitted waffle slab punching behavior. These are necessary since they establish a baseline against which punching shear design provisions can be created, calibrated, and evaluated. This work presents an experimental approach to investigate the punching shear of reinforced concrete waffle slabs strengthened with carbon fiber reinforced polymers (CFRP) sheets. Retrofitted waffle slabs were tested under concentric monotonic loading. A series of tests on construction materials were also conducted. The testing program was divided into two categories (IWS1 and IWS2), with a total of ten specimens: solid sections (275 × 275) and (515 × 515) mm, respectively. The IWS1 category consisted of eight slabs; one slab was without strengthening as a reference slab, and the remaining slabs were strengthened. While IWS2 consisted of only two slabs. However, the waffle slabs' observed punching failure mechanism was like flat slabs. All waffle slabs were punctured in a sudden position. Research showed that the CFRP retrofitting process enhanced the ultimate punching shear performance by 47.1% and the initial cracking load by 67.02%, respectively. When the solid size regions were increased, the ultimate punching load increased by 41.5 %, and the initial cracking load increased by 40.8%, respectively. Significant enhancements were documented in the proposed retrofitting mechanism.

# دراسة تجريبية للقص الثاقب للبلاطات الوافل الخرسانية المقواة بألياف الكربون البولمرية

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**الخلاصة**
على مدى العقود الخمسة الماضية، كان الباحثون يدرسون قص التثقيب للسقوف المقواة ثنائية الاتجاه في دعامات الأعمدة في المختبرات الإنشائية. تتوفر اختبارات محدودة على سلوك تثقيب لوح الوافل االمقواة. هذه ضرورية لأنها تنشئ خطًا أساسيًا يمكن من خلاله إنشاء أحكام تصميم القص ومعايرتها وتقييمها. يقدم هذا العمل طريقة تجريبية لفحص القص الثاقب لسقوف الوافل الخرسانية المسلحة المقواة بأشرطة ألياف الكربون البوليمرية (CFRP). تم اختبار ألواح الوافل المقواة تحت حمل أحادي المركز. كما تم إجراء سلسلة من الاختبارات على المواد المستعملة مختبرياً. تم تقسيم برنامج الاختبار إلى فئتين بإجمالي عشر عينات. هاتان الفئتان (IWS1 وIWS2) ذات أبعاد الراس الصلب (٢٧٥ ملم × ٢٧٥ ملم) و (٥١٥ ملم × ٥١٥ ملم) على التوالي. تتكون فئة IWS1 من ثماني بلاطات، وكان بلاطة واحد بدون تقوية كبلاطة مرجعية، وتم تقوية العينات المتبقية. بينما يتكون IWS2 من لوحين فقط. على الرغم من أن آلية فشل التثقيب الملحوظة لبلاطات الوافل كانت مشابهة لتلك الموجودة في الألواح المسطحة، فقد تم ثقب جميع بلاطات الوافل في وضع مفاجئ. أظهرت نتائج البحث أن عملية التعديل التحديثي للبلاستيك المقوى بألياف الكربون عززت أداء قص التثقيب النهائي (Ultimate Loads) بنسبة ٤٧,١٪ وزيادة حمل التكسير الأول ( First Cracking Loads) بنسبة ٦٧,٠٢٪ على التوالي. عند زيادة المساحة الصلبة، زاد حمل التثقيب النهائي بنسبة ٤١,٥٪، وهو ما يمثل زيادة في حمل التكسير الأولي بنسبة ٤٠,٨٪ على التوالي. تم توثيق تعزيز قوي من آلية التعديل التحديثي المقترحة.

**الكلمات الدالة:** بلاطة الوافل، ألياف الكربون البولمرية، الخرسانة المسلحة، القص الثاقب، التعديل التحديثي.

## 1.INTRODUCTION

The waffle slab system is becoming more popular because of its economic advantages [1-3]. It comprises a grid of ribs evenly spaced, spread in orthogonal directions, and covered with a thin slab, as shown in Fig. 1. Consequently, columns are then installed at various locations to support the whole slab, transferring load from the slab to the columns through introducing solid sections. Punching shear is a kind of brittle failure that occurs in slabs supported directly on the column when the flexural strength of the slab is greater than its shear strength. This failure may eventually cause the structure to collapse [1, 4]. However, the waffle flat slab's strength is directly attached to the solid head's size around a column. Small areas for the solid head can promote figuration of the punching shear cone behind the solid region and induce shearing of ribs. Experimental studies, such as Al-Bayati et al. [1, 5], Silva et al. [6], and Arunkumar et al. [7], showed that the solid head's reduction in waffle flat slabs could reduce their ultimate strength, leading to the punching shear cone extending beyond the solid area. A rule of thumb among designers is to use the solid head's length to be at least 15% of the clear span between columns. However, Al-Bayati found that the solid head should extend for a distance of at least 2.5 times the slab's effective depth from each column face. Also, building codes are silent on the solid head's dimensions around the column. The waffle slabs with shear reinforcement in the ribs were in significant. The slabs with punching reinforcement showed resistance, around 26%, confirming the inclined stirrups' efficiency as punching reinforcement. It was observed that the code Brazilian NBR 6118 did not provide satisfactory estimates for the strength of the ribs, with and without shear reinforcement [8]. However, excessive loading, corrosive assault, seismic activity, fire, and frost and thaw damage can damage or fail the reinforced concrete (RC) slabs, or unintentional errors can occur during the design or execution phases. Therefore, the RC slabs must be reinforced, upgraded, or refurbished for use in these environments. To strengthen a concrete slab, joining steel plates was the most widely used method before the 1980s. However, since the early 1990s, civil engineers have been using fiber-reinforced polymers (FRPs) instead of steel plates for reinforcement due to their lightweight, high strength, and corrosion resistance [9 - 11]. However, the literature review showed that studies on reinforcing reinforced concrete slabs with FRPs have been most quantitative, with no explanation of a failure mechanism. Particularly in the case of punching strengthening, the process by which FRP strengthens RC slabs has not been given much thought. Furthermore, studies on reinforcing reinforced concrete slabs of two-way slabs are very few compared to strengthening other reinforced concrete structures [10]. Therefore, there is a lack of information and limited recommendations in the relevant design standards for reinforced concrete slab reinforcement in two directions compared to other reinforced concrete structures [12]. Experimental research exploring the various rehabilitation impact techniques on the strengthening behavior of bidirectional waffle slabs is presented in this section. Failure behavior of the FRP sheet-enhanced RC two-way slabs under full composite action can be divided into three types [13 - 15]: Pure flexural failure, expected to be the failure mode that occurs in slabs with a low tensile reinforcement ratio, inclusive of FRP reinforcement; flexural punching failure, i.e., the most common failure mode that occurs in slabs with a mild tensile reinforcement ratio, including FRP reinforcement; and punching shear failure, a customary failure mode that occurs in slabs with a high FRP and steel reinforcement ratio. It is the most brittle of the other two failures [12], as shown in Fig. 2.

