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EXPERIMENTAL STUDY OF PUNCHING SHEAR ON REINFORCED CONCRETE WAFFLE SLABS STRENGTHENED BY CFRP SHEETS

By

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بِسْـــمِ اللَّهِ الرَّحْمَٰنِ الرَّحِيـمِ

﴿ يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنكم والَّذِينَ أُوتُوا العِلْمَ دَرَجاتٍ واللَّهُ بِما تَعْمَلُونَ خَبِيرٌ﴾

سورة المجادلة آية 11

صَدَق اللَّهِ الْعَظِيْم

DEDICATION

I dedicate this work to the spirit of My late friend Yahya Kamel Nehme, I ask God to dwell in paradise.

To all those who supported and helped me, made the difficult easy, present my effort to them with all of my respect and appreciation.

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In the Name of Allah.

All my thanks for Allah who led me during my way to complete this work.

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Special thanks go to my father and my mother for her great efforts. Also, thanks go to my brothers, my friends and all the staffs of the Laboratory Concrete of the Technical Institute of Amara their technical support throughout the experimental program.

SUPERVISOR CERTIFICATION

I certify that the preparation of this thesis entitled "**Experimental Study of Punching Shear on Reinforced Concrete Waffle Slabs Strengthened by CFRP Sheets**" was presented by "**Ridha Sabry Khamees**", and prepared under my supervision at The University of Misan, Department of Civil Engineering, College of Engineering, as a partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering (Structural Engineering).

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In view of the available recommendations, I forward this thesis for discussion by the examining committee.

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EXAMINING COMMITTTEE'S REPORT

We certify that we have read this thesis entitled "**Experimental Study of Punching Shear on Reinforced Concrete Waffle Slabs Strengthened by CFRP Sheets**", and as an Examining committee, we examined the student (**Ridha Sabry Khamees**) in its content and in what is connected with it and that in our opinion it meets standard of a thesis for the degree of Master of Science in Civil Engineering (structures).

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ABSTRACT

The current study presented an experimental investigation to evaluate the punching shear behavior of concrete waffle slabs strengthened with Carbon Fiber Reinforced Polymer (CFRP) strips externally bonded. The primary goal of this study is to create a practical methodology for enhancing the shearing capacity of reinforced concrete waffle slabs without significantly altering the waffle slab's internal structure. This study chose to analyze the strengthening performance of waffle slabs using only two categories of waffle slabs first category that have a solid head of (275x275mm) and second category (515x515mm), respectively. The first category consists of eight slabs, one slab was without strengthening as a reference slab, and the remaining slabs were strengthened. While second category consists of two slabs only. Structural tests were carried out on ten scaled waffle slab specimens, with span of length (1000x1000mm), slab depth (100mm), and slab voids cross-section (65x85mm) for all waffle slab specimens under concentric monotonic loading, to simulate the conditions at waffle slab supported on interior columns connections were bending moment transfer are small enough to be neglected. A series of tests on construction materials had also been conducted. Variables considered were; solid head without strengthening, solid head with strengthening, CFRP Configuration, and Area of CFRP sheets. The second category results showed that the unstrengthened waffle slab with the largest solid region experienced punching shear and behaved in a similar way as solid flat slabs, indicating compliance with the codes in relation to their punching shear strength provisions. The results show that a square solid area whose length is less than 15% of the span of column, the shear capacity is relatively reduced because some of the potential failure surface is lost when it extends into the waffle section. The first category Internal waffle slab with a solid area of (275x275) has been strengthened by CFRP strips and is compared to the reference slab unstrengthened. The results from the tests showed that waffle slabs with small solid areas can be strengthened with externally bonded CFRP sheets. Where the experimental results showed that the CFRP strengthening increased the ultimate punching load of the waffle flat slabs by (11.09- 47.11) %, also the first cracking load increased by (4.26-67.02) %. The strengthened slabs showed less deflection during loading by about (21.46) % compared to the unstrengthened reference waffle flat slab. Strengthening the waffle flat slabs with CFRP sheets enhanced its load capacity in both categories. However, applying the configuration of the grid, in the first category, significantly improved the waffle slab behavior. In contrast, the same configuration does not significantly affected on the behavior of the second category with a Strengthening percentage that is almost imperceptible. The results showed that applying CFRP strengthening on waffle slabs with a square solid area (solid head) whose length is less than 15% of the span, can increase the ultimate load capacity and enhance the stiffness of reinforced waffle slabs, thus reducing the deflection of waffle slabs. The most common failure mode for reinforced waffle slabs is brittle punching failure.

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LIST OF SYMBOLES

Symbol	Description	Unit
A	Assumed failure surface	mm^2
$b_w - b_{rib}$	Ribs width	mm
Ec	Modulus of elasticity of concrete	MPa
f_{cu}	Concrete cube compressive strength	MPa
$f'c$	Concrete cylinder compressive strength	MPa
h	Total depth of slab	mm
hf - h_1	Thickness of the topping slab	mm
h_b - h	Ribs height	mm
P_{ACI}	Predicted failure load by ACI	kN
P_{EC2}	Predicted failure load by EC2	kN
P_{BS}	Predicted failure load by BS8110	kN
P_{CAN}	Predicted failure load by CAN	kN
P_u	Ultimate load	kN
P_y	Yield load	kN
P_{cr}	First crack load	kN
P_{test}	Test failure load	kN
P_{exp}	shear strength ultimate	kN
s - w	Spacing between the faces of the ribs	mm
W/C	Water to cement ratio	%
ρ	Average flexural reinforcement of solid section	%
Δy	Yield displacement	mm
Δu	Ultimate displacement	mm

LIST OF ABBREVIATIONS

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
AFRP	Aramid Fiber Reinforced Polymer
BS	British Standard
CFRP	Carbon Fiber Reinforced Polymer
CAN-CSA	Canadian Standards Association Standard
EB	Externally bonded
EC	Euro Code
FRP	Fiber Reinforced Polymer
FEM	Finite Element Method
FRP_S	Fiber Reinforced Polymers
GFRP	Glass Fiber Reinforced Polymer
HSS	Hollow Steel Section
IWS	Internal Waffle Slabs
IS	India Standards
Le	Effective Length
LIP	Load Incremental Procedure
NBR	Norma Brasileira
NSC	Normal Strength Concrete
RC	Reinforced Concrete.
SCC	Self-Compacting Concrete
SSD	Saturated Surface Dry
UPS	Upward Punching Shear
U_2 or U_o	Failure Perimeter

CHAPTER ONE: INTRODUCTION

1.1 General

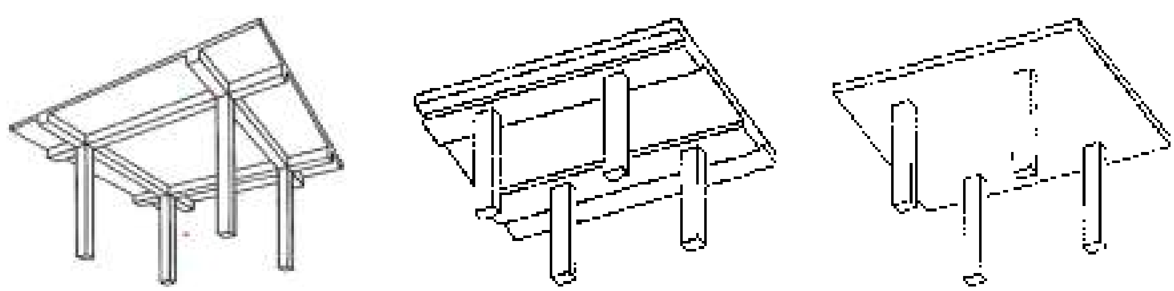
Reinforced concrete (RC) slabs are commonly employed in constructing roofs, floors, and bridge decks in long-span structures. Slabs can be classified as one-way or two-way slabs depending on dimensions and boundary conditions. Concrete slabs can be supported by concrete or steel beams, masonry or concrete walls, or columns[1,2,3]. Issues such as excessive loading or deterioration due to corrosion attack, seismic action, fire damage and freezing and thawing can lead to damage or failure of RC slabs. Therefore, RC slabs must be strengthened, retrofitted, or rehabilitated for applications in the environments. Before the 1980s, bonding steel plates were the most popular technique to strengthen a concrete slab. However, the lightweight, high strength, and corrosion-resistant nature of Fiber Reinforced Polymers (FRPs) has pushed civil engineers to substitute steel plates with FRP for strengthening since the early 1990s [4,5,6]

1.2 Types of Slabs

A slab is part of a reinforced concrete structure. In most cases, slabs are horizontal members but they can be used as vertical members, such as walls, to infill panels, side to drains and sewers appurtenances[7].

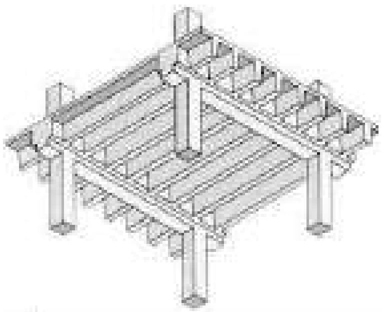
A reinforced concrete system frequently allows the designer to combine the architectural and structural functions. Concrete has the advantage that it is placed in a plastic condition and is given the desired shape and texture by means of the forms and the finishing techniques. This allows such elements as flat plates or other types of slabs to serve as load-bearing elements while providing the finished floor and ceiling surfaces, in addition to having the ability to resist gravity, wind, or seismic loads. Finally, the choice of size or shape is governed by the designer and not by the availability of standard manufactured members [8]. On the basis of reinforcement provided, beam support, and the ratio of the spans, slabs are generally classified into one-way slab and two-way slab. The former is supported on two sides and the ratio of long to short span is greater than two. However, the latter is supported on four sides and the ratio of long to short span is smaller than two. Varying conditions and stipulations ask for the selection of appropriate and cost-effective concrete slab, keeping in view, the type of building, architectural layout, aesthetic features, and the span length. Some of slab systems are classified into five general types shown in Figure (1-1)[9,10].

1. Solid slab with wide beam across longitudinal column lines.
2. Slabs, in which the slab is thickened along the column line.
3. Flat plates without any cross or edge beams.
4. Ribbed slab, interior beams distributed across short direction.
5. Waffle slab, two-way joist system.

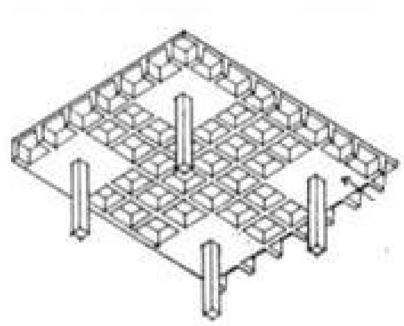


(1) classical slab with cross beams | (2) slab with wide beams | (3) Flat plate with cantilevered edges

Figure 1. 1 Slab and flooring system classification[9].



(4) ribbed slab



(5) waffle slab

Figure 1. 1 Countinue

1.2.1Waffle Slabs

Waffle Slabs can be defined as "A reinforced concrete slab consisting of a grid of ribs, distributed in orthogonal directions, regularly spaced, and topped by a thin slab as shown in Figure (1-2)[11].

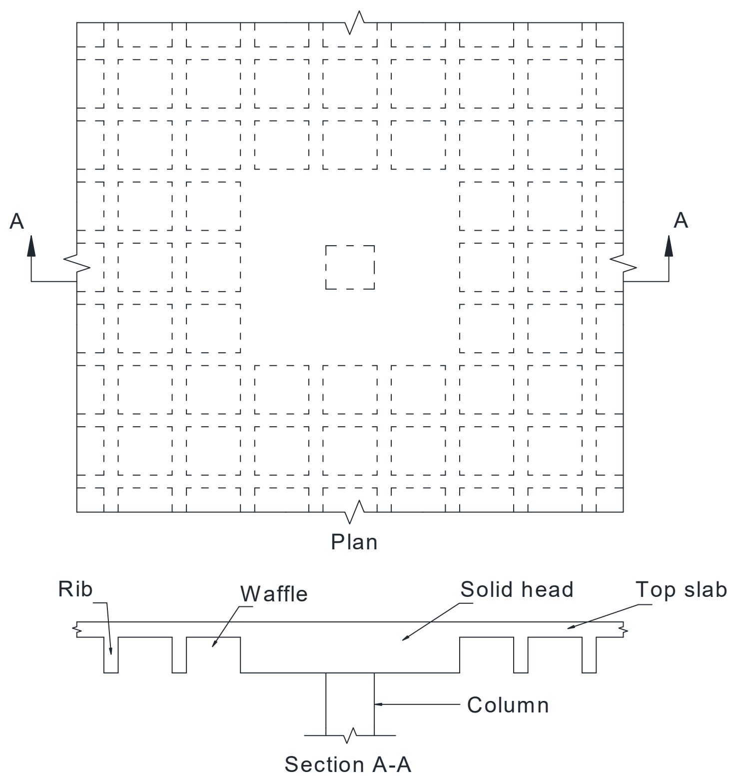
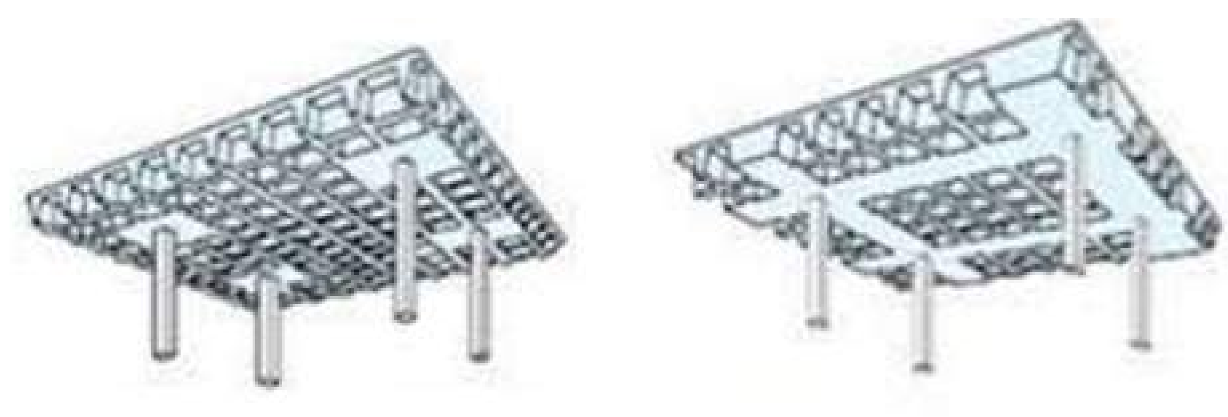


Figure 1. 2 Waffle slab.

Waffle slabs can be divided basically into two types, the flat slabs and two-way slabs, according to where recesses are omitted to provide larger solid areas. Figure (1- 3a) and Figure (1- 3b) show two possible arrangements. In the flat-slab type of configuration, solid areas, are provided near the column shown in Figure (1-4); this is comparable to a drop panel or column capital providing a path for shear transfer and the extra compression area in the highly stressed negative-moment regions surrounding the column. In the two-way-slab type of configuration, the recesses along the column lines have been omitted to form solid areas which are equivalent to beams since they are the areas of concentrated flexural stiffness, even though they do not extend below the lower surface of the slab. In practice, R.C waffle slabs are usually designed as one of the above two types or as a hybrid shown in Figure (1-5). In some flat-slab type of configuration, the local solid area around the column is provided by an extra column capital to enhance the shear resistance and to allow for load transfer from the slab to the columns [12].



(a) Waffle Slab with Solid Heads (flat waffle slab)

(b) Waffle Slab with Band Beams (Two-way waffle slab)

Figure 1. 3 Waffle Slab Types[13].

Figure 1. 4 Waffle Slab Structural Floor System.

Figure 1. 5 Hybrid configuration of waffle slab.

Reinforced concrete waffle slab construction has been used to improve the efficiency of concrete slab systems since 1950's. In conventional two-way flat slab constructions, the need of longer spans and/or the necessity for heavier loads demands increased slab thickness in order to limit deflections. As a solution to this, concrete below the neutral axis is eliminated, this allows an economic increase on the total thickness of the slab with the creation of voids in a rhythmic arrangement. Therefore, there occurs a reduction on the structure self-weight and a more efficient use of materials, steel and concrete. The resulting slab system is typically denoted as waffle slab construction. For long span structures like auditorium, car parking and meeting hall which are having spans up to 20 m, providing columns within short spans for the structure will not be appealing and it occupies more space. If flat slab construction is employed, the columns can be provided without soffit beams and at the corners of the floor system. Waffle and grid slabs are forms of flat slab construction and hence, the columns need not be provided and the entire floor is supported at the corner columns, shown in Figure (1-6). This reduces the space occupied by the columns and also reduces the concrete quantity incurred by columns. Providing waffle slabs give aesthetic appearance and provides easier provision for false roof ceiling [9,14,15].