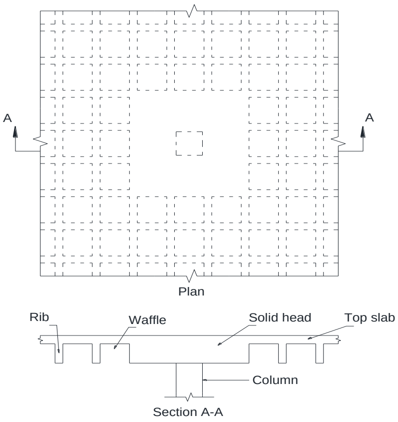



**Fig. 1** Waffle Slab.

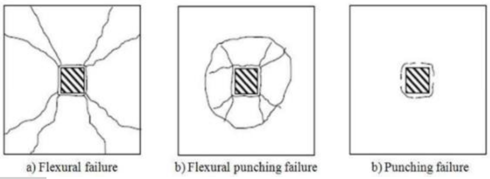



**Fig. 2** Failure Modes of FRP Reinforced Slabs.

## 2.EXPERIMENTAL PROGRAM

### *2.1.Details of Specimens*

Tests were conducted on 10 waffle slab samples (scale 1/5) to simulate the conditions in the connections of waffle slabs of internal columns, where bending moment transfer was small enough to be neglected. Tested slabs are classified into two categories: The variables considered are the solid section's size, different CFRP configurations, and the CFRP strips' number and area. There was an unstrengthened control sample for each category. The remaining specimens were strengthened with CFRP sheets. The variables considered were the CFRP's sheets area and form, as shown in Table 1. All models had a total depth of 100 mm, a rib width of 35 mm, and 35 mm in top slab thickness, as shown in Fig. 3. The waffle slabs' geometric properties were chosen according to the ACI code 318-19 [16]. All samples were cast upright to simulate casting positioning for a prototype; however, when tested inversely, with the top waffle slabs facing down, four steel rollers were fixed on a top frame at the four edges to support specimens. The samples were loaded centrally. The central specimens' deflections were measured with a digital gauge under the slab at the center.

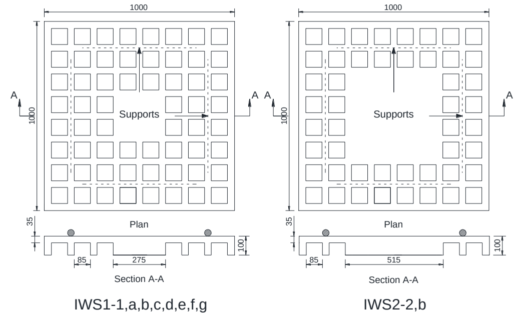



**Fig. 3** Waffle Slab Specimens (mm).

### *2.2.Strengthened Sample Layouts*

The CFRP sheets were glued to the specimens' tension surfaces, as shown in Figs. 4 and 5, showing the CFRP sheets' positions for IWS1 and IWS2 category waffle slabs. The length of CFRP sheets required was estimated to transfer stresses sufficiently based on the suggestion of Teng and Chen [17] for the effective length of FRP, as shown in Eq. 1. The critical punching area was assumed to be twice the effective depth (2d) from the face of a column according to Eurocode 2 [18] and the length of the column, as shown in Fig. 5.

$$\textbf{Le (Effective length)} = \sqrt{\frac{Eftf}{\sqrt{f'c}}} \qquad \textbf{(1)}$$

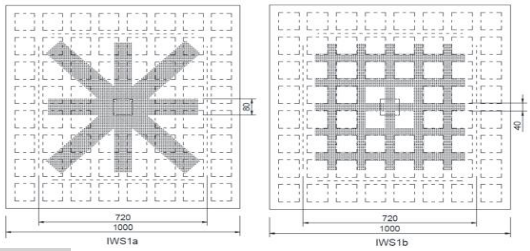



**Fig. 4** CFRP Sheets on the Tension Surface of Specimens.

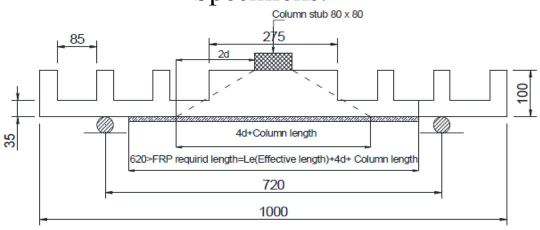



**Fig. 5** Required and Actual Lengths of CFRP.

**Table 1** Classification of Waffle Slab Specimens.

| Waffle Slab Category | Size of Solid Panel (mm) | Slab No. | ρ (Solid Section) (%) | No. of CFRP Strips | Area of CFRP (m²) | Form of CFRP Strips |
|---|---|---|---|---|---|---|
| IWS1 | 275 x 275 | IWS1 | 0.96 | 0.0 | 0.0 | / |
| | | IWS1a | | 4 | 0.25 | Plus & cross |
| | | IWS1b | | 10 | 0.25 | grid |
| | | IWS1c | | 4 | 0.25 | orthogonal |
| | | IWS1d | | 4 | 0.25 | skewed |
| | | IWS1e | | 2 | 0.25 | cross |
| | | IWS1f | | 2 | 0.25 | plus |
| | | IWS1g | | 6 | 0.15 | grid |
| IWS2 | 515 x 515 | IWS2 | | 0.0 | 0.0 | / |
| | | IWS2b | | 10 | 0.25 | grid |

Table 2 shows the estimated required CFRP sheets length for the two categories. The final CFRP length was 620 mm for all CFRP-reinforced samples.

### *2.3.Materials*

Waffle slabs consisted of materials such as carbon fiber-reinforced plastic sheets (CFRP sheets), steel bars, and concrete. It is essential to understand the mechanical properties of these components. The concrete mix was designed to achieve a compressive strength of 30.5 MPa at 28 days. Use a plasticizer of 1% by weight of cement to facilitate concreting the narrow ribs, a water/cement ratio of 0.48, and a cement content of 438 kg/m$^3$. The largest aggregate size allowed was 10 mm. Before a concrete component is mixed, the material must be checked physically and chemically. The materials' inspection included testing of cement according to the Iraqi standards [19], while other testing, such as sieve analysis for sand and gravel, was according to Iraqi specification No. 45/1984 [20] and ASTM C33-18 [21]. The additives met the requirements for a superplasticizer according to ASTM C494M-17 [22]. The mixture's details are shown in Table 3. Three 150 mm$^3$ concrete cubes were tested for strength at 28 days. Control cubes were tested per BS 1881-P 116 [21] to assess the compressive strength of concrete. Reverse osmosis (R.O.) water was used for concrete mixing and curing. Sika ViscoCrete - 5930, used in this work, is a third-generation superplasticizer for the concrete and the mortar. It met the superplasticizers requirement according to ASTM-C- 494 Types G and F [22]. Flexural reinforcement consisted of (5.5mm) diameter steel bars with a 488.25 MPa average yield strength, as shown in Fig. 6, and was used in this investigation. To prevent early bond failure, all slab samples used in the present study were strengthened with adequate bent steel rods at the ends [23]. At a spacing of approximately 28 mm, tensile reinforcements were positioned on the slab's upper portions. While all the ribs were double-reinforced. According to Eurocode 2 [18], a 10 mm cover for reinforcements was generally kept on all specimens. The FRP sheets for waffle slab reinforcement were unidirectional CFRP sheets of type (SikaWrap- 300C), as shown in Fig. 7. CFRP fibers showed no plastic conduct (yielding) before rupturing when tension force was applied. The stress-strain relationship in the tensile conductivity of CFRP fibers was described as linearly elastic up to failure. The CFRP's characteristics were adopted per the manufacturer's specifications (Technical Data Sheet of Sika 2017), [24] as shown in Table 4. Sikadur-330 type impregnating resin was used to bind the CFRP sheets to the concrete slab surface, consisting of two components (resin part A and hardener part B), as shown in Fig. 8. The bonding epoxy's characteristics were conducted according to the manufacturer's recommendations (Technical Data Sheet of Sika 2020) [25], as shown in Table 5. According to the Concrete Society Technical Report No. 55 [26], a CFRP composite was created by an adhesive substance, and the CFRP sheets were combined.

**Table 2** Estimation of Required FRP Lengths Based on the Proposal of Tang and Chen [17].

| Category | Column Length (mm) | Effective Slab Depth (d) (mm) | Effective Length (Le) (mm) | Required FRP Length (mm) |
|---|---|---|---|---|
| IWS1&IWS2 | 80 | 84 | 82 | 500 |

**Table 3** Concrete Mix Detail.

| Cement (kg) | Water (Liter) | Coarse Aggregate (kg) | Fine Aggregate (kg) | Superplasticizer (Liter) |
|---|---|---|---|---|
| 438 | 210 | 990 | 660 | 4.5 |

**Table 4** CFRP Composite Properties [24].

| Fiber Orientation Deg | Weight (g/m$^2$) | Thickness (mm) | Tensile Strength (MPa) | Tensile E-modulus (MPa) | Elongation (%) |
|---|---|---|---|---|---|
| 0$^o$ | 300 | 0.167 | 4000 | 220000 | 1.7 |

(a) Compression Reinforcement (b) Tension Steel Reinforcement

**Fig. 6** Steel Reinforcement.

**Fig. 7** CFRP Sheets.


**Fig. 8** Two Components of Epoxy Resin.

**Table 5** Properties of Epoxy Resin [25].

| Appearance | Mixing Ratio | Open Time (min) | Tensile Strength (MPa) | Tensile E-Modulus (MPa) |
|---|---|---|---|---|
| Part A: white<br>Part B: gray | A: B<br>4: 1 | 30(at +35°C) | 30 | 4500 |

### *2.4.Experimental Preparation*

Steel profiles were used to make the supporting frame. Specimens were supported on the four-edged roller for realistic support during testing, as shown in Fig. 9. Ten waffle slab specimens were cast and cured in the lab. Three 150 $mm^3$ standard cubes were cast from the concrete of each of the five waffle slab specimens. Due to the difficulties in obtaining small molds, polystyrene was used. The specimen molds were treated with oil before pouring the concrete. The ribs were first cast, then the solid section. The top of the concrete was leveled with a hand trowel to have a smooth surface. After 24 hours, the waffle slab specimens and corresponding cube samples were removed, de-molded, and placed in water. The burlap sacks were placed over the waffle slabs and wetted down. The burlap sacks were monitored and kept wet for seven successive days, as shown in Fig. 10. It is crucial to properly prepare the concrete surface before applying the CFRP to create a strong bond between CFRP sheets and concrete. The bond ensured that the force applied to the structure's member was efficiently transferred to CFRP [27]. For two days at laboratory temperature, the model suggested for reinforcement with CFRP sheets was dried after being cured. For a suitable flat concrete surface for a good CFRP-Concrete bond, the CFRP sheets' marked areas were milled to remove layers of substrate or mortar defects, as shown in Fig. 11. Cleaning the waffle slab samples and removing the grinding dust and adhesion-impairing deposits of dirt when attaching the CFRP sheets. The specimens' apparent concrete surfaces were painted to detect crack propagation easily. All waffle slab specimens were tested using a steel frame with a hydraulic jack maximum capacity of 600 kN. Under a compressive load applied to the steel column stub of the column region, i.e., in the middle of the slab, as shown in Fig. 12, loaded in successive increments until failure. The deviations and cracks were gradually marked.