Waffle slabs are now widely used in industrial and public buildings, multi-story car parks and highway bridges, Waffle slabs are becoming increasingly popular are now in Iraq see in Figure (1- 5) one of the buildings in Iraq located in Maysan City.

Figure 1. 6 A Waffle slab with dimensions 20 * 20 - a fire station at San Vicente city in Spain [16]

1.3 The Advantages of the waffle slab

- Load bearing capacity of waffle slab is higher than other types of the slab.
- Waffle slabs have good structural stability of deflection and vibration.
- Waffle slab can be used for larger span with less number of columns.
- Waffle slabs are lightweight as compared to other types of slabs because of the less dead load of the slab.
- Waffle Slabs are attractive and have good Aesthetical appearance when exposed.
- Using of this type of slab is overall affordable in large area construction.
- The services like lighting, electrical and air conditioning are easily provided in the waffle slab without any difficulty, waffle pods can be cut for services like pipes and plumbing, it's crucial to avoid compromising their structural integrity.

1.4 The disadvantages of a waffle slab

- The Formwork which is required for the construction of the waffle slab is very costly.
- The Construction of the waffle slab required skilled workmanship.
- Waffle slab Construction cannot suitable to bear high wind loads.
- The floor height in the waffle slab is high as compared to the conventional slab.
- The Maintenance of waffle slabs is expensive and difficult.

1.5 Code Recommendations

1.5.1 ACI 318

For waffle slabs, the American code recommends that the ribs should have a minimum width (b_w) of 100 mm, a maximum height (h_b) of 3.5 times the minimum width of the rib and a maximum spacing between the faces of the ribs (s) of 750 mm. The thickness of the topping slab (h_f) must be at least 37.5 mm and at most s/12 ratio Figure (1- 7) [17].

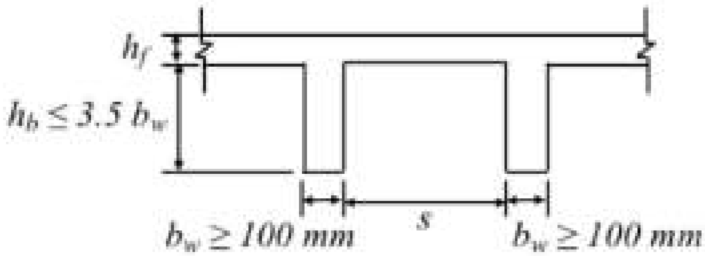


Figure 1. 7 Rib geometry to ACI 318.

1.5.2 Eurocode 2

For waffle slabs, the European code recommends that the topping slab and the ribs do not need to be analyzed separately when there is sufficient torsional stiffness between these two elements, and the waffle slab can be analyzed as solid slab. However, this condition is only acceptable if the spacing between the faces of the ribs (s) does not exceed 1500 mm, if the height of the rib (h) does not exceed 4 times its width (b_w) and if the height of the table (h_f) is at least the greater of these two factors: (s/10) or (50 mm) Figure (1- 8) [18].

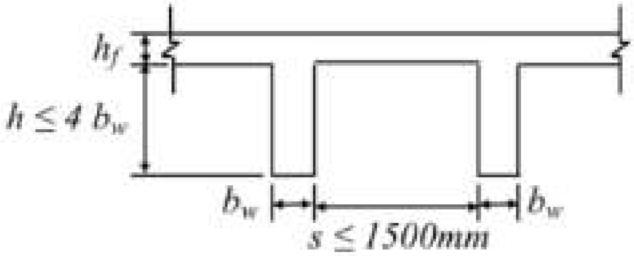


Figure 1. 8 Rib geometry to Eurocode 2.

1.5.3 Norma Brasileira (NBR) 6118

For waffle slabs, the Brazilian code recommends that the ribs should have a minimum width (bw) of 50 mm and if it has compression reinforcement, the minimum width (bw) should be 80 mm Figure (1-9). The topping slab thickness must be at least 50 mm when there is conduit wiring of ϕ10mm, or at least (40 mm + ϕ) when conduit wiring inside the slabs has a diameter greater than ϕ10mm, or at least (40 mm + 2ϕ) when there is a conduit crossover inside the slabs.

If the spacing between axes of the ribs is less than or equal to 650 mm, checking the topping slab as an independent slab and the shearing of the ribs are not needed. When the spacing between the axes of the ribs is between 650 mm and 1100 mm, the bending behavior of the topping slab must be checked and the ribs must be dimensioned as beams, with verification of the shear. However, when the spacing between the axes of the ribs is up to 900 mm and the average width of the ribs is greater than 120 mm, checking the topping slab is not needed. In case the spacing between the axes is greater than 1100 mm, the topping slab must be checked as a solid slab, supported on a beam grid, and must meet the minimum thickness limits [19].

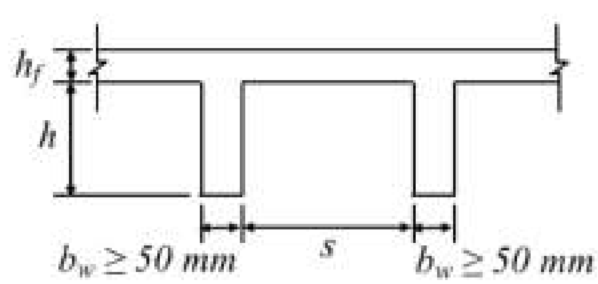


Figure 1. 9 Rib geometry to NBR 6118.

1.6 Strengthening of Concrete Structures

Buildings and structures are often used in different ways from how they were originally designed. Due to increasing service loads and/or degradation of existing concrete structures, the need for strengthening or retrofitting of aging infrastructure is increasing. Today, a significant portion of our infrastructure is currently either structurally or functionally deficient. Existing RC structures may need to be strengthened or retrofitted to overcome damages that occur due to actions such as earthquakes, corrosion attacks, fires, and so on. Moreover, the structure's ability to sustain the excessive design loading must be increased in some cases [4,5,6].

Beyond the costs of maintenance, the real consequences for our society are losses in production and overall economy due to functional deficient infrastructure. It is not always economically viable to replace an existing structure with a new one. The challenge is to develop robust and economical viable techniques for reparation and upgrade that can be used to prolong the life of our existing structures.

1.6.1 RC Buildings Repairing Techniques

It is not always economically viable to replace an existing structure with a new one. The challenge is to develop robust and economical viable techniques for reparation and upgrade that can be used to prolong the life of our existing structures. If the inspections reveal that the integrity of the structure do not fulfil the requirements the damage cause and type must be determined in order to take appropriate action of: Continue regular maintenance, issue some restriction in use, Repair, Upgrade and Demolish and rebuild [20].

1.6.2 Repair and Upgrading Methods

The repair and upgrading methods of concrete structures can be classified into:

- Repair and upgrading systems for protection of concrete and reinforcement.
- Structural repair or upgrading systems for existing concrete structures.

Systems for protection include methods like surface coating, filling of cracks to increase the physical resistance and protection of ingress of chemicals, moisture etc. Patch repair is by far the most common technique to structural repair damaged or deteriorated areas in concrete structures. patch repairs are also used to reinstate the spalled or delaminated areas of concrete. Increasing demands and changed use of infrastructure often lead to that the structural components of the infrastructure need to be upgraded. This often results in introducing external systems such as: Plate bonding of steel, FRP plates or sheets to the surface of the structure to be strengthened [21].

External strengthening of structural members has been practiced since the mid-sixties with steel plates bonded to the tension side of structures. The in-situ rehabilitation or upgrading of reinforced concrete members using bonded steel plates is an effective, convenient and economic method of improving structural performance. However, disadvantages inherent in the use of steel plates such as: handling of the heavy steel plates, corrosion of the interface adhesive steel, have stimulated research to find alternative strengthening systems. Steel plates were substituted by Carbon Fiber Reinforced Polymer (CFRP) plates, a lightweight, non-corrosive and no length limited material; this was first introduced in Switzerland in the early 1990s [5,22].

1.6.3 FRP in Repair and Strengthening of Concrete Construction

Clearly, the first step in characterizing the behavior of FRP strengthened RC structures is to characterize FRP. FRPs are composed of fibers and resins in the form of a resin matrix reinforced with fibers, thus making a composite material. The fibers in the matrix improve its mechanical characteristics such as strength. The resin transfers the external loads to the fibers and protects them from possible external damage [23].

Different possibilities of strengthening concrete structures are shown in Figure (1- 10) [5,23]. FRP strengthening is suitable for concrete beams, walls, slabs and columns.

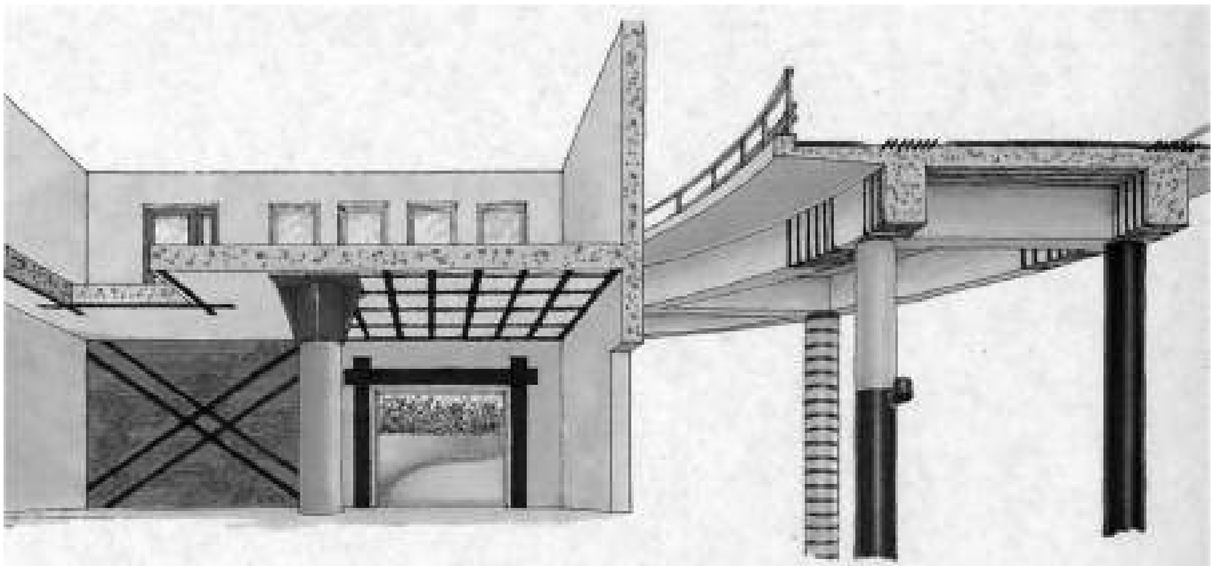


Figure 1. 10 Examples of FRP strengthening of concrete structures [24].

Fibers are classified into different groups such as **carbon fibers, glass fibers, and aramid fibers**. Accordingly, the FRPs are divided into three main groups: carbon fiber reinforced polymers (CFRP), glass fiber reinforced polymer (GFRP) and aramid fiber reinforced polymers (AFRP)[25]. The strength of an FRP composite is related to the direction of the fibers. FRP laminates, which have fibers in different directions, can provide the required strength in different directions. A plain woven FRP (bidirectional FRP) has the same mechanical characteristics in two perpendicular directions of the FRP plane. Figure (1-11) shows schematically a unidirectional FRP and a woven FRP [26].

Despite the variation in fiber materials, all FRPs exhibit similar stress-strain behavior and retain their elasticity up to their fracture point. In addition, FRPs are less ductile than steel; this may decrease the ductility of the whole FRP strengthened structure. Figure (1- 12) shows a comparison between CFRP, GFRP, and steel in terms of their stress–strain behavior [27].

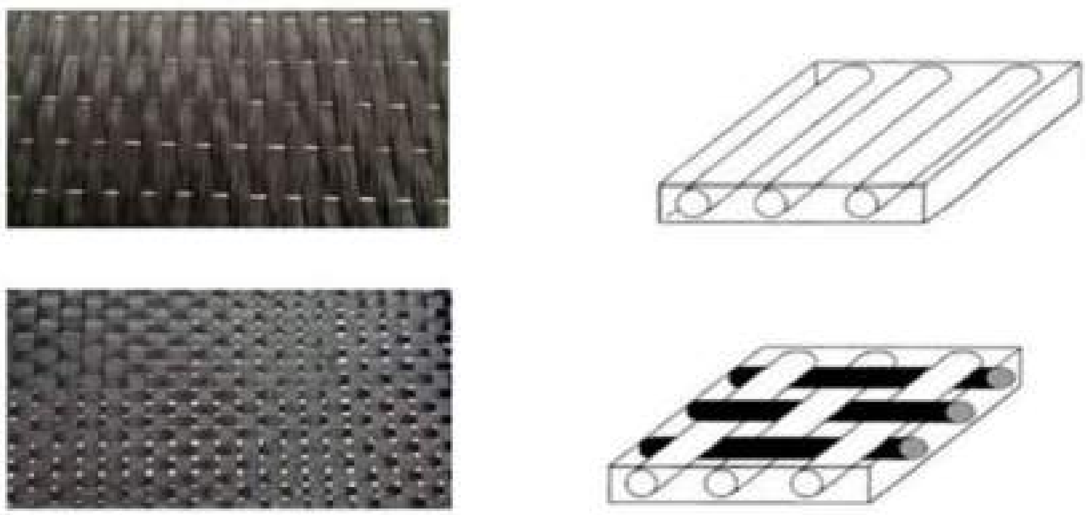


Figure 1. 11 Unidirectional FRP and woven FRP.

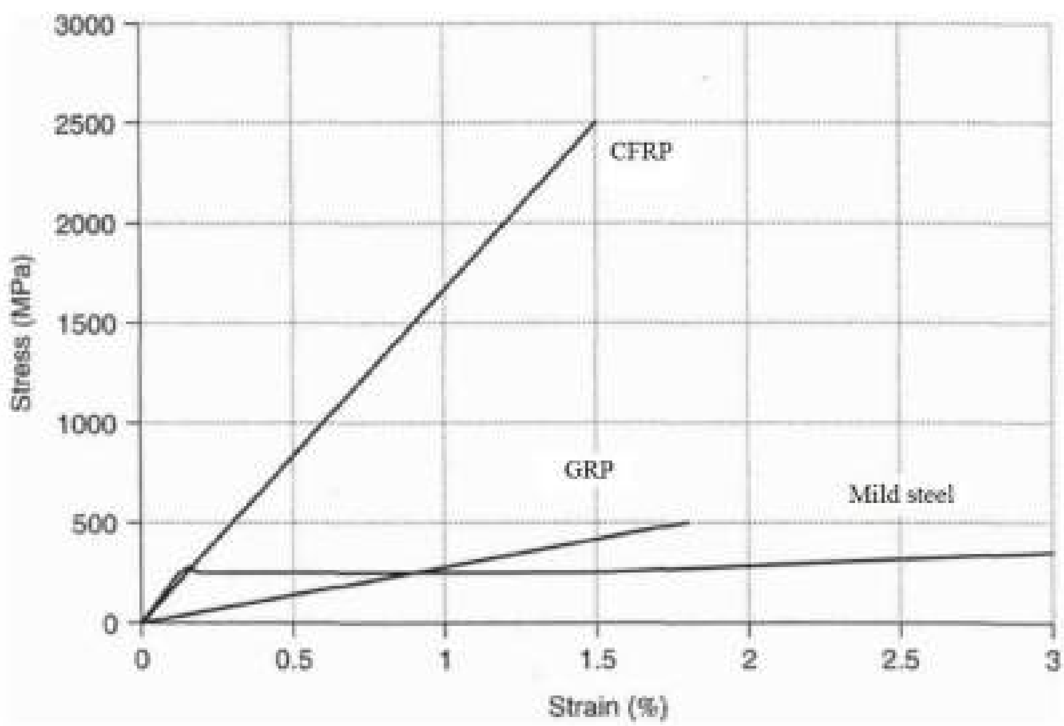


Figure 1. 12 Stress-strain curve for FRPs and mild steel [27].

Using CFRP sheets and strips that are externally bonded (EB) allows for the restoration and strengthening of existing reinforced concrete structures to their previous (original) state of design. As an external reinforcement for RC structure rehabilitation, fiber reinforced polymer composites have become increasingly common. More reinforcement can be achieved by adhering CFRP sheets to the outsides of the concrete elements. As a result of their low weight, simple installation, and high tensile strength, CFRP sheets are a highly promising material for use in restoration and as tensile reinforcement alternative[25,26].

1.7 Motivation

CFRP systems have been increasingly used as materials for strengthening and rehabilitating reinforced concrete structures which lead to study the punching behaviors of reinforced concrete two-way slabs strengthened with CFRP sheets. While the existence of researches is very limited, have been published on the use of GFRP strengthened waffle-slab, there are less resources dedicated to the study of Carbon fiber composite strengthened waffle-slab. Since CFRP laminate possess; outstanding tensile qualities, extended durability, its punching-shear performance in of strengthened waffle-slabs, especially for rehabilitation/repairing applications, is of significant interest.

As a result, carbon fiber reinforced plastic (CFRP) has been selected for use in RC waffle-slab structures rehabilitation applications, and the structural performance criteria of these waffle-slabs have been studied in order to draw conclusions about the viability of using Externally-Bonded CFRP sheets as a strengthening material, compared to other types of Externally Bonded FRP-systems.

1.8 Purposes of The Research

The primary goal of this study was to create a practical methodology for enhancing the waffle-slab shearing capacity of an existing reinforced concrete waffle-slab construction without significantly altering the waffle-slabs' internal structure.

1. Experimental and comparative study of the performance of bidirectional reinforced concrete waffle-slab reinforced with CFRP panels attached to the tension surface. The main variable for the experimental work is the area and composition of the CFRP sheets.
2. Experimentally investigate the ultimate strength and failure mode of unstrengthened waffle flat slabs with varying sizes of solid areas (solid head) around the column. Additionally, the size of the solid area around the column was also correlated with the failure mode, which could be either punching shear in the solid area or shearing of the ribs with the punching shear cone extending beyond the solid area.
3. To perform punching shear tests on R.C. concrete waffle-slabs that have been strengthened by CFRP composites and to acquire a deeper understanding of the structural behavior of a reinforced concrete waffle-slab strengthened with a carbon fiber reinforced polymer (CFRP) strips permanently bonded with epoxy resin.
4. Examining at the various ways in which CFRP-strengthened concrete waffle-slabs might fail (failure mechanism).
5. Conducting a comparative study between the analytical data and the experimental data that were obtained in lab.

1.9 Layout of the Thesis

Specifically, there are six sections to this thesis. The following are brief introductions and summaries of each chapter:

I. The first chapter provides a broad overview of the thesis's central topic.

II. Chapter 2 provides a comprehensive review of the relevant literature; a comparative approach is taken between the various authors' works; and the emphasis is placed on three main themes: the bonding behavior of CFRP laminates/sheets during punching shear strengthening and the CFRP shear contribution percentage of each type of strengthening configuration (layout) methods.

III. Chapter 3 present experimentation methods and procedures. Test results for the various components of the construction mixture, including the CFRP fibers composites, portland cement, fine aggregate, coarse aggregate, superplasticizer, mixing water, steel rebars (mechanical properties), and bonding adhesive (Epoxy), are included as appendices to this study. This chapter also details the procedures for preparing tests for the control waffle-slab and the waffle-slab that has been strengthened using CFRP composite.

IV. The mechanical performance of slabs strengthened with equal intervals CFRP sheets (Punching shear Strengthen) under static stress has been discussed in detail in Part-I of Chapter Four. Data-acquisition device-recorded findings are displayed in the form of curves in straightforward graphical representations; furthermore, conclusions generated from the testing results are provided.

V. Chapter 5 summarizes the findings and provides suggestions for further research. The findings of the study are summarized and the results are reported in this section.

VI. Appendix (I) provide mathematical formulations for design and analysis of waffle-slab punching shear strength, FRP strengthening calculations, and International Design Code provisions and recommendations. Calculations also presented in detail.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

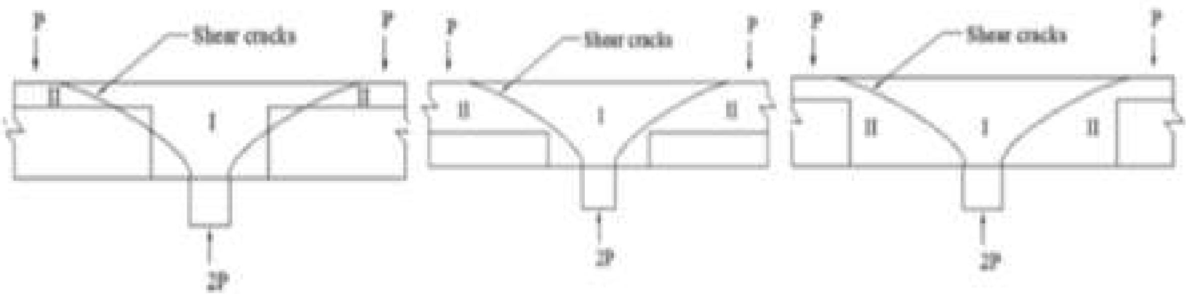
Punching shear failure is characterized by local, brittle failure in areas of intense stress or column support. The tragedy of such a collapse is compounded by the absence of any precursory signs. In the last two decades, there have been multiple devastating punching shear breakdowns. Punch shear failure brought down five stories of the Sampoong shopping hyper-market in Seoul, South Korea on June 30, 1995. (Figure 2.1). In this disaster, almost 500 people lost their lives and over a thousand were injured [28].

Figure 2. 1 Collapse of Sampoong commercial store [28].

Although shear and flexure are the most common causes of structural failure, column connections can also break due to other mechanisms. In a waffle plate failure, the column is simply pierced through a level portion of the slab above it. The failure mode of a typical punching shearing is shown in Figure. (2.2). This type of failure is one of the most crucial considerations for determining plate thickness at column and slab intersections[29].

Figure 2. 2 bridge deck slab failing due to punching shear[29].

Similar to flat slab, waffle slab can develop local shear The failure is known as a punching shear failure, as shown in the Figure (2.3). in A solid revolution of concrete ("I") surrounded by the inclined shear cracks separates normally from the slab, leaving the rest of the slab ("II") rigid[30]. However, despite the increasing popularity of waffle slabs, only a limited amount of research has been carried out. As a result, the shear design procedures for waffle slabs subject to punching have not been considered in the current design codes[30,31]. Therefore, it is not clear how one could apply (if necessary) the codes' design clauses for flat solid slabs to waffle slabs because when the solid sections are very wide or top slabs are sufficiently thick, the punching failure surface could form within the solid section Figure (2.3 b and c). However, when the solid section is narrower, the punching failure surface could pass through the reduced depth section Figure (2.3 a). As result, a smaller shear failure surface could be mobilized, which consequently leads to a lower punching shear capacity.



(a)Narrow solid section (b) Thick top slab (c) Wide solid section

Figure 2. 3 Punching shear mechanism of waffle slab[30].

2.2 Reviews And Investigations Conducted by Scientists and Researchers

Literatures works on two-way slab, ribbed slab, waffle slab, flat slab punching shear, strengthening of slab-column connection region, shear failure theories, FRP sheet/laminates, deck slab system, and developed design methods as well as ACI Code provisions and guidelines will be presented in brief as follows;

In November 1994, Shuangxi Pei [32], Found that the punching capabilities of waffle slabs was found to be insensitive to the loading orientations and the local arrangement of the ribs near the loading pad, according to both experimental and theoretical research. This is because the punching shearing force was diminished to a wider area than that of the loading pad and was rebuffed by both the perpendicular ribs and the deck of the slab. The plastic theory (upper bound method) study showed that the addition of the stirrups would reduce the dimensions of the punching perimeter, resulting in less strength being mobilized than envisaged, whereas the usage of the localized solid region in the waffle slabs might improve the punching shear strength more efficiently. After comparing test findings with those obtained using other analytical approaches, it concluded that the Upper Limit Analysis Which is provided by the BS8110 a specific in terms of the nominal shear stresses at the periphery of the loaded area which is related to the strength of the concrete, and the

Alternate Method using the waffle-solid slab are the most straightforward and accurate ways to forecast the punching shear strength of R.C. waffle slabs. some failure models are shown in Figure (2.4).

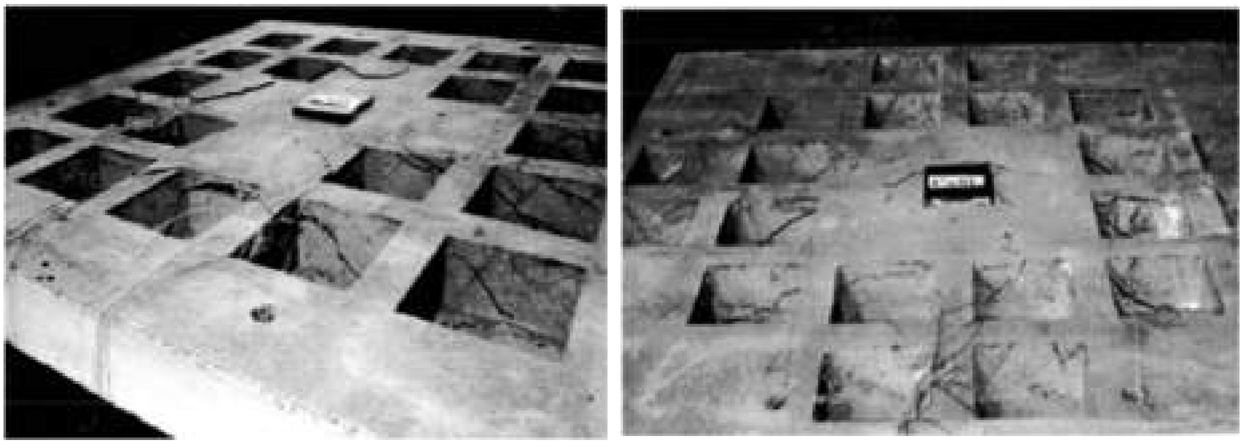
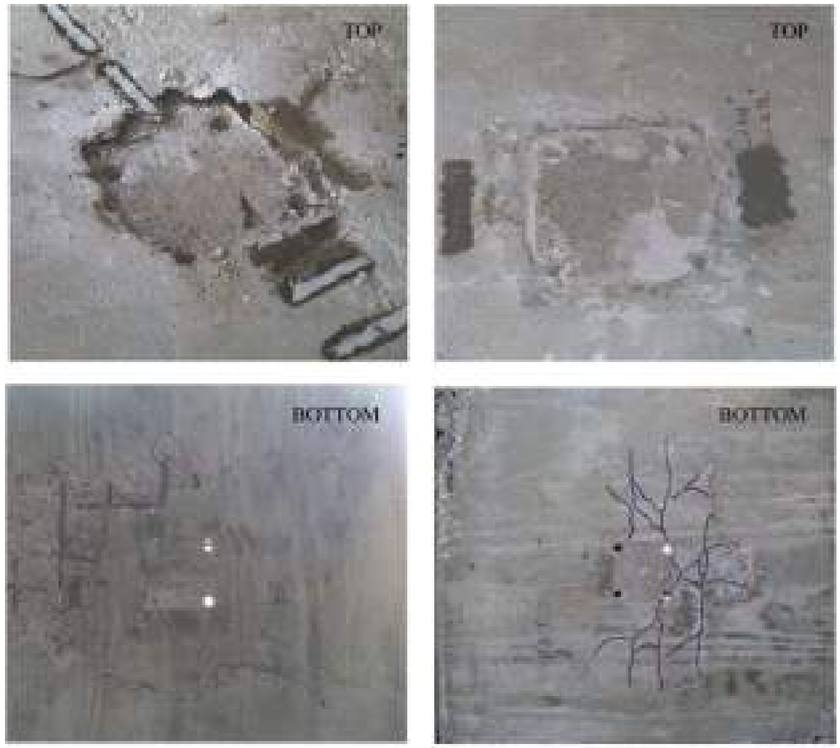


Figure 2. 4 Crack pattern after punching failure.

In August 2003, El-Ghandour et al [33], presented the results of a two-stage experimental program studying the punching shear performance of fiber reinforced concrete (FRC) flat slabs containing/without carbon fiber reinforced polymer (CFRP) sheets as shear reinforcement. In the first step, difficulties of bond slip and crack localization were found. Punching shear failure of the slabs was achieved by reducing the flexural bar spacing in the second phase, which had previously avoided those issues. However, due to its brittleness CFRP shear reinforcement was shown to be ineffective in greatly increasing the slab capacity. There is a proposed and confirmed model for predicting the punched shear capacity of FRC slabs without shear reinforcement. The concrete shear resistance is proposed to be lowered for slabs with FRP shear reinforcement, however a maximum strain of 0.0045 is recommended for the reinforcement. Results from using the updated ACI 318-19, ACI 440-98, and BS 8110 punched shear code calculations to account for FRP reinforcement are either overly optimistic or overly cautious when compared to the actual slab capacity.

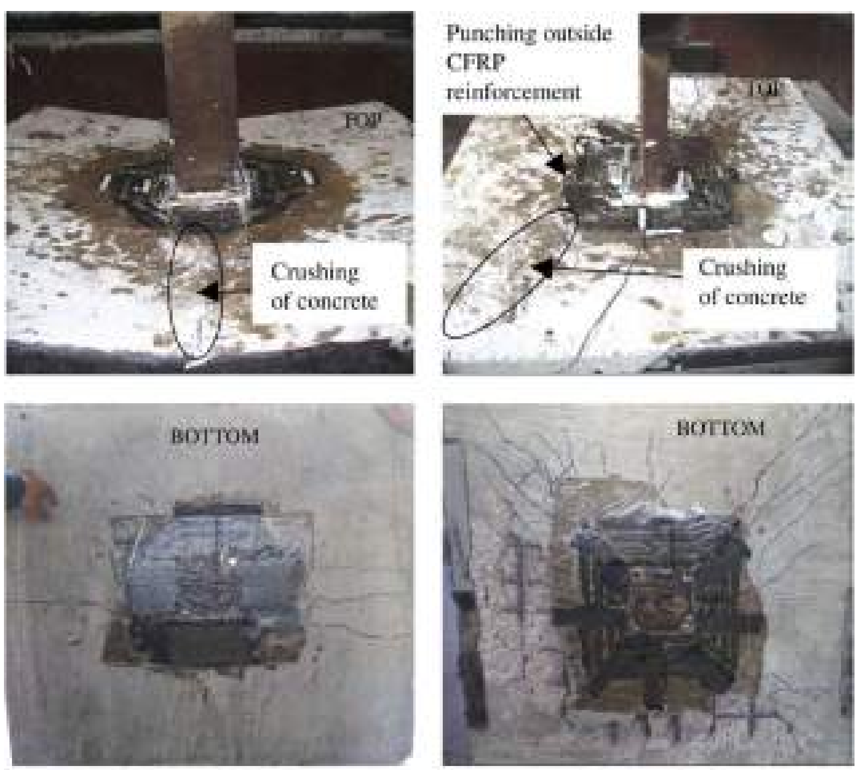
In October 2004, Baris Binicia and Oguzhan Bayrakb [34], they conducted an experimental program on upgrading of reinforced concrete slab–column connections subjected to monotonic shear and unbalanced moment transfer are presented in this study. Externally installed carbon fiber reinforced polymer (CFRP) stirrups acting as shear reinforcement around the slab–column connection area was used with two patterns of CFRP arrangements, see into the Figure (2.5), (2.6) and (2.7). It was found that the proposed method resulted in punching shear capacity increases up to 60% relative to the specimen without any strengthening. In some cases, punching shear failure was eliminated with the use of CFRPs as shear reinforcement. Capacities of test specimens were evaluated using punching shear strength provisions of ACI 318-02 and yield line analyses for the test specimens. On the basis of the results of this study, use of CFRPs as externally installed stirrups was found to be successful in strengthening slab–column connections.

Figure 2. 5 Specimen details.



(a) Specimen CC (b) Specimen CE

Figure 2. 6 Crack pattern after failure.



(a) Specimen A4E (b) Specimen B4E

Figure 2. 7 Crack pattern after failure.

In October 2004, Ehab El-Salakawy et al [35], presented the results of punching shear experimental tests conducted on seven large-scale RC concrete slab-column edges connectors that were strengthened in a variety of ways. In this investigation, three slabs had holes near the column whereas the other four did not. The slabs measured 1,540 by 1,020 by 120 millimeters, and the columns were 250 by 250 millimeters in size. Each specimen had a square hole (150 mm on a side) cut into it, with the opening's axes running perpendicular to the columns. A reinforcement ratio of 0.75 was used on average for the slabs. Two additional methods of reinforcement were examined in addition to the two standard slabs. In Method I, either one or two layers of fiber reinforced polymer (FRP) extensible sheets are externally attached to the tension face or both the tension and compression faces of the slab and then placed around the column. Looked at both glass and carbon fiber reinforced plastic sheets. Technique II involves employing either the first or the second scheme for bonding FRP sheets externally, and then putting steel bolts through holes cut into the slab's thickness and into the column. The results of the tests indicate that the punching capability of the connections was much improved by the addition of FRP sheets and steel bolts.