## 3.RESULTS AND DISCUSSION

### *3.1.Failure Modes*

In general, all of the specimens were punctured in sudden failure mode, which is remarkably similar to the failure modes seen in the strengthened solid flat slabs [12], waffle slabs [8], and hollow slabs [28]. For the unstrengthened waffle slabs, the cracking pattern in sample IWS1 showed a different behavior from sample IWS2; for sample IWS1, whose length of the solid section (solid head) less than 15% of the clear span between columns, losses on the punching failure surface, as it extended into the waffle portion, were observed to cause an incomplete revolution. Also, it was noted that the failure surface propagated from a column face to the support, as shown in Fig. 13, observed this crack configuration of the waffle slab (the compression side), with fine cracks observed on the solid region (solid head), spread to the outside toward the edges. Unlike the pattern of waffle slab IWS2, a localized (very limited) cracking pattern occurred at the perimeter of the column loading area. For the strengthened waffle slabs, the cracking pattern showed almost similar behavior to that without CFRP strengthening (IWS1). In all waffle slabs, flexural cracks on the tensile face began near the center (semi-random phenomena) and radiated toward the edges near the supports. It intersected approximately with shear cracks at a distance of (2.5-2.9) times the waffle slab's overall depth from the column faces. It was observed that the failure surface extended from the column faces to the supports. No cracks were observed in the compression face of any waffle slab except IWS1b. Fine cracks were observed in the solid area, as shown in Fig. 16. This cracking configuration in the top surface of the waffle slab (the compression side) was also observed when subjected to column-concentrated loading. Unlike the pattern of reference waffle slab IWS1, a localized (very limited) cracking pattern occurred at the perimeter of the column loading area. Figs. 14 and 15 show the waffle slab failure surface, and

Fig. 16 shows the crack patterns of the waffle slab at the end of the tests.

**Fig. 9** Support Frame.

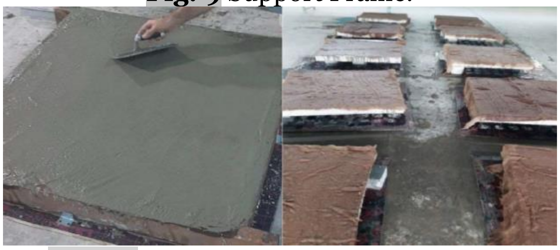
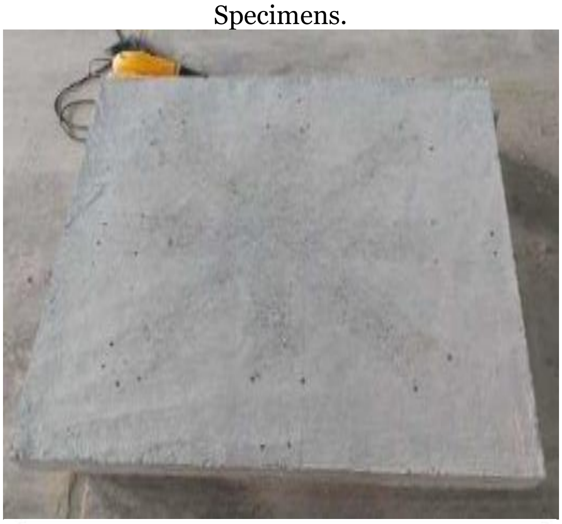


**Fig. 10** Casting Concrete and Curing of Specimens.



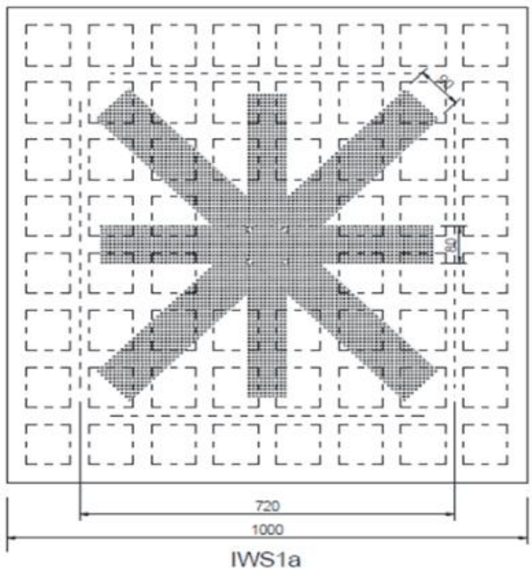
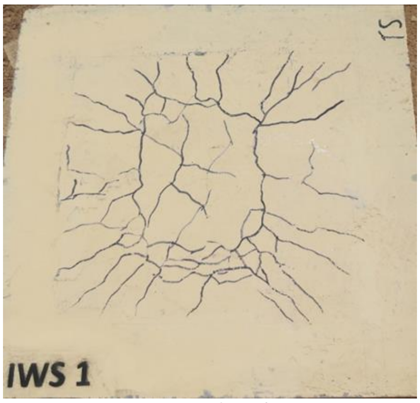


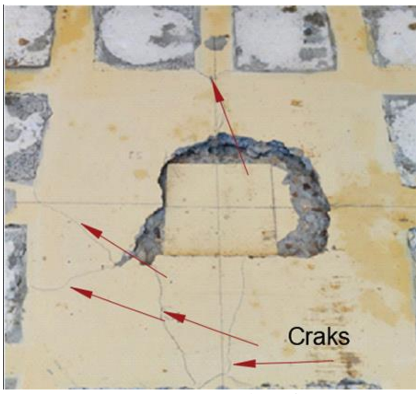

**Fig. 11** Practical Steps to Grinded Surface Samples.

**Fig. 12** Testing Procedure.




Tension Side of IWS1


Tension Side of IWS2




Compression Side of IWS1


Compression Side of IWS2

**Fig .13** Punching Failure Mechanism of Waffle Slab Specimens.

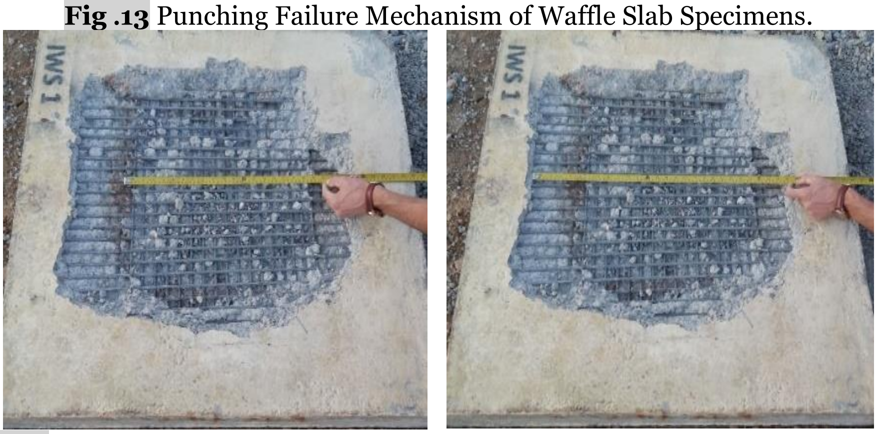



**Fig.14** Punching Shear Failure Angle Measurements of Control Specimen IWS1.

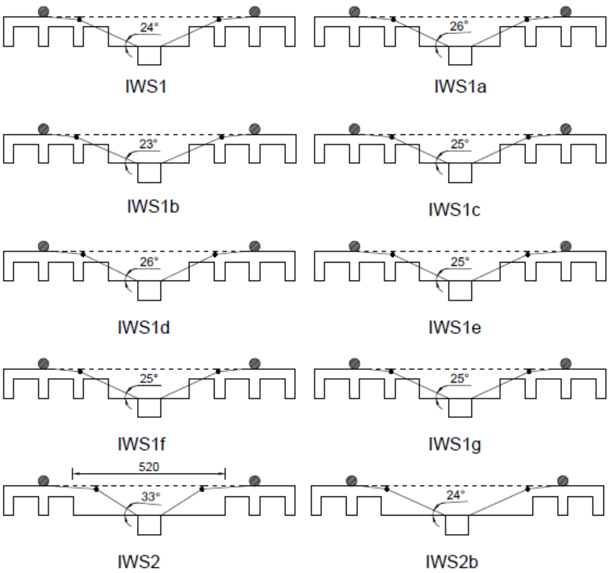



**Fig. 15** Waffle Slabs Failure Surface.

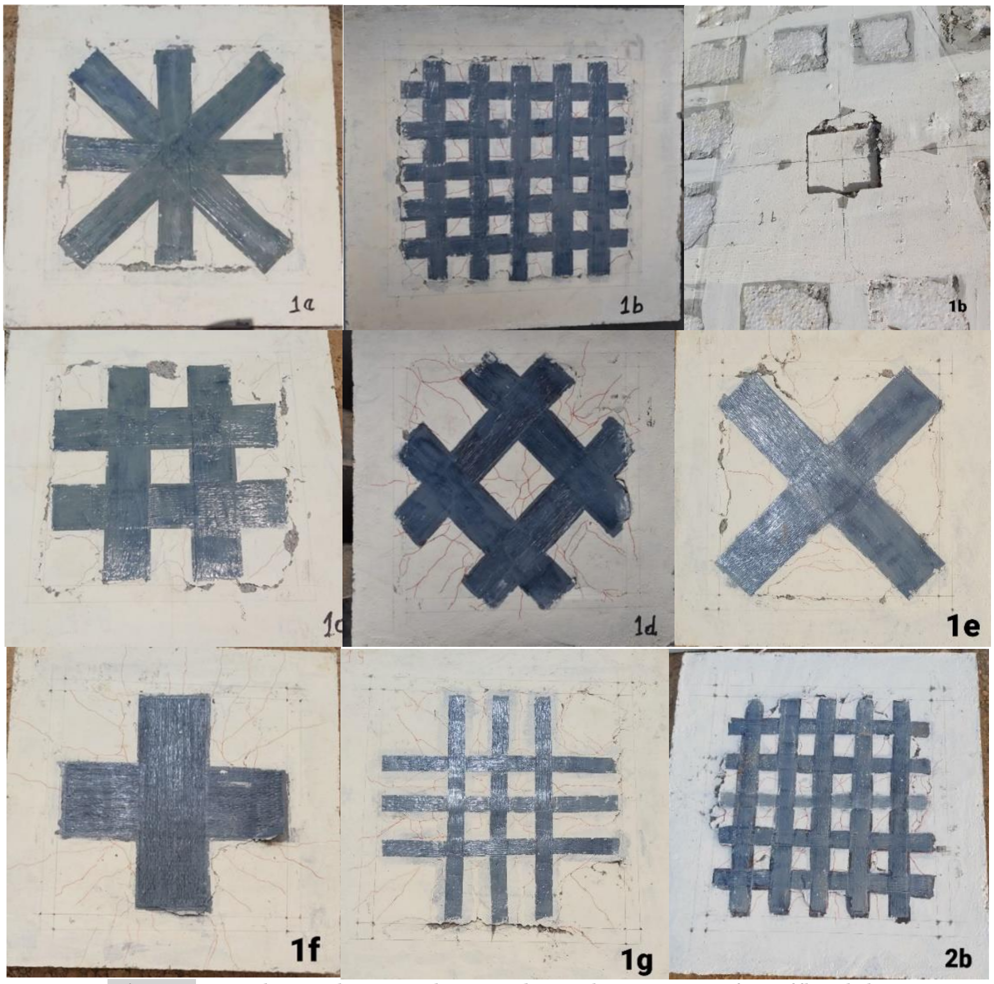



**Fig. 16** Punching Shear Failure and Crack Patterns of Waffle Slab.

### *3.2.Failure Loads*

The ultimate load from the tests is shown in Table 6. It is important to remember that the dead weights of the scaled waffle slab samples were not included. The results of the unstrengthened waffle slabs indicated that the overall punching shear strength decreased with reducing the solid head's size when the solid region was small at the column's periphery. The compression strut of the ribs outside the rigid region may reach its ultimate capacity first. This situation resulted in punching failure being initiated outside the solid area for specimen IWS1 and, consequently, a reduction in the energy dissipation and the ultimate punching capacity of the waffle slab. However, the failure surface was observed to propagate from the column faces to the supports. Reducing the punching capacity depends on the loss of the shear area, which depends on the solid section's size. It was observed that the solid head's size significantly impacted the punching strength. Compared with specimen IWS2, with a 515 mm solid head, Specimen IWS1 decreased ultimate punching load by 29.36% with a solid section to 275 mm. Due to losses on a failure surface, as it extended into the waffle portion, as shown in Fig. 17. There was an incomplete revolution and, consequently, a reduction in the ultimate punching capacity of the waffle slab. However, for the strengthened waffle slabs, it is