In May 2006, Anil K. Sharma and Brendon C. Inniss [36], studied the region of a slab close to a support may experience shear failure, with the resulting failure surface taking the shape of a cone or pyramid. Flat-plate and flat-slab constructions typically collapse due to this failure, known as "Punching Shear Failure." There are theoretical principles for preventing punching shear failure of slab-column connections, and there is a wide range of empirical approaches applied by different codes. In this study, an in-depth look at the shear resistance of slab-column joint connections for interior columns. The evaluation of strength does not take into account shear reinforcement in the slabs. The punching shear capacity is studied in relation to several different factors, such as the ratio of column side width to effective depth of slab, the concrete strength, and the proportion of flexural steel.

In June 2009, Ebead, et al [37], presented a experimentally tested about the effect of applying different FRP patterns Figure (2.8) to increase the flexural strength of the RC slabs. The researchers applied sheet- middle strips and sheet-separated strip strengthening patterns called S-MS and S-SS, respectively. The areas of the RC slabs that were covered by the FRP sheets in both strengthening patterns were the same. Table 2-1 lists the main characteristics of both the control and strengthened specimens, such as load capacities and deflections. This enables a direct comparison of different samples. Depending on the increase of the maximum load capacity (see Table 2.1), there is no significant difference between applying the separated and middle FRP strips. The failure mode changed from pure flexural failure in the control specimen to flexural punching failure for the FRP strengthened RC slabs. The maximum increase of the load capacity for the FRP strengthened samples was 60.5% (with the S-MS pattern) compared with the control specimen and there was no significant difference in the crack distribution for different strengthening patterns.

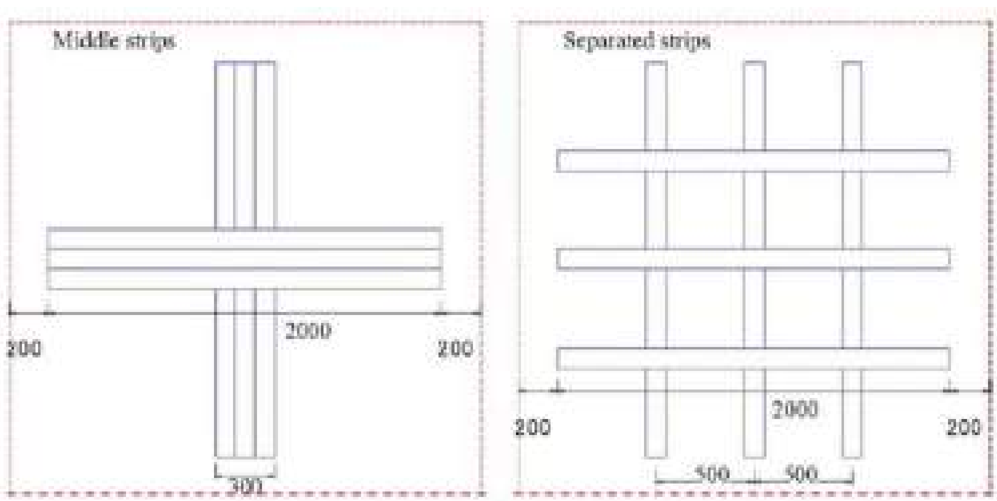


Figure 2. 8 FRP strengthening patterns in Ebead et al [37].

Table 2. 1 Specimen characteristics in Ebead et al [37].

Slab	Initial crack load (kN)	Yield load (kN)	Ultimate load (kN)	Deflection at ultimate load (mm)
S0(Control)	54.5	86.6	135.6	91
S-MS	48.3	113.4	226.3	55
S-SS	55.8	109.1	217.7	53

In October 2011, Souza and Oliveira [38], presented an experimental analysis of 8 two-way reinforced concrete waffle flat slabs under centered load. The dimensions of the slabs were the same and equal to 1800 mm x 1800 mm x 140 mm. The ribs were 80 mm (height) by 50 mm (width), solid region (800x800mm) and the compressive concrete strength was approximately 40 MPa. The main variables considered were the types of shear reinforcement in the ribs, consisting of trusses, vertical closed stirrups and open stirrups inclined at 45 degrees and the use of stirrups inclined at 45 degrees with punching reinforcement in the solid region. The slabs with shear reinforcement in the ribs did not achieve significant resistance in relation to the unstrengthened reference slab, as for the slabs with punching reinforcement, they showed superior resistance, around 26%, confirming the efficiency of the inclined stirrups as punching reinforcement. The experimental results were compared to those estimated by the Brazilian code NBR 6118:2003. It was verified that the resistance of the ribs is not satisfactorily estimated by the code, which excessively underestimates the results for ribs with and without shear reinforcement. Figure (2.9) shows the failure surface of the slabs.

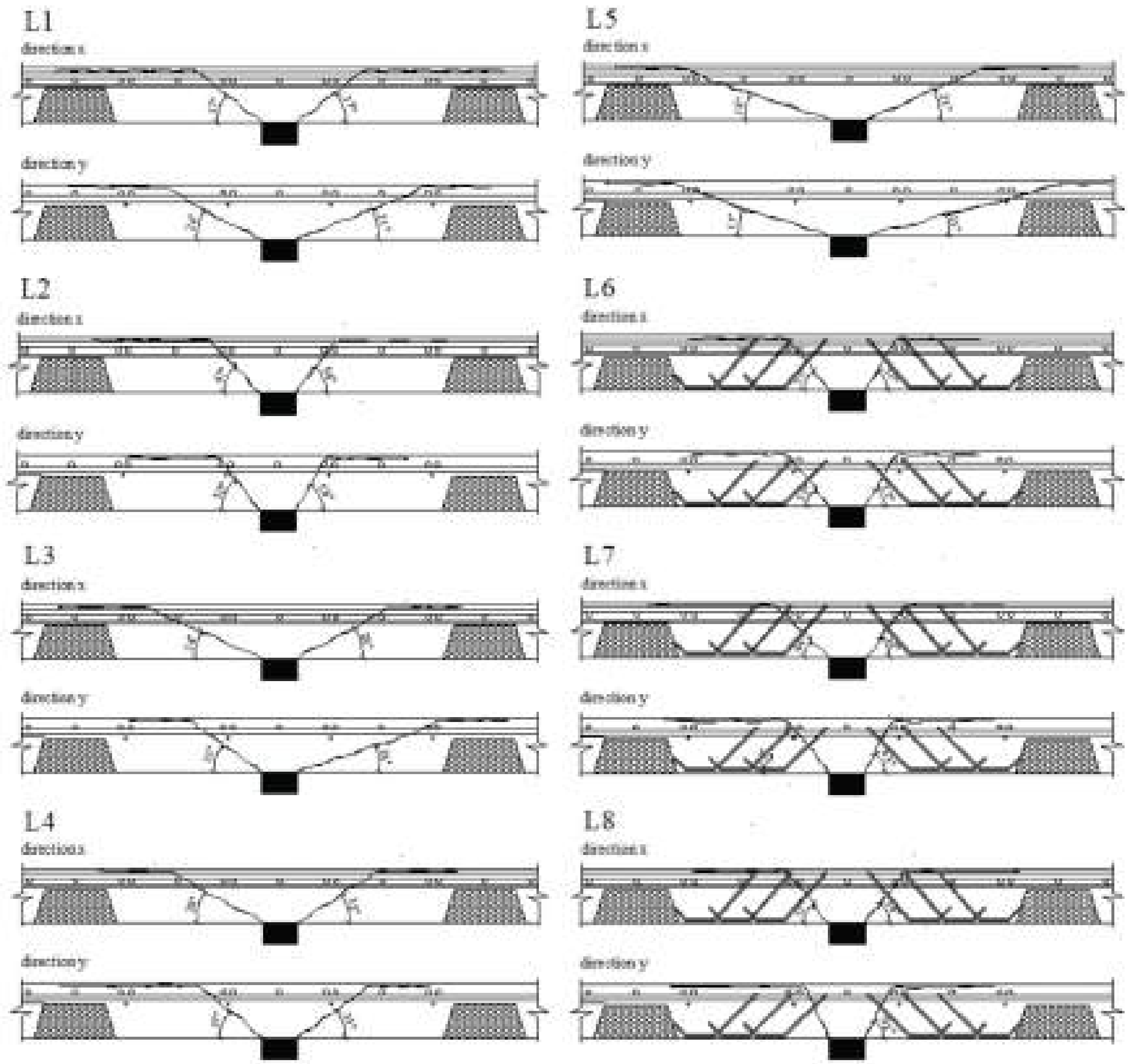


Figure 2. 9 Slabs failure surface in the solid region.

In September 2013, Hameed Khalaf Maro, [39]the purpose of this research is to examine the response of CFRP-stiffened reinforced concrete slabs to a punching load and to compare these findings to those obtained from a Finite Element model. A total of 32 slabs with dimensions of 800 x 800 x 70 and 800 x 800 x 90 mm will be tested as part of the experimental program. The slabs are organized into four-slab groups, for a total of eight groups. The categories are separated by the primary research factors. One slab in each set of four was left unreinforced to serve as a standard, while the three remaining slabs were strengthened in various ways using carbon fiber reinforced polymer (CFRP). The study investigated how slab punching shear strength is affected by variables such as concrete strength, flexural reinforcing quantity, slab thickness, and CFRP distribution form. The punched shear failure mode is used for all slabs in this research. Ultimate punching shearing load of the tested slabs were found to increase by (5-26) % after CFRP strengthening, and the first cracking load was found to increase by (12-200) %. During loading, the reinforced slabs exhibited 36% less deflection than the non-reinforced slabs. Comparing high strength concrete (50 MPa) to regular strength concrete (27 MPa) using a comparison based on the ACI code, which depends on $\sqrt{f'c}$, shows that the ultimate punching load of the former is between (20-50) % higher.

In April 2014, M. Hasan Meisami, et al [40], experimentally studied the centrally loaded, two-way flat slabs. The specifications for the slabs were developed in accordance with standards set by the American Concrete Institute. Four slabs of 1200 × 1200 mm and 105 mm thick, were strengthened using various carbon fiber-reinforced polymer (CFRP) grid configurations, including (1) with pre- installed and (3) with post-installed fiber-reinforced polymer (FRP) strengtheners. The fifth slab fabricated as a control and was not modified in any way. Eight, sixteen, and twenty-four strengtheners were utilized. Slabs can be further strengthened with carbon fiber reinforced polymer (CFRP) grids and epoxy resin in drilled holes, and a method was created to forecast their maximum loading capacity. The experimental results demonstrate that the proposed mechanism of strengthening approach increases ultimate loading and displacement capacities. The shear capacities of the strengthened slabs with eight and sixteen CFRP grids were increased by 29.8 and 49%, respectively, compared to that of the unstrengthened control slab and the strengthened slab with twenty-four CFRP grids exhibited an increased shear capacity of 56%. The proposed strengthening approach also protects against brittle failures caused by vertical concentrated loads. Due to the shallow slab depth, deboning of FRP grids is identified as the primary source of failure for FRP-reinforced flat slabs. As an added bonus, this strengthening technique can switch the mode of slab failure from shear to flexure failure once the slab's shear capacity has been raised to a suitable number. Figure (2.10) shows the cracking pattern on the tensile surface of the slabs.

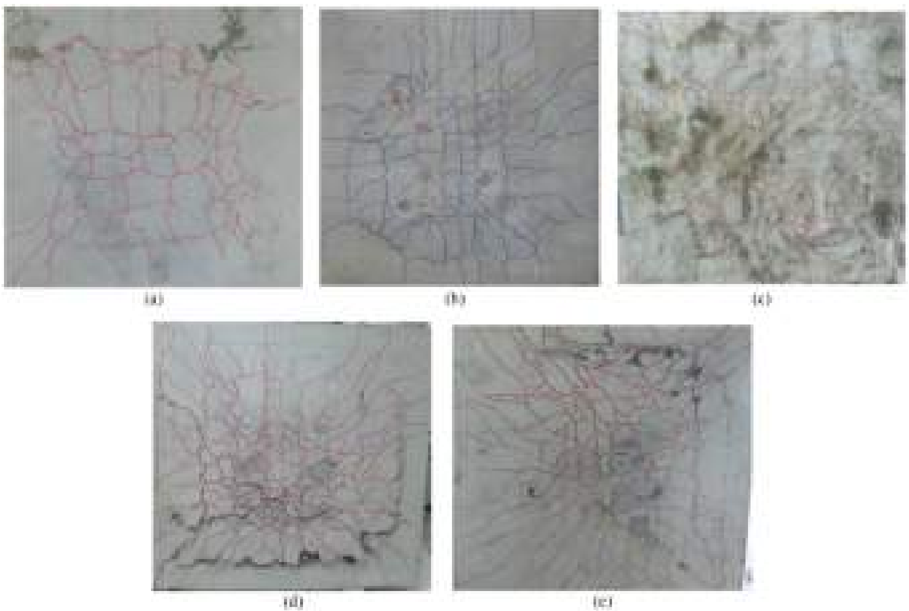


Figure 2. 10 Tension surface crack patterns.

In February 2015, Mohamed Hassan; et al [41], conducted an experimental study on punching shear behavior of two-way concrete slabs with glass-fiber-reinforced polymer (GFRP) bars as flexural reinforcement and FRP stirrups (glass or carbon) as shear reinforcement. A total of 10 full-scale interior slab-column specimens measuring 2,500×2,500 mm, with thicknesses of either 200 (Series I) or 350 mm (Series II), and 300×300-mm square column stubs were fabricated and tested under monotonic concentric loading until failure. These tests aimed at investigating the behavior of GFRP-reinforced two-way concrete slabs reinforced with FRP stirrups as shear reinforcement and evaluating the contribution to the punching shear capacity. The investigated parameters were the flexural reinforcement ratio and the shear reinforcement type (glass FRP and carbon FRP stirrups) and ratio. The test results revealed that using FRP stirrups as shear reinforcement increased the punching shear strength and deformation capacity of the test slabs. The average increase in the punching shear capacity was 29 and 23% in Series I and II, respectively. In addition, the average increase in the deflection at failure of Series I specimens was 107%. The increased punching shear strength and deformation capacity were proportional to the flexural- and shear-reinforcement ratios. In addition, the performance was enhanced by reducing the brittleness of the specimens when FRP stirrups were used as shear reinforcement.

In March 2015, Souza et al [42], examined the performance of waffle slab without moment transfer and with solid panels enclosing internal columns. Six types of square waffle flat slabs were tested; each model had a side length of 2400 mm, a height of 185 mm, a thickness of 70 mm along its top, a height of 115 mm along its ribs, a width of 50 mm, and a distance of 270 mm between its ribs. Solid panel with different dimensions, beams web steel percentage, type, and layout were the independent factors. All of the models failed in shear due to diagonal stress of the ribs except for the one that failed in flexure due to crushing of the beams at the solid panel. The punching shearing of the solid panels surrounding the column and the ribs shear adjacent to the solid panels were studied and compared with existing equations from codes and other studies available in the literature, as well as with the results of the tests themselves. Lastly, suggestions are made for design processes in the slab region inside the zero moment lines and around the columns, with respect to the specification of the solid region size as function of the ribs' resistance values toward shear and flexure.

In November 2015, Al-Bayati et al,[43] presented an experimental study to test of fifteen 1/10-scaled micro-concrete waffle slabs exposed to circumferential punching shear, dimensions of slabs (650x650 and 510x510 mm), Variables considered were; the size of solid section, the column shape and size, and the concrete strength All slab specimens had an overall depth of 70 mm and top slab of 20 mm. While waffle slabs were discovered to have a punching failure mechanism comparable to that present in flat slabs, However, for a slab with a width of solid section less than five times the effective depth, the observed failure surface of a waffle slab was as incomplete surface of revolution due to the losses in the failure surface when it extended into the waffle section, as shown in Figure (2.11) Since the shear strength mechanisms of waffle slabs is not taken into account in the present codes of practice, compared with the test results showed that BS8110 and EC2 exaggerated the punching capability of waffle slabs, while ACI prediction was cautious, some results are shown in Table (2.2). To anticipate the failure loads, a model was constructed based on the upper-bound theoretical methods, and it showing great agreements with the testing.