noticed that the ultimate load increased by (16.6-47.1) % compared to the ultimate load in reference waffle slabs (IWS1). However, it was noted that the IWS1b specimen of the waffle slab was stronger than IWS1a, IWS1c, IWS1d, IWS1e, and IWS1f. The increase in shear strength is attributed to the uniform distribution of CFRP sheets in specimen IWS1b. However, comparing the samples IWS1g and IWS1b, it was observed that reducing the CFRP sheets' area by 40% in IWS1g resulted in a 24.5% resistance reduction. It was observed that the ribs' reinforcement by the CFRP sheets significantly impacted the ultimate load compared to specimens IWS2, IWS1, and IWS1b. However, the ribs' strengthening by CFRP sheets in the IWS2b sample resulted in a small increase in strength by 2%, which was expected due to the large size of the solid panel compared to the specimen IWS1. In the implicit sense, the waffle slab IWS2b with a larger solid area behaved as a flat slab, which leads to an unsatisfactory result in terms of ribs' strengthening by CFRP sheets, i.e., the configuration of CFRP for IWS1b.

**Table 6** Experimental Model Results.

| Specimen Category or Group | Specimen | Angle of Failure Surface (Degrees) | Pcr (kN) | $P_{ACI}$ (kN) | Pu (kN) | Ultimate Deflection (mm) | $Pu_{con}$ /Pu | Failure Mode |
|---|---|---|---|---|---|---|---|---|
| | IWS1 (Con) | 24 | 47 | | 88.3 | 5.73 | 1 | Flexural punching |
| | IWS1a | 26 | 54 | | 110.3 | 5.96 | 0.80 | Flexural punching |
| | IWS1b | 23 | 68.6 | | 129.9 | 6.07 | 0.68 | Flexural Punching |
| IWS1 | IWS1c | 25 | 63.7 | | 109.8 | 5.05 | 0.80 | Flexural Punching |
| | IWS1d | 26 | 51.48 | 99.6 | 105.4 | 5.3 | 0.84 | Flexural Punching |
| | IWS1e | 25 | 49 | | 103 | 5.55 | 0.85 | Flexural Punching |
| | IWS1f | 25 | 78.5 | | 107.9 | 4.75 | 0.82 | Flexural Punching |
| | IWS1g | 25 | 76 | | 98.1 | 4.5 | 0.90 | Flexural Punching |
| IWS2 | IWS2 (Con) | 33 | 66.2 | | 125 | 6.71 | 1 | Flexural Punching |
| | IWS2b | 24 | 76 | | 127.5 | 4.91 | 0.98 | Flexural punching |

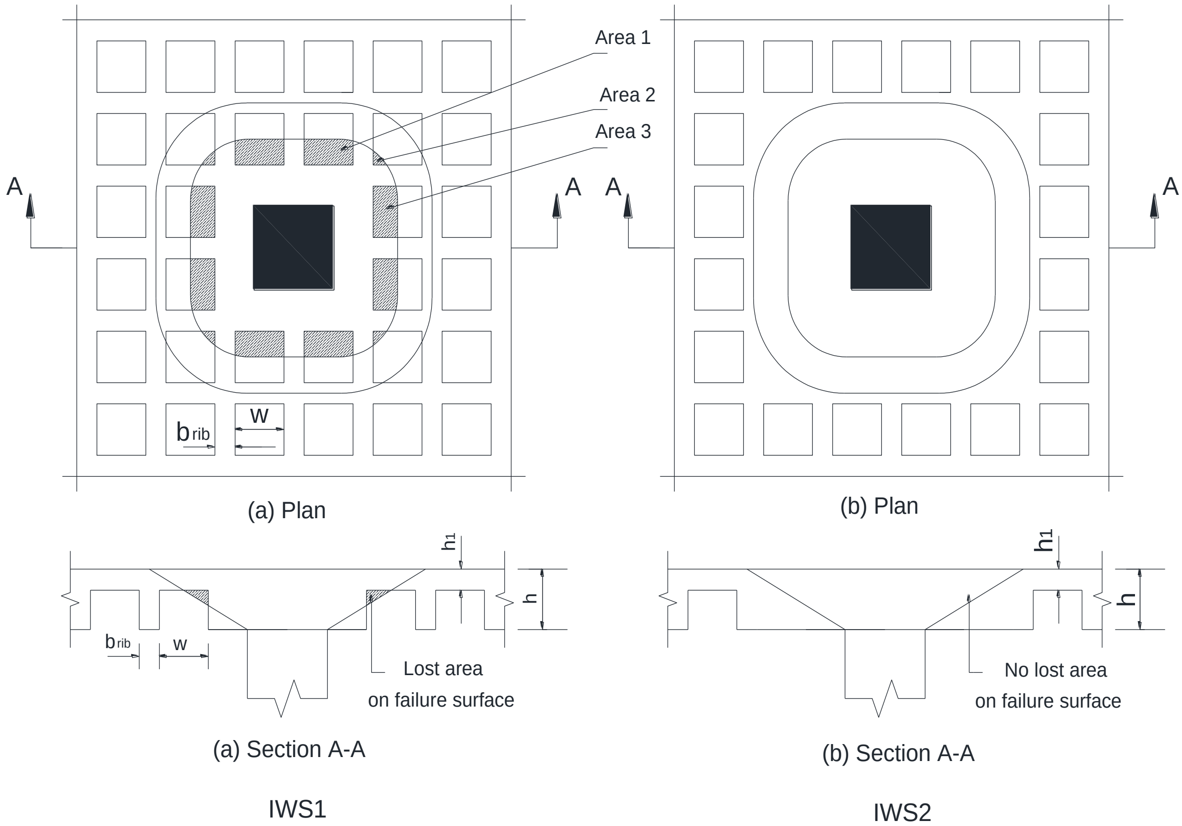


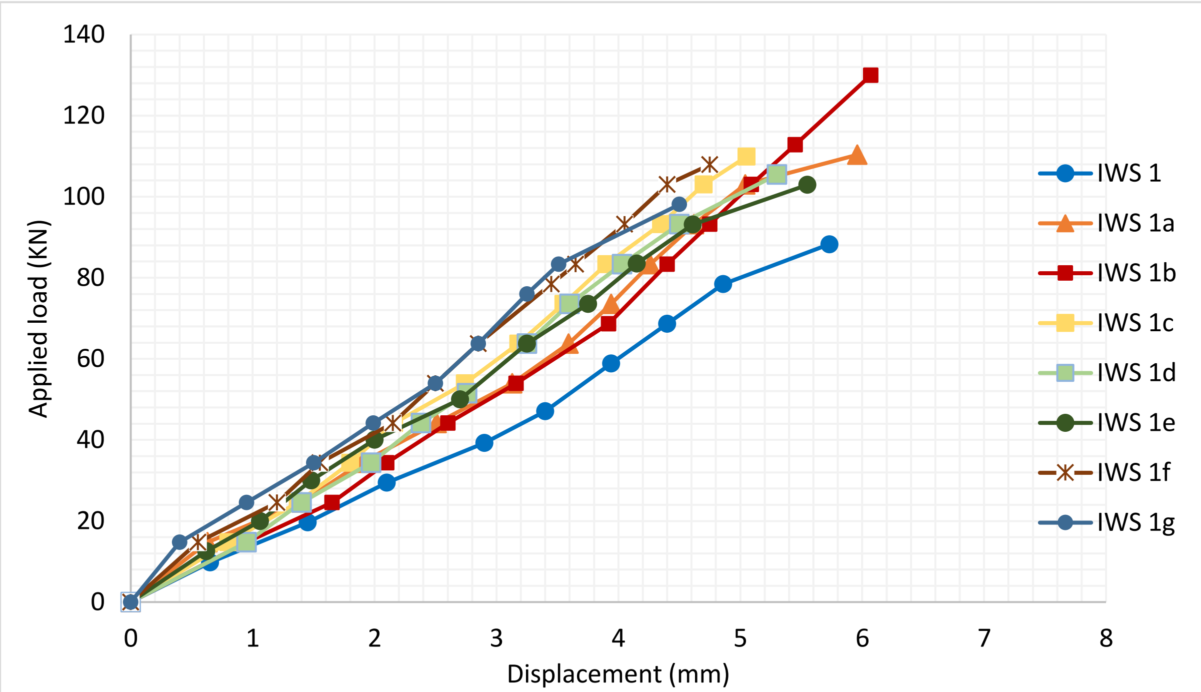

**Fig. 17** Proposed Punching Failure Surface with Losses.

### *3.3.Deflection*

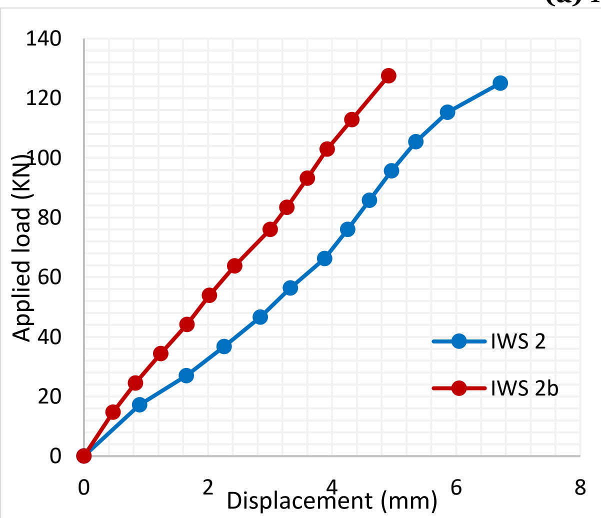
Figure 18 shows a typical load-deflection curve taken during these tests for the IWS1 and IWS2 categories. The deflection was measured in the slabs' center, as shown in Fig. 19. In general, the failure of concentric perforation in flat slabs with high reinforcement ratios corresponded to the load-deflection curve of waffle slabs [29, 2]. Visualizing the load-deflection curve as two straight lines inclined at two different angles is possible. The stiffness of an uncracked portion is represented by the first slope, and the stiffness of a cracked section is represented by the second slope. These curves indicate that the tested reinforced waffle slabs had a higher limit and slope for the first crack load. Models IWS1f, IWS1g, and IWS2b had the highest values among categories IWS1 and IWS2, as shown in Fig. 18 (a), (b). The highest ultimate resistance models were not there, meaning that the CFRP sheets layout for the IWS1f, IWS1g, and IWS2b models was better at reducing cracks and improving the elastic behavior of the waffle slab. However, Model IWS2 had the highest value compared to IWS1, as shown in Fig. 18 (c), meaning that the increase in the IWS2 solid panel size was better at reducing cracks and improving the elastic behavior of the waffle slab. In summary, to evaluate the strengthening's efficiency, the failure mode and load at failure of the concrete waffle slabs were utilized to measure effectiveness. The test results indicated that for waffle slabs with a solid panel size of 275 mm strengthened with CFRP sheets the ultimate load increased by 47.9% higher than the ultimate load of non-strengthened waffle slabs. Besides, for waffle slabs with a solid panel size of 515 mm strengthened with CFRP sheets, the ultimate load increased by 2% higher than the punching strength of non-strengthened waffle slabs. Besides, when the solid panel's size increased, the ultimate load increased by 41.5%, as shown in Fig. 18 (c).