Table 2. 2 Comparisons between the shear strengths[43].

Slab No.	Size of solid section(mm)	P_{test}, kN	P_{ACI}, kN	P_{EC2}, kN	P_{BS}, kN
IWS1	200 x 200	50.5	46.8	61.2	68.5
IWS2	200 x 200	42.1	45.4	58.4	72.9
IWS3	200 x 200	46.3	47.8	59.4	74.3
IWS4	250 x 250	63.2	39.2	54.3	67.6
IWS5	290 x 290	63.2	38.3	53.5	66.6
IWS6	470 x 470	65.3	37.8	53.0	65.9

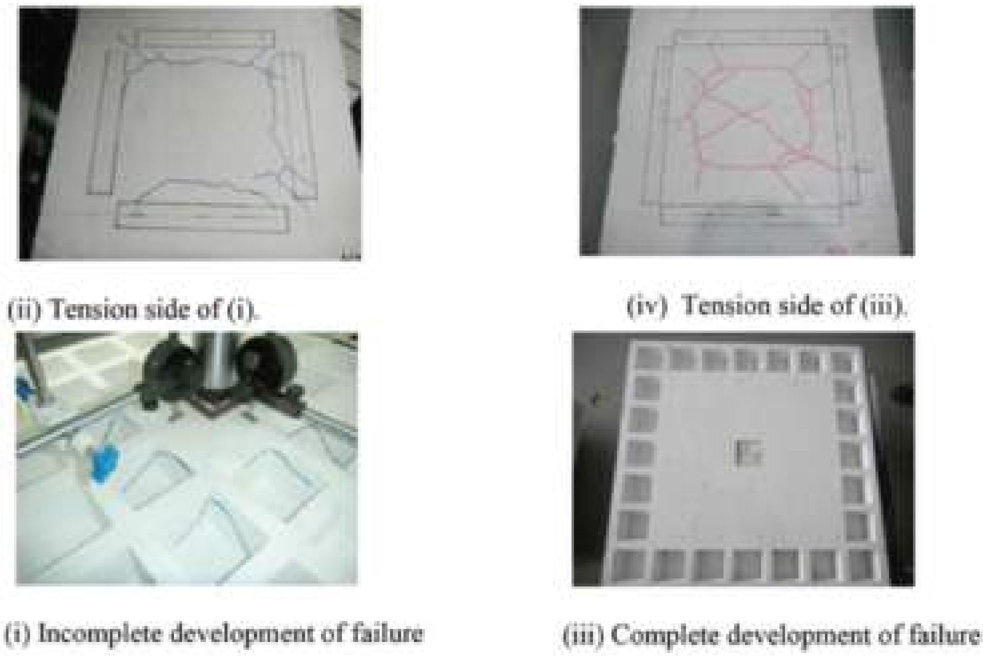


Figure 2. 11 Punching shear mechanism of waffle slab specimens.

In September 2017, K. Sakethe et al [44], presented a study the of behavior punching shear in waffle slabs at slab column joint subjected to concentric punching shear. Although it was observed that waffle slabs are very similar to that of flat slabs, the shear capacity is relatively reduced because some of the potential surfaces is lost when it extends into waffle section. The current Indian Standard (IS) code of practice do not consider the punching shear mechanism of waffle slabs. The analytical part is done using Finite Element software ANSYS, by applying the concentric load at the slab-column joint on waffle slabs, waffle slabs of different sizes and comparing the analytical results with normal RC slab. Waffle slabs of different sizes are created by increasing the depth of slab by 20%, width of the rib by 25% and one by increasing solid section. The comparison of the test results with the RC slab reveals that waffle slab gives more strength and when comparing between the waffle slab models of different sizes, with 20% increase in slab depth shows that strength is increased significantly by around 24%, providing more thickness of ribs gives extra strength to the structure against punching shear.

In November 2018, Mohammadtaher Davvari [45], presented a study that elaborated on an investigation of make a comparison between the effects of different strengthening methods such as FRP strengthening, applying vertical (shear) reinforcement, and their combination, on the behaviour of flat slabs with different conditions (tensile reinforcement ratios). Eight slab specimens were cast with dimensions were 650 × 650 mm2 square specimens with a thickness of 60 mm; which were classified into two categories: low and high tensile reinforcement ratios. The experimental and validated numerical results demonstrate that the most efficient strengthening strategy is a combination of strengthening methods in both categories. Strengthening with FRP sheets improves the slabs load capacity in both categories, it led to an increase in the ultimate load by (1.46 and 0.42) low and high tensile reinforcement ratios respectively. The results also show that applying vertical (shear) reinforcement in the critical punching area strengthens the critical compressive strut of the RC slab. This shifts the critical punching area from the column vicinity to the outside of the shear reinforced zone and enhances the RC slabs load capacity. Figure (2.12) shows the concrete cracks on the slab tension surface according to the experimental and numerical models.

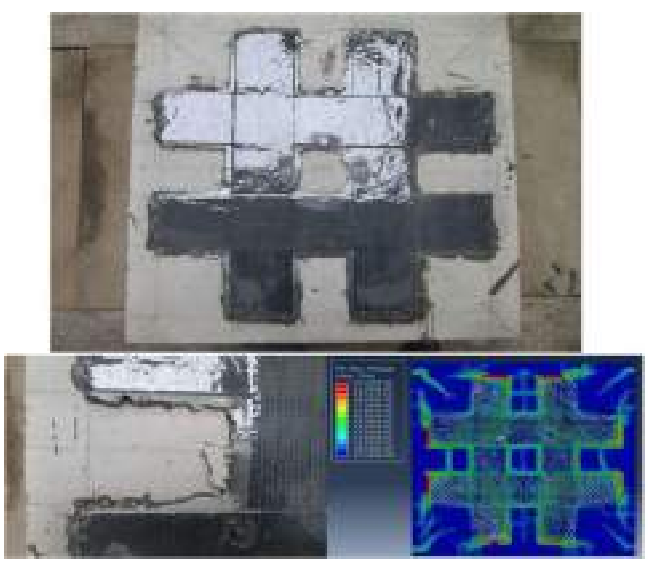


Figure 2. 12 Concrete cracks in the tension surface of LFS.

In February 2019, Hamdy M. Afefy and El-Tony M. El-Tony [46], conducted a study on the use of different methods of reinforcement in an effort to address the limitations of existing methods. Internal single-leg stirrups, a double-skin steel assembly, and adequately anchored externally bonded glass fiber-reinforced polymer (EB-GFRP) sheets are used as part of the strengthening strategies for punching shear of RC slabs. There are a total of nine slab specimens, which are prepared and arranged into four groups. In comparison to other methods, the one using a slab equipped with adequately anchored single-leg stirrups and an orthogonal steel assembly with two skins is the most effective. This method increases the slab's punching load bearing capacity by a factor of 1.69 compared to that of the unreinforced control slab. Furthermore, it causes the slab to exhibit strain hardening and softening curves characteristic of ductile punching failure. All strengthened slabs' experimental shear resistance is compared to the resistance required by various design standards. When compared to the experimental findings, the failure characteristics required by German codes are found to be the most reasonable.

In May 2020, Ahmed E. Salama et al [47], presented a study on GFRP reinforcing bars inside concrete edge-slab–column connections. Using FRP stirrups as shear reinforcement are not covered by existing codes and standards. This study describes the experimental results for large-sized edge slab–column joint connections strengthened with GFRP bars and stirrups. GFRP stirrups and extension from the column end affect the tested connections' performance. In furthermore, a nonlinear numerical analysis (FEA) is employed to do an in-depth research. Next, edge connections with varied stirrup diameters, extensions at different distances from the column, and spacings are investigated parametrically. The punching-shear response improved with GFRP stirrups as shear reinforcement in the slab all around column. The finite-element model's ultimate load, cracking patterns, reinforcement and concrete strains, and load-deflection relationships match experimental results, proving its accuracy. The results show that punching-shear strength decreased with stirrup separation and rose with stirrup size and column extension. Based on the numerical-simulation results, a simple design strategy to predicate the ultimate bearing capacity of the tested connections is given. The model yielded good yet conservative estimates with respect to the experimental data as well as the existing results in the literature.

In October 2020, Mohammed G. El-Gendy, S. and Ehab F. El-Salakawy, [48], made a study about predict the punching shear of two-way slabs with FRP rebars, several empirical models have been presented over the past two decades. This research examines the viability of using these models for FRP-RC slab-column interior joint and edge joint connections under gravity loads. The models are validated by comparing their predictions with data from experiments the authors have previously performed on FRP-RC edge connections that were subjected to cyclic lateral loads in the opposite direction. They used the results of (68 and 25) specimen tests respectively, including 6 edge tests conducted under reversed-cyclic lateral loads, to compare the models. A universal model is proposed based on the analysis, which can forecast the capacity of interior and edge specimens under gravity or cyclic loads. The proposed model yielded an average test-to-predicted strength of 1.010.14 for internal specimens and 1.010.09 for edge specimens. A design model is also proposed to evaluate gravity shear limitations for FRP-RC connections subjected to cyclic load and no shear reinforcement.

In February 2021, Nithyambigai G et al, [49] They conducted a study is performed to investigate the behaviour of the waffle slab, for five specimens waffle slab and dimension is of 1020 x 500 x 90 mm. and sample Solid Slab. Waffle slab types of construction are economical for building where there are long spans, over between 5 m and 6 m with light to moderate live load. It reduces slab weight by reducing amount of concrete. The waffles slab less in dead load and high in load caring capacity. In this project work the waffle slab system with various spacing of grid beams are casted and tested for the load carrying capacity. It is inferred that the waffle slab system performs far better than the conventional slab in terms of load, and that spacing between the beam and load bearing capacity is inversely proportional to each other.

In February 2021, Silva et al[50], presented a study to compare the final load of ten flat waffle plates with different sizes of solid surface area and spacing between the ribs, For punching shear strength of waffle flat slabs with several dimensions of the solid area around the column and different spacing of the ribs, shown in Figure (2.13).by simulating panels with dimensions of 2220 mm x 2220 mm x 180 mm, with a cover layer (topping slab) of 60 mm and concrete beams (ribs) of 60 mm width till collapse applying software package ANSYS in a non-linear fashion. Failure mechanisms and loads were investigated, and indeed the results indicated that when the mode of failure was shearing of the ribs, the models with small solid region provided less bearing capacity than the models with more solid area. Slabs with the most extensive solid areas were subjected to punching shear and exhibited the same behavior as solid flat slab, demonstrating conformity with the codes in terms of their punching shearing capacity limitations, in particular with the NBR 6118. The findings demonstrate that the shearing strength of the ribs is underestimated by the ACI, Eurocode 2, and NBR 6118 standards, indicating that a squares solid region with a 15% of span length of is acceptable. The occurrence of shear failures in the ribs in slabs L1, L2 and L6 was influenced by the formation of punching shear cones extending beyond the solid areas, unlike the other slabs that behaved as completely solid flat slabs Figure (2.14).

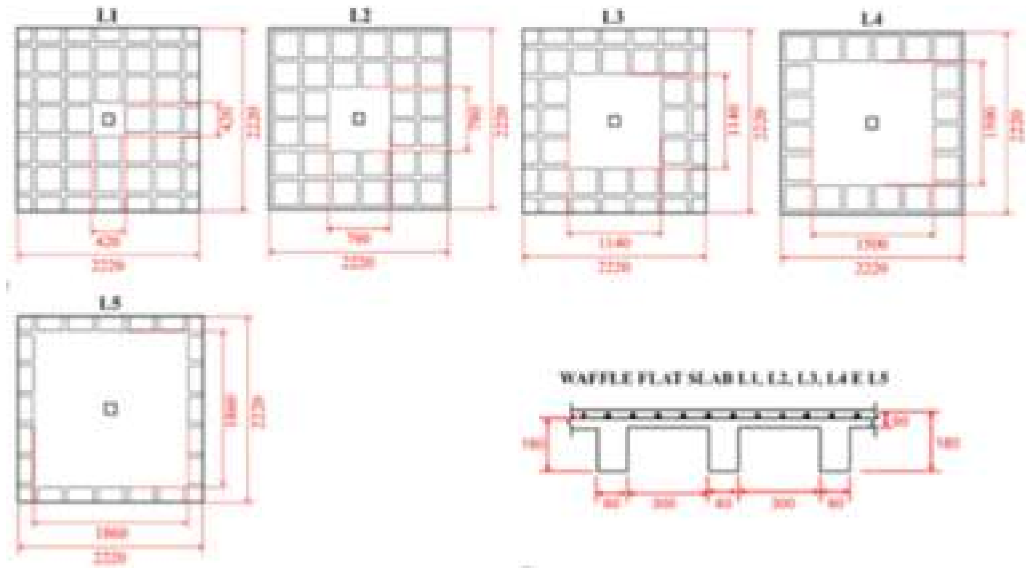


Figure 2. 13 Waffle flat slabs (mm).

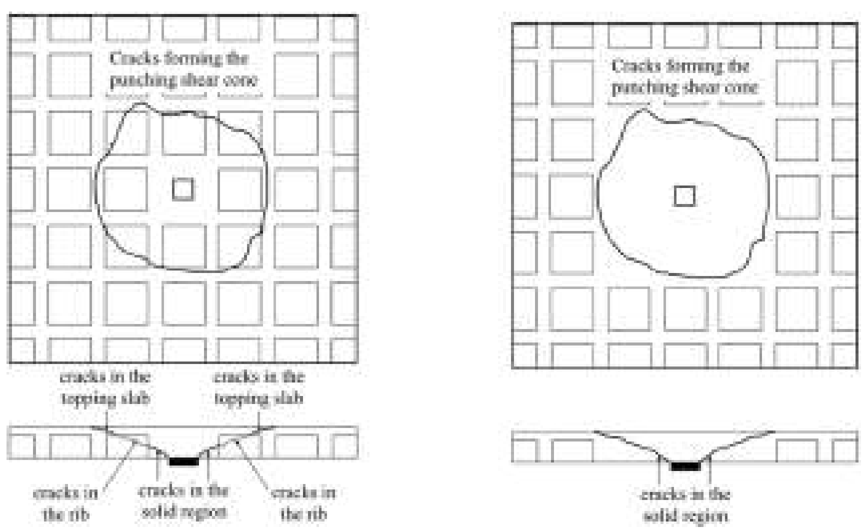


Figure 2. 14 Cracks forming the punching shear cone in waffle flat slab with smaller solid area and larger solid area[50]

In February 2021, Demewoz W. and Aikaterini S. [51], investigated the flat slabs for punching shear performance after being retrofitted with Ultrahigh-Performance Fiber-Reinforced Concrete (UHPFRC) in a variety of configurations. computational nonlinear finite-element analysis, wherein regular concrete and

UHPFRC are modeled using a combined damaged plasticity-based model, is used to suggest and evaluate two optimal retrofitting configurations. Reading about tried-and-true slab-column connections in the literature helps to ensure the model is correct. Parametric experiments are then conducted to verify the model's prediction capability by examining how changing the depth and area of the UHPFRC layer affects the slabs' punched shear performance. Composite slabs with varying UHPFRC layer thicknesses, areas, and orientations have their maximum shear resistance, displacement, and crack growth patterns analyzed. The ability to punch and shear increases with UHPFRC layer thickness. But when the UHPFRC layer thickness grows, the maximum displacement also shrinks. Using a UHPFRC layer only in the most stressed parts of a slab can be more efficient and cost-effective than using UHPFRC throughout the entire slab. This is because less UHPFRC is required and the slab's ductility is improved.

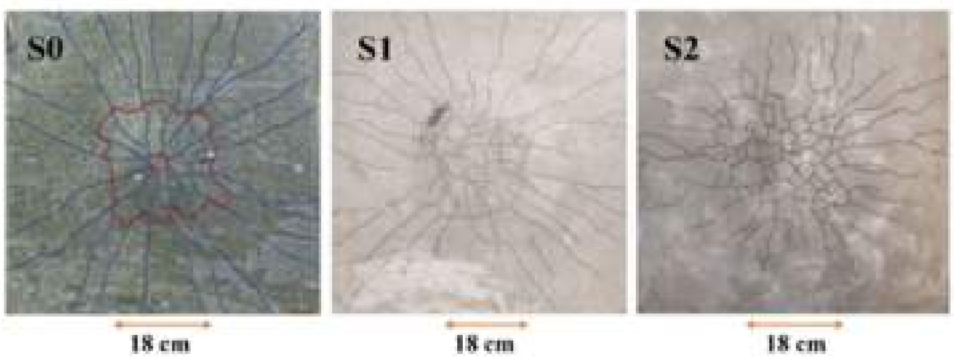
In July 2021, Marília G. Marques et al [52], studied the flat slabs with openings and stud-like reinforcement and analyzed theoretically to determine their punching shear resistance in this study. Damage from a punch is more easily inflicted on perforated flat slabs. The amount, size, and location of the opening in the slab determine the extent of the strength loss. When a load is applied to the slab, a rotation occurs, resulting in seven forces, as described by the theoretical approach offered in this study. Concrete and flexural and shear reinforcement are the sources of these stresses. Finding the solution to nonlinear equations derived from the equilibrium of horizontal, vertical, and rotating forces yields the failure load. These slabs with shear punching reinforcement have their failure criteria categorized as either internal to the shear reinforcement or externally to the shear reinforcement. The theoretical breaking loads were within (7) percent of the experimentally obtained values.

In August 2021, Mohammad AlHamaydeh, and M. Anwar Orabi [53], investigated the GFRP-Reinforced flat slabs punching shear failures. Failure mechanism may be the design factor due to the floor plates' thinness and lack of beams. Plastic fibers reinforced self-consolidating concrete (FR-SCC) was used to improve punching shear capability of GFRP-reinforced flat slabs in this study. Synthetic fiber is inert and corrosion-resistant, and SCC allows high fiber doses without affecting concrete placement quality. Punching shear behavior was evaluated on six large interior slabs. Three synthetic fiber–reinforced self-consolidating concrete (SNFRSCC) specimens were compared to SCC controls. Experimentally, longitudinal reinforcement spacing did not affect punching shear capacity. SNFRSCC specimens had slightly better punching shear capabilities than controls. Toughness improved significantly in FR-SCC specimens (2.34 multiply). Analytical expressions estimated punched shear capacity and load-rotation relationships for GFRP rebars with SCC and SNFRSCC slabs. Analytical expressions used critical shear fracture theory (CSCT). The updated CSCT predictions matched SCC and FR-SCC specimen load-curvature behavior and punching shear capacity.

In August 2021, Hikmatullah Akhundzada et al [54], demonstrated how well near surface-mounted (NSM) carbon fiber-reinforced polymer (CFRP) bars work to prevent punching shear failure in slab-column connections. Two "control" samples and six "stronger" samples will be made and tested throughout the course of the experiment. The experiment's primary controls are the reinforcing plan and the CFRP bars' cross-sectional area. According to the findings, there is a 44 percent increase in ultimate load after NSM strengthening. The concrete's initial crack forms later due to the strengthening, and the load-displacement and load-strain curves remain linear even at the maximum load. Strengthening with NSM enhances flexural rigidity by more than 100% and keeps a firm grip on the concrete no matter how much weight is applied. The slab's flexural strength rises, boosting its punching shear capacity. By adapting and using the method developed by Chen and Li, we are able to compare the experimental results to those generated by a number of design algorithms. When comparing the computed ultimate bearing capacity of the strengthened specimens with the experimental data, there is a good agreement.

In July 2022, Su-Min Kang; et al [55], Conducted experimental program on post-tensioned (PT) slab-to-column connections are required, according to current design rules, to undergo bidirectional shear strength analysis. The purpose of this paper is to do research into the aforementioned interaction with regards to PT transfer slabs. The examined PT slab specimens had their shear strength in both directions measured, and their mode of failure analyzed. Recent PT transfer slabs with low shear span-to-depth ratios were subjected to concentric compression tests for quantitative analysis of the interaction. The quantity and arrangement of post-tensioning reinforcement were among the test parameters. The results showed that the PT transferring slab specimens had a higher two-way shear strength by a range of 53%-87% compared to the traditional RC transferring slab specimen. An increase was observed in correlation with a more concentrated arrangement of post-tensioning tendons. Current design methodologies for PT flat plates and the strut-tie model were used to compare the test specimens' two-way shear strengths with expectations.

In February 2023, Khuong Le-Nguyen;et al [56], presented an alternative to fiber-reinforced polymer (FRP sheets/laminates) strengthening systems for reinforced concrete slabs, using fabric-reinforced polymeric matrix (FRPM) composites have been the subject of extensive research. Three-dimensional (3D) finite-element modeling (FEM) of FRPM-reinforced RC slabs under shear was performed using the test results as input. (One) control slab and (two) strengthened slab specimens measuring 1,600 millimeters by 1,600 millimeters by 100 millimeters were then subjected to punching shear testing. The results show that FRPM strengthening works well under punching shear, The maximum load of the strengthened slabs increased by (60-74) % over the maximum load of the reference Slab S0, the radial cracks were fewer and shorter for the two strengthened slabs, as shown in the Figure (2.15), The punched shear performance of reinforced concrete slabs can be predicted with a fair degree of precision using the findings of the numerical study.



Crack patterns on the bottom face

Figure 2. 15 Punching failure, upper face[56].

Reinforced concrete (RC) slabs systems that are deficient in two-way shear strength are susceptible to brittle failure at a slab–column junction that may propagate and lead to progressive collapse of a larger segment of the structural system. Deficiency in two-way shear strength may be due to design/construction errors, material under-strength, or overload. Fiber reinforced polymer (FRP) composite laminates in the form of sheets and/or strips are used in structurally deficient flat slab systems to enhance the two-way shear capacity, flexural strength, stiffness, and ductility. Glass FRP (GFRP) has been used successfully but carbon FRP (CFRP) sheets/laminates are more commonly used as a practical alternative to other expensive and/or challenging methods such column enlargement as shown in Figure (2.16).

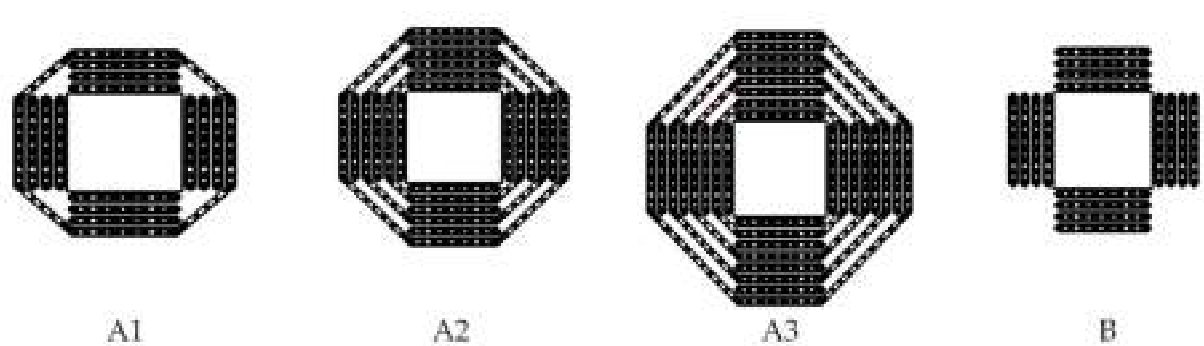


Figure 2. 16 Carbon fiber reinforced polymer (CFRP) pattern A with diagonal strips provide higher two-way shear capacity compared to pattern B with orthogonal strips[57].

Concluding Remarks;

Although the traditional system of solid slabs resting on beams is still extensively used, the structural system of waffle slabs has become increasingly popular, particularly for buildings with enormous spans that must be bridged. Since the code's prescriptions, like ACI-318 [17], ignore the impact of torsion in ribs and stress concentration on the ribs-solid region connection [30], research in this area is highly relevant to assess, for example, the behavior of the solid area and the ribs spacing which decided on preliminary design stage. For instance, the ACI code suggests evaluating waffle slabs, solid slabs, or beams according to the maximum allowed rib spacing. However, Al-Bayati [30]'s research showed that the system checks proposed based on the principles of a solid slab are not fully applicable since the dimensions of the wide-beam immediately imply the type of slab failure.

Experimental studies such as those by Al-Bayati et al. [30, 43] Silva et al. [50] and Arunkumar et al.[58] showed that the reduction of the solid area in waffle flat slabs can reduce the ultimate strength, leading to the punching shear cone extending beyond the solid area. There is a rule of thumb among designers to use the length of the solid area to be at least equal to 15% of the clear span between columns, but Al-Bayati found that the solid section should extend for a distance at least 2.5 times the slab effective depth from each column face.as well as, building codes are silent on the subject on the dimensions of the solid area around the column.

Also, from previous literatures works, it was found that, main parameters involved in defining the slab strengthening design are; FRP material characteristic strength, FRP strengthening area ratio, FRP strengthening length, orientation and location, RC strengthened slab span and its current deflection and cracking conditions, Slab thickness, concrete cover and concrete compressive strength. Bonding material and application procedure has important effect. Finally, the number of FRP layers, textile type, the strengthening configuration, and the matrix material are also important.

Reinforced concrete waffle flat slabs continue to be among the most economic floor systems due to speed of modular construction and inherent flexibility it overs in relation long span roof and partitions walls distribution freedom. However, flat waffle slab floor systems that are deficient in two-way shear strength are susceptible to brittle failure at a slab–column junction that may propagate and lead to progressive collapse of a larger segment of the structural system. Deficiency in two-way shear strength may be due to design/construction errors, material under-strength, or overload.

Fiber reinforced polymer (FRP) composite fabrics are used in sheets and/or strips in structurally deficient flat slab systems to successfully enhance bidirectional shear capacity, flexural strength, stiffness, and ductility. But CFRP sheets/laminates have not yet been used in waffle slabs systems as a practical alternative to other expensive and/or difficult methods such as shaft expansion.

This study focused on the methodology and effectiveness of utilizing CFRP sheets/strips at the column/slab intersection to enhance punching shear strength of waffle flat slabs. Research will present a hybrid model that was deployed to assess the influence of key parameters affecting punching shear strength, including the width of the square solid area, CFRP strengthening geometry, CFRP strengthening orientations, percentage of CFRP strengthening area, and CFRP strengthening participation to slab overall shear strength.

CHAPTER THREE: EXPERIMENTAL TESTING PROGRAM

3.1 Introduction

To study the effects of fiber-reinforced polymer (FRP) strengthening under concentrated column loading on the punching shearing strength and behavior of simply supported waffle slab, an experimental program was designed and conducted. Two groups are included in the program by pouring waffle slabs with different dimensions layouts [IWS-1 and IWS-2] and strengthening arrangements using same concrete mix batches and almost same concrete compressive strength. This testing program comprised the use monotonic static incremental loading techniques. The main objective of this chapter is to present the properties of materials (cement, fine and coarse aggregate, superplasticizer, steel reinforcements and CFRP) used in the current study. The details of the test specimens and strengthening schemes, and testing setup are described hereafter. Standard specification of the American Society for Testing and Materials (ASTM) [59] and Iraqi specifications No. [5, 45], 1984 [60,61] are adopted to determine the properties of materials. The purpose is to realize a better understanding of the behavior of waffle slabs strengthened with (CFRP) sheets, which may lead to the development of guidelines on determining the most efficient strengthening strategy for rehabilitating RC slabs under different conditions.

3.2 Experimental Program

Testing program were arranged according to the following steps:

1. Preparation of materials and trail mixes.
2. Evaluating Mechanical properties of aggregates, cement, super-plasticizer, and mixing water.

3. Casting, and a series of concrete tests on materials and samples are part of the experimental program (cubes, cylinders, prisms) according to ASTM.
4. laboratory testing of ten simply supported waffle slabs (eight in group IWS-1 and two in group IWS-2) comprise the strengthening experimental program with and without large solid part under concentrated column loading.

3.3 Parameters Studied in This Research

Throughout the study, the longitudinal top and bottom reinforcement rebars, waffle slab size, dimension of column, and load position were all kept constant. While the variable parameters are the including of CFRP (sheets) layout arrangements with the same concrete compressive strength, the different solid head's part dimensioning are also investigated.

3.4 Design of Waffle Slab and Their Details

The waffle slabs were designed according to ACI 318M-19 [17]. Ten reinforced concrete waffle slabs with span of length (1000x1000mm), slab depth (100mm), and slab voids cross-section (65*85mm) as listed in Table (3.1). Tension reinforcements were deformed steel rebars (φ5.5mm) with equal spacing (28mm) across the top slab surface, while all ribs were doubly reinforced at bottom side with two rebars (φ5.5mm) as shown in Figure (3.2) and (3.3). Each specimen is designed to fail under flexural-punching shear, design formulation is supplied in Appendix (I)

Each waffle slab was tested according to the predesigned load-support configuration shown in Figures (3.4), (3.5), (3.6), and (3.7). Supports were constructed as simply support saddle points as shown in Figure (3.1). The support system locations were chosen beyond the contraflexure limiting points of (L/6) from column face and in both directions as specified in ACI 318M-19 for top reinforcement curtailment length.

Waffle slabs are tested accordingly in the loading frame of 60 KN loading capacity and end conditions were set as simply supported and the slab panel is placed on the test setup, as shown in Figure (3.1). All the primary settings were carried out and check is done for the proper functioning of dial gauge. After all the initial settings are carried out the load is applied on the center of the panel until cracking is observed on the panel. The initial crack, ultimate load and maximum deflection are recorded for all cases, and graphical comparison are presented in next chapter.

Table 3. 1 Specimens Dimensions.

Category	Size of solid section (mm)	Overall slab height (h) (mm)	Effective slab depth (d) (mm)	Column length (mm)	ρ Solid section	F_{cu}, MPa
IWS1	275 x 275	100	85	80	0.0096	30.5
IWS2	515 x 515					

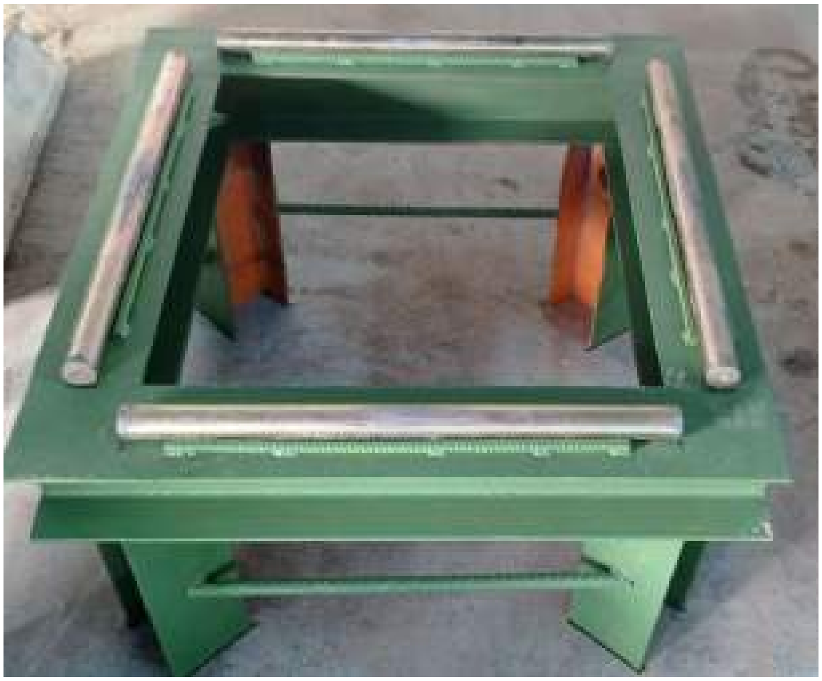


Figure 3. 1 Waffle slab support system frame

3.4.1 Specimen Details

Structural tests were carried waffle slab specimens, to simulate the conditions at waffle slab supported on interior columns connections. Variables considered were the solid section's size and the CFRP sheets' Form and area, as shown in Table (3.2). All waffle slab specimens had an overall depth of (100mm), effective slab depth (85mm), the width of rib (35mm), top deck slab of (35mm) thick, squared column side length (80x80mm), as shown in Figures (3.4) to (3.7). The geometrical proportion of the waffle slab were chosen in accordance with ACI code 318M-19.

Table 3. 2 Specimens Reinforcement and Strengthening Layout Dimensions.

waffle slab category	Size of solid section (mm)	Slab No.	No. of CFRP strips	Area of CFRP (m^2)	Configuration of CFRP strips
IWS1	275 x 275	IWS1-1	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	IWS2-2	0	0.0	---
		IWS2b	10	0.25	grid

(a) Compersssion reinforcement (b) Tension reinforcement

Figure 3. 2 Waffle slab Steel reinforcement of IWS1.