### *3.4.Waffle Slab Punching Shear Strength (Strengthened Types)*

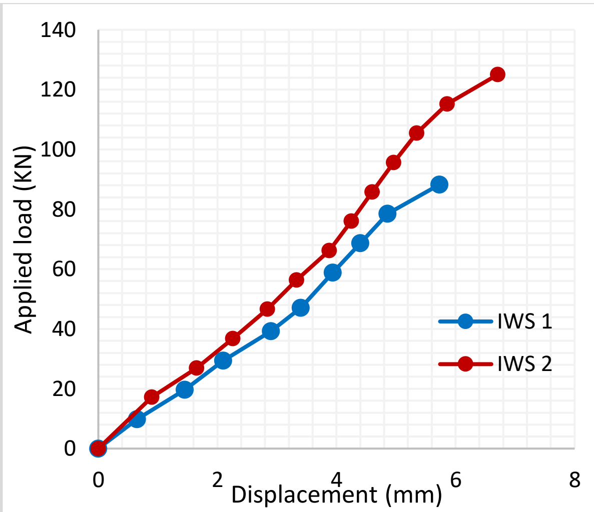
Table 2 presents a clear picture of CFRP strengthening efficiency. The relationship between the ultimate load of strengthened waffle slabs and the unstrengthened waffle slabs was demonstrated. The CFRP strengthening layout (configuration or arrangement) is key in enhancing the ultimate load capacity of concrete Waffle slabs when the length of the solid area (solid head) is less than 15% of the clear span between columns. The success rate for samples (IWS1a) to (IWS1f) varied as follows (24.92%, 47.11%, 24.35%, 18.91%, 16.65%, and 22.2%). It was concluded that the best arrangement of CFRP sheet strips depends on two major factors: distributed area and orientation. The results indicated that the most effective strengthening configuration was observed in the sample (IWS1b) when strengthening the ribs, attributed to the extension of the failure surface beyond the solid area (solid head) and the occurrence of shear in the ribs. On the other hand, sample (IWS1e) was the least preferred due to their limited strengthening area and orientation (45 with steel reinforcement orientation). Also, the same CFRP configuration used in (IWS1b) is applied to concrete waffle slabs. When the solid area's (solid head) length was greater than 15% of the clear span between columns or if the solid section extends for a distance of at least 2.5 times the effective depth of the slab from each column face, as in the sample (IWS2b), it reduced the ratio by (45.11%) because the failure surface did not extend outside the solid area, i.e., the shear did not occur at the ribs, meaning that the solid area's dimensions have a clear effect on the strengthening configurations or arrangement.




**(a)** IWS1.




**(b)** IWS2.




**(c)** IWS1 and IWS2.

**Fig. 18** Comparison of Load - Central Deflection Curves.

**Fig. 19** Dial Gauge Deflection.

## 4.CONCLUSIONS

- It was found that the tested waffle slabs did not meet the design codes in terms of the control perimeter when the solid area's (solid head) length was less than 15% of the clear distance between the columns. The ultimate failure loads for specimen IWS1 were less than the punching shear strength estimated by the code ACI-318M.
- For the unstrengthened waffle slabs, it was concluded that strength was gained when the solid head's length was greater than 15% of the clear span between columns or the solid section extended for a distance of at least 2.5 times the slab's effective depth from each column face and behaved like solid flat slabs.
- Externally strengthened waffle slabs (slabs whose length of the solid head is less than 15% of the clear span between columns) with CFRP sheets showed a considerable increase in the waffle slabs' ultimate loads. This increase was approximately (11.09-47.1) % compared to non-strengthened waffle slabs (control).
- From the overall study, it is evident that the reinforcement of ribs with CFRP sheets for waffle slabs with small solid areas showed a noticeable increase in the ultimate load capacity.
- Waffle slab serviceability was greatly enhanced by adding CFRP strengthening layouts, as can be seen from the deflection reductions (14.89%, 45.96%, 35.53%, 9.53%, 4.26%, 67.02%, and 61.70%), respectively. The specimens with concentrated CFRP strips showed better initial performance (first crack loading) with an enhanced ratio of (67.02%).
- However, the best configuration that increased the ultimate load of 47.1% for the samples cannot be applied when the solid head extends at least 2.5 times the slab effective depth from each column face because it gave an almost unnoticeable increase.
- Waffle slabs with a strengthening (Plus and cross) configuration have a more ductile punching failure mode owing to the development of wide tensile cracks on the strengthening waffle slab compared to the reference waffle slab.

## ACKNOWLEDGEMENTS

The authors are sincerely grateful for the support provided by the Civil Engineering Department, College of Engineering, Misan University, towards this research. This article is one of the requirements of the Master of Structural Engineering of Postgraduate student for the first author as stated at the Misan University order numbered (H S/ A/1280 dated 9/11/2020), and the enrollment order from the College of Engineering numbered (S A 333) dated on 15/11/2020.

## NOMENCLATURE

| | |
|---|---|
| $b_{rib}$ | Ribs Width, mm |
| $h1$ | Thickness of the Topping Slab, mm |
| $h$ | Total Depth of Slab, mm |
| $P_{ACI}$ | Predicted Failure Load by ACI, KN |
| $Pu$ | Ultimate Load, KN |
| $Pcr$ | First Crack Load, KN |
| $Pu_{con}$ | Ultimate Load of the Control Specimen, KN |
| $Le$ | Length of FRP, mm |
| ***Greek Symbols*** | |
| $\rho$ | Average Flexural Reinforcement of Solid Section |
| $Ef$ | Elastic Modulus of FRP, MPa |
| $tf$ | Thickness of FRP, mm |
| $f'c$ | Compressive Strength of the Concrete Cylinder, MPa |

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