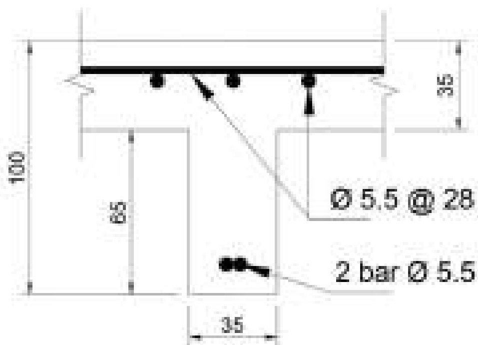


Figure 3. 3 Rib Steel reinforcement for IWS1 and IWS2.

Since most design Concrete Codes (ACI [17], CAN [62], and Eurocode EC.2 [18]) are basically different in major factor "Failure perimeter" (denoted in strength equations as U_2 or U_o). This important parameter was investigated in present research to study the punching shear control perimeter variations. This was the main reason why eight specimens were chosen for the first set of testing model (IWS1) and only two specimens were used for the second set of testing model (IWS2). Both critical punching envelopes are shown in Figures (3.4) and (3.6) and strengthening CFRP sheet accordingly. Punching shearing strength of the waffle slab is directly related to the size of the solid heads area above the supporting column. Small solid head areas can initiate/promote the formation of the punching shear cracks, will not develop conical shape failure, but extend beyond the solid heads area to outside shearing ribs and produce compound failure consist of rib diagonal shearing and slab crushing. Solid head areas limit length was determined by Al-Bayati [43] and Silva [50] to be less than and greater than 15% of the span in each direction from column, and greater than 2.5 times the slab effective depth from each column face (275 x 275), (515 x 515) respectively. Also, in order to avoid a bearing capacity reduction of the waffle slab, it is of fundamental importance that the punching shear cone is located within the solid head area of the waffle slab. The problem is that most design codes [CAN, NBR[19] EC2 and ACI318] are silent on this point and don't have any strict recommendation to the dimension of this solid head area [50]. A constant flexural reinforcement ratio of (0.96 % ~ 1%) was applied for all waffle slab specimens. Flexural reinforcements were reinforced by (ϕ 5.5 mm) diameter tested steel rebars with yield strength of 488.25 MPa, as shown in Figure (3.3). Tension reinforcements were placed mesh at approximately (28mm) spacing across the top slab regions, while all ribs were doubly reinforced. In general, 9.5 mm covers to reinforcements were used in all specimens. No shear reinforcement in the ribs has been used for the sake of results clarity and research focusing. An experimental program was conducted to consider the strengthening effect on the load carrying capacity, energy absorption, stiffness, deflection, crack patterns, and failure modes of waffle flat slabs. Altogether, ten two-way RC waffle flat slab specimens were prepared, to study the effect of the following variables on the punching shear behavior and strength: solid head without strengthening, solid head with strengthening, CFRP configuration, and area of CFRP sheets. specimens' dimensional properties, steel reinforcement, and CFRP strengthening detailing are listed in Tables (3.1) and (3.2).

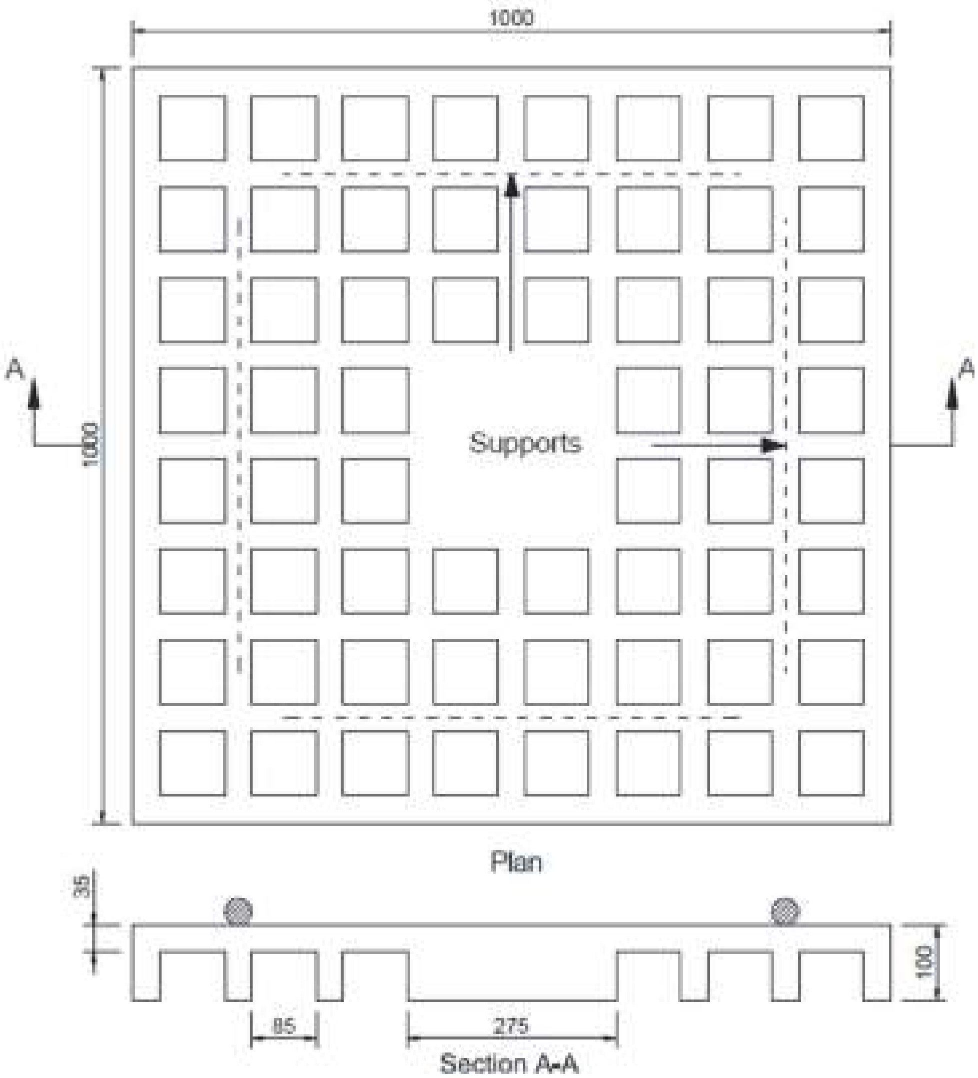


Figure 3. 4 Geometry of waffle slab specimen IWS1.

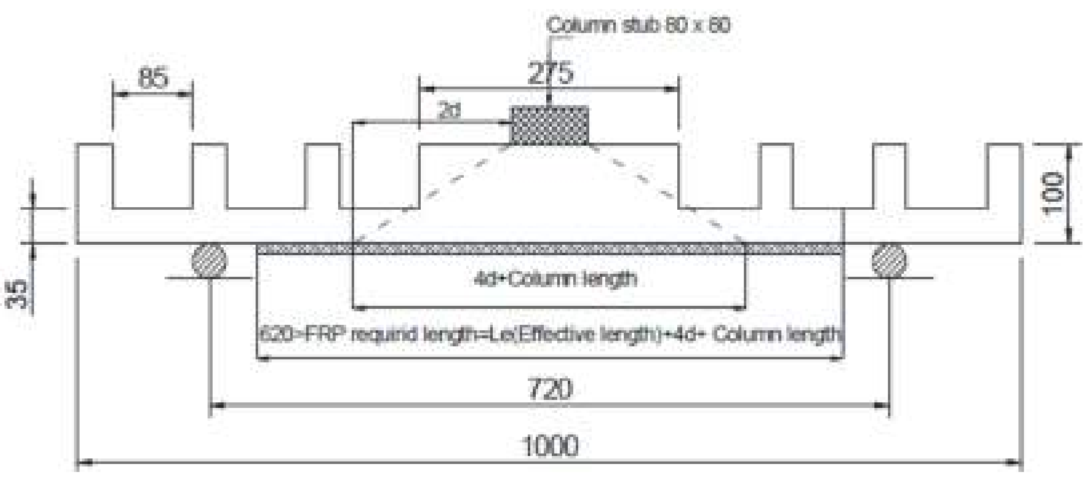


Figure 3. 5 Loading and support system of waffle slab specimen IWS1.

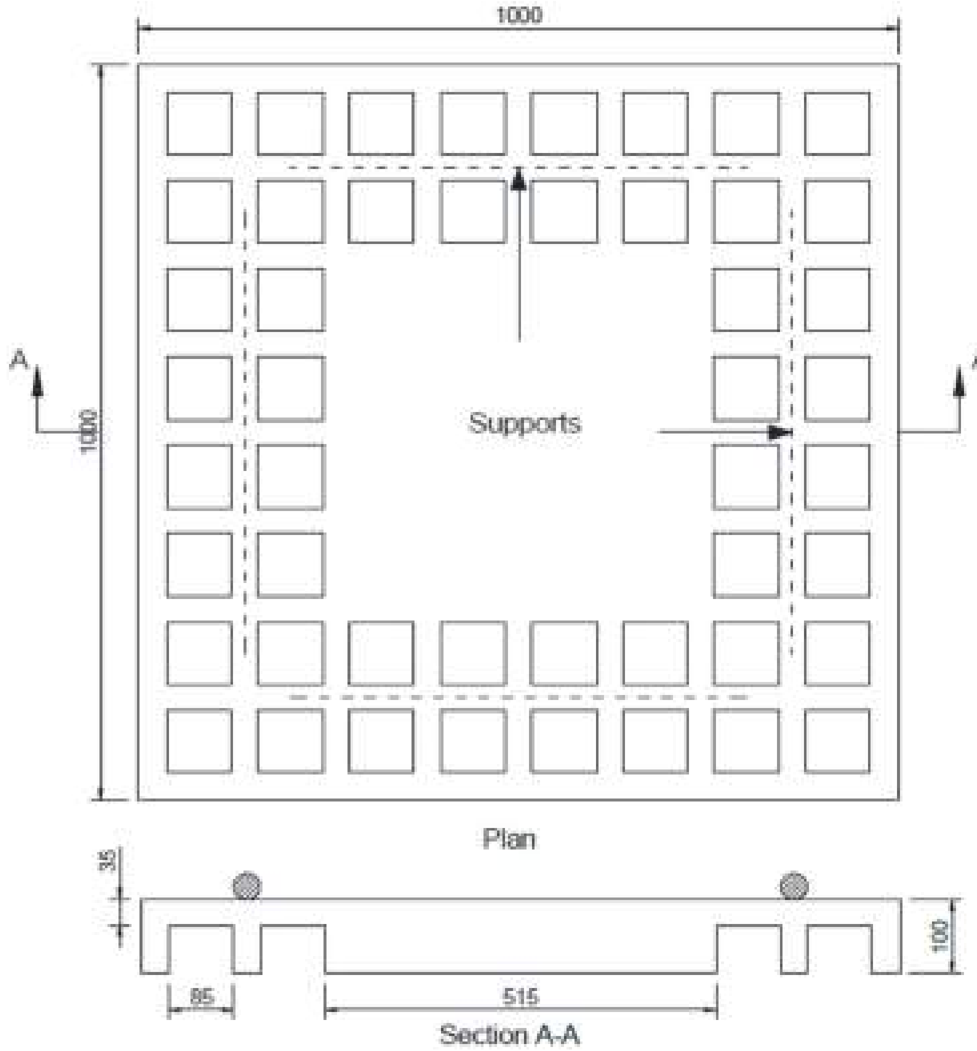


Figure 3. 6 Geometry of waffle slab specimen IWS2.

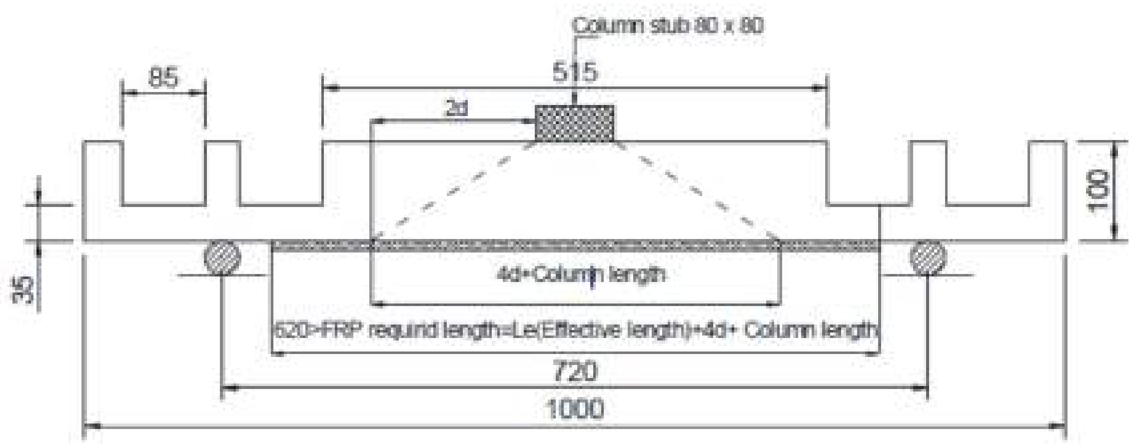


Figure 3. 7 Loading and support system of waffle slab specimen IWS2.

3.5 Materials

All tests on aggregates, trail mixes, concrete molds, freshly mixed concrete testing, and hardened concrete tests were carried out inside controlled environment in the Southern Technical University - Technical Institute of Amara / Heavy structures and construction materials laboratory.

3.5.1 Cement

In this research Ordinary Portland cement (Type I) labeled (Karasath) was used and it was stored in standard conditions to prevent exposure to moisture or dampness. Tables (3.3) and (3.4) show the physical properties and the chemical composition of the cement used during this work, respectively. The results were accomplished according to the requirements of the Standard specification of the American Society ASTM C150 [63].

Table 3. 3 Physical Properties of the Cement

Physical Properties	Test Results	ASTM C150
Specific Surface Area (Blaine Method) (m^2/kg)	315	≥ 250
Setting time (Vicat's method) Initial setting time:(hrs: min) Final setting time: (hrs: min)	 131 4:41	 ≥ 45 min ≤ 10 hrs
Compressive strength MPa For 3-day For 7-day	 14.4 22.1	 ≥ 12 MPa ≥ 19 MPa

Table 3. 4 Chemical Composition of Cement

Compound composition	Chemical Composition	Content % by Weight	ASTM C150
Lime	CaO	53.01	—
Silica	SiO2	17.8	—
Alumina	Al2O3	5	≤ 6 %
Iron Oxide	Fe2O3	3.1	-
Magnesia	MgO	3.15	≤ 6 %
Sulfate	SO3	2.03	≤ 3 %
Loss on Ignition	L.O. I	2.8	≤ 3 %
Insoluble residue	I.R	0.6	≤ 1.5 %
Lime saturation factor	L.S. F	0.7954	-
Main Compounds (Bogue's Equation)			
Tricalcium aluminates	(C3A)	8.01	-
Tricalcium silicate	(C3S)	36.67	-
Dicalcium silicate	(C2S)	23.43	-
Tricalcium alumina ferrite	(C4AF)	9.42	-

3.5.2 Fine Aggregate

Washed natural sand with a max size of (4.75 mm) from Al-zubair region in Basrah governorate result has been used in concrete mixes. Table (3.5) and Figure (3.8) shows the sieve analysis results and graph of the tested sand. Table (3.6) shows its physical properties of fine aggregate. The results indicate that the sand grading and the sulfate content are within the requirements of Iraqi Specification No.45/1984 [Zone 2] [61].

Table 3. 5 Sieve analysis (grading) of the used fine aggregate

No.	Sieve size (mm)	% Passing by weight	Limits of the Iraqi Specification No.45/1984 Zone 2
1	9.5	100.0	100
2	4.75	95.0	90-100
3	2.36	86.0	75-100
4	1.18	73.0	55-90
5	0.60	55.0	35-59
6	0.30	24.0	8-30
7	0.15	5.00	0-10

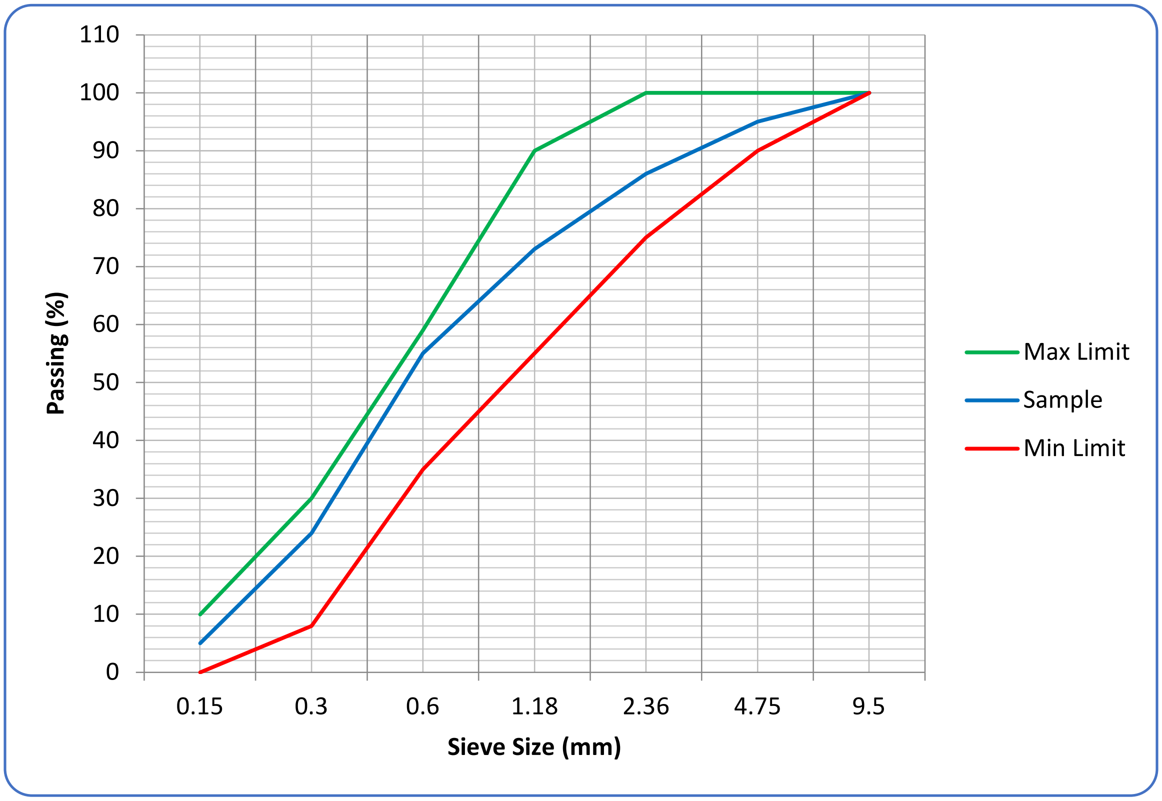


Figure 3. 8 Grading of fine aggregate.

Table 3. 6 Properties of Fine Aggregate

Physical properties	Test result	Limits of the Iraqi Specification No.45/1984
Specific gravity	2.65	-
Absorption%	1.00	-
Fineness modulus	2.541	-
SO_3 %	0.37	< 0.5

3.5.3 Coarse Aggregate

Coarse aggregate used was filtered across series of mechanical vibrators and selected with a maximum particle size of (9.5mm) from the Ajlat Gravel Query in Maysan governorate. Coarse aggregate was washed and exposed to air-dry for obtaining saturated surface dry (SSD) state. Table (3.7) displays the gradation of coarse aggregate utilized in this project. Test apparatus are shown in Figure (3.9). The findings of the physical are presented in Tables (3.8), and Figure (3.10) shows the sieve analysis results and graph of the tested coarse aggregate. Physical tests results indicate that the course aggregate grading and sulfate content match the standards of Iraqi Specification No. 45/1984 [61].

Figure 3. 9 Coarse aggregates (air dryed) sieve analysis.

Table 3. 7 Grading of the used coarse aggregate (gravel)

No.	Sieve size (mm)	%Passing by weight	ASTM C33-03
1	12.5	100.0	100
2	9.5	96.36	85-100
3	4.75	17.02	10-30
4	2.36	1.05	0-10
5	1.18	0.00	0-5

Table 3. 8 Physical and chemical properties of coarse aggregate

No.	Properties	Test results	Limits of the Iraqi Specification No.45/1984
1	Specific gravity	2.66	-
2	Absorption%	0.59	-
3	SO3%	0.090	< 0.1

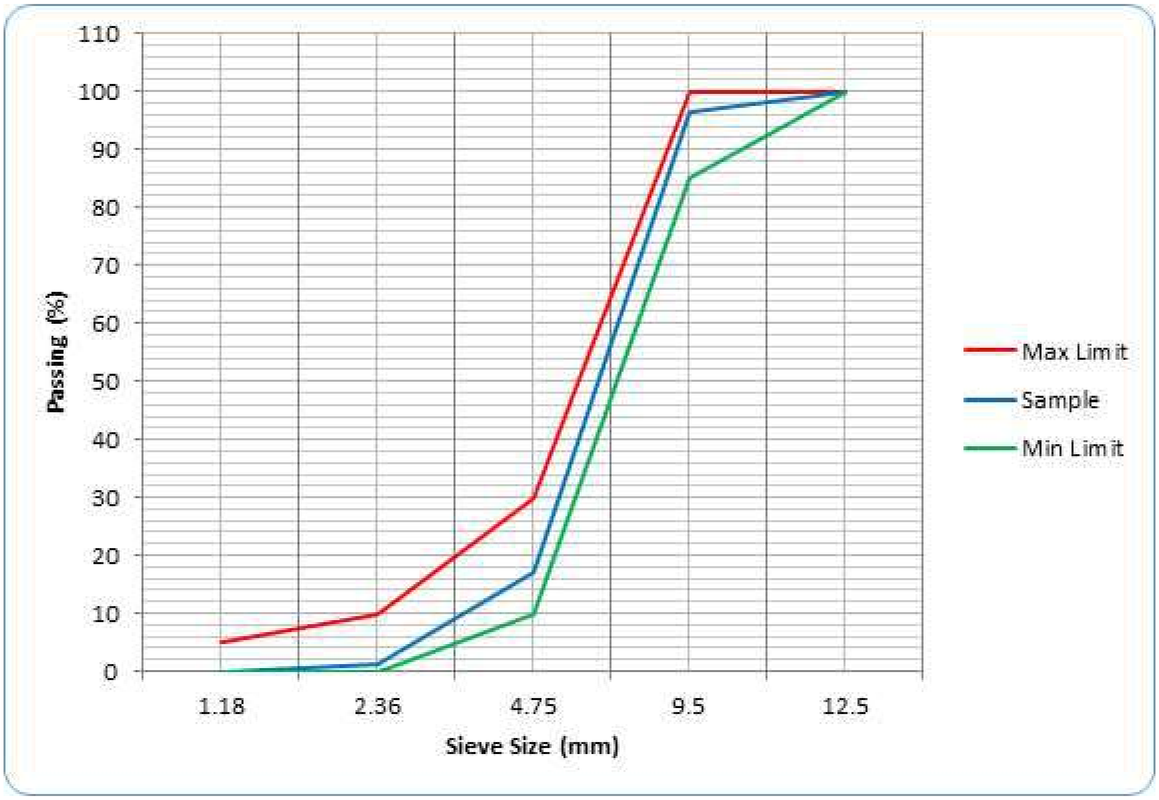


Figure 3. 10 Grading of coarse aggregate.

3.5.4 Water

Concrete has been mixed and cured using only potable water (Reverse Osmosis purified) from the local factory supplier, without the addition of any chemicals.

3.5.5 Superplasticizer

Sika ViscoCrete-5930, a high-performance plastic blend founded on ViscoCrete-5930 polymer with long strings engineered to optimize the performance of concrete's water content, was employed as the superior plasticizer here. In particular, it was designed for use in the production of precast, lightweight, and aerated concrete. To get the most durability and performance out of concrete, this effect has been exploited in high strength, low water/carbon proportion, flowable concrete mixes. ViscoCrete-5930 is not like the Sulfonated melamine and naphthalene formaldehyde-based superplasticizers that are often used because ViscoCrete-5930 causes particles to repel each other electrostatically. ViscoCrete-5930 initiates the same electrostatic repulsion, and the continual repulsion of the large side chain attached to the polymeric matrix increases the mixture's stability. ViscoCrete-5930 meets the standards set out by ASTM C494 [64], Type G. The technical details of the superplasticizer employed in this experiment are detailed in Table (3.9). However, the ViscoCrete-5930 is depicted in Figure (3.11).

(a) Superplasticizer container (b) Measuring tube

Figure 3. 11 Superplasticizer and Measuring.

Table 3. 9 The Properties of Superplasticizer

Technical Properties @ 25 C°	
Appearance and Color:	Turbid liquid – Yellowish.
Freezing point:	-1°C
Specific gravity	1.07 ± 0.03
Chloride content: BS5075	Nil
Basis	Aqueous solution of modified Polycarboxylate
Advantages	-Strong self compacting behavior. Therefore, suitable for the production of self compacting concrete. -Extremely high water reduction (resulting in high density and strengths). -Excellent flowability (resulting in highly reduced placing - and compacting efforts) -Increase high early strengths development. -Improved shrinkage- and creep behavior. -Reduced rate of carbonation of the concrete. -Improved Water Impermeability.
Packing and Storage	5 Kg, 20 Kg pails 200 kg drums temperatures between + 5 °C and + 35°C
Dosage	-For soft plastic concrete: 0.2 - 0.8 % liter by weight of cement. -For flowing and self-compacting concrete (S.C.C.) 0.8 - 2 % liter by weight of cement.
Standards	complies with BS EN934-2:2001 and ASTM C494, Type G and F.
***Supplied by the manufacturer**	

3.5.6 Reinforcing Steel Rebars

Ten Waffle slabs were tested using deformed steel reinforcing bars with diameters of (∅ 5.5 mm) as listed in Table (3.10). Three samples of rebar have been subjected to tensile tests the results, Static yield stress, and ultimate strength of the tested bars are summarized in Table (3.10). The testing machine is shown in Figure (3.12).

Table 3. 10 Reinforcing steel rebar Tensile test

Nominal Bar Diameter (mm)	Measured Diameter (mm)	Area (mm^2)	Yield Tensile Stress (MPa) Fy	Ultimate Tensile Stress (MPa) Fu
6	5.5	23.758	488.25	519.37

Figure 3. 12 Machine Used for Steel Bars.

3.5.7 FRP Strengthening Sheet

The applied strengthening sheets for waffle slabs were made of unidirectional Carbon Fiber Reinforced Polymer (CFRP) Roll sheets of type (SikaWrap- 300C) as shown in Figure (3.13). CFRP fibers didn’t show any plastic ductility (elongation yielding) before rupturing when tension force is applied, this might been related to the higher elastic modulus they possessed (220 GPa) compared with only (23.22 GPa) provided by concrete stratum. The stress-strain relationship in the tensile conduct of CFRP fibers is described as linearly elastic up to failure. The CFRP's characteristics were adopted as the manufacturer's specifications listed in Table (3.11) under the Technical Data Sheet of Sika (2017). The required CFRP length to transfer the stresses properly was estimated based on Monti and Liotta's [65] suggestions were presented in Appendix (I). For the required length of FRP (refer with: Figures 3. 5 and 3. 7).

Table 3. 11 CFRP Sheet strengthening composite properties[66].

Fiber orientatin Deg.	Weight g/m^2	Thickness mm	Tensile strength MPa	Tensile Modulus MPa	Elongation %
0º	300	0.167	4000	220000	1.7

Figure 3. 13 CFRP Roll sheets.

3.5.8 Bonding Epoxy-Resin

Sikadur-330 type impregnating resin was used in to bind the CFRP sheets to the concrete slab surface, consisting of two components (Resin part A + Hardener part B) as shown in Figure (3.14). The bonding epoxy's characteristics was carried according to the manufacturer's recommendations (Technical Data Sheet of Sika 2020), Table (3.12) list the tensile strength and elastic modulus of boding epoxy according to the Concrete Society Technical Report No.55, which states; a CFRP composite was created by the adhesive substance and the CFRP sheets combined. The excellent adhesive properties of epoxy resins are due to the attractive forces between the epoxy resin and the top-surface of the roughened concrete substrate. These forces are usually polar forces (direct bonds) that can form between reactive sites in the resin and reactive (or polar sites) on the top-surface of the concrete substrate.

Table 3. 12 Mechanical Properties of epoxy resin[67].

Appearance	Mixing ratio	Open time (min)	Tensile strength (MPa)	Tensile E-modulus (MPa)
Part A: white Part B: gray	A: B 4: 1	30 (at +35°C)	30	4500

Figure 3. 14 Two Components of Epoxy Resin.

3.6 Normal Strength Concrete

Normal strength concrete was used to cast of ten Waffle slabs eight of are parametrized concrete and the others are reference slabs. Four trail mixes were constructed with various preparations to attain the required design compressive strength for this type of concrete (characteristic strength), which was (30.0 MPa). The concrete was designed using the ACI-211.1 [68] approach. In this trial, all mixtures were different in compressive strength with standard deviation of (3.887 MPa) was recorded. All of the mixtures exceeded the acceptable ranges of slump rang value (20-75) mm provided by ACI-211.1. This return to the fact added superplasticizer has change the flowability of the concrete mixture. The trial mixtures is shown in Table (3-13). Mix design (No.3) was chosen, since it provides the nearest acceptable results of compressive strength (30.5).

After reaching the fourth (4) trail mix which gives almost the target strength, then began to replace 10% and 15% of the cement weight and coarse aggregate with a normal weight aggregate, and the compressive strength of the two mixtures was more than the target strength, then super plasticizer was added by (0.8 - 2 %) in order to fix the target compressive strength and to facilitate the concrete casting the narrow ribs. Also, other trail waffle slab specimens were casted with the same mix proportions, and the compressive strength ware rechecked.

Table 3. 13 Trail mixes for normal strength concrete

Mix	Cement Kg/m³	Sand Kg/m³	Gravel Kg/m³	w/c	Water l/m³	SP L/m³	Target comp. MPa fcu	The Obtained comp.
MIX-1	410	735	975	0.45	185	3.0	30.0	27.65
MIX-2	420	765	1102	0.46	193	3.5		29.83
MIX-3	438	660	990	0.48	210	4.5		30.50
MIX-4	440	850	950	0.44	194	4.5		35.81

3.7 Proportions of the Concrete Mix Design and Testing Sequences

More than four trail mixes were made to reach the mix that achieves suitable requirements desired strength of (30.0 MPa), workability, and durability. For the concrete tests, three (150*150*150 mm) cubes, a prism with a dimension of (100*100*500mm), and three (100*200 mm) cylinders were prepared from each trial mix, as shown in Figure (3.15). The compressive strength, modulus of rupture, and splitting tensile strength tests were specified at 7 days.

Waffle slab specimens were made of normal weight concrete mixtures of normal range (2267 kg/m^3), with a mix the proportion of [1:1.51:2.26] of ordinary Portland cement: fine aggregate of maximum size of 4.75 mm: coarse aggregate of maximum size of (9.5 mm) with a water/cement ratio (w/c) of 0.48. It was designed to achieve a concrete compressive strength of about (30 MPa) at 28 days.

Waffle slabs were designed to fail under punching shear and then strengthen with CFRP sheets with different layout arrangements. Concrete mix is designed to achieve compressive strength (30 MPa) at 28 days, with a cement content of 438 kg/m^3, use a plasticizer of 1% by weight of cement to facilitate the concreting of the narrow ribs, shown in Table (3.14). all component material were checked physically and chemically. The inspection of materials included testing of cement according to the ASTM standards, while the other testing, such as the sieve analysis for sand and gravel according to the Iraqi specification No. 45/1984. Also, superplasticizer additives, submit to the requirements of ASTM C494 [64].

Table 3. 14 Concrete mix design properties.

Parameter	Quantity (kg)
Cement (kg/m^3)	438
Water (Liter/m^3)	210
Superplasticizer (Liter/m^3) (1 %)	4.5
Coarse Aggregate (kg/m^3)	990
Fine Aggregate (kg/m^3)	660
Slump (mm)	125


(a) Casting of testing samples


(b) Curing of testing samples


(c) Weighting of concrete samples

(d) Testing of cube samples.

(e) Testing of cylinder samples.


(f) Concrete prisms after testing.

(g) Testing machine outputs

(h) Testing machine monitoring

Figure 3. 15 Testing of concrete samples.

3.8 Mold Preparing, Castings, Finishing, and Curing

In order to cast the concrete waffle slabs specimens, wooden (plywood) molds were designed and fabricated inside the same laboratory building. Casting molds fabricated of plywood are 18 millimeters thick, and the length, width, and thickness of each mold were respectively (1000x1000x100mm). Additionally, the side frame is made from Hollow Steel Section (HSS) with squared cross-section. These steel framed molds assembled and connected by threaded bolts that can be easily removed in order to strip off the hardened waffle slabs after casting after each casting course. Before the reinforcement rebars cages were set in place and maintained a specific concrete cover from all sides (10mm), the formworks were wiped down and oil-lubricated for optimal performance. Two of these molds as shown in Figure (3.16) with steel reinforcement and styro-board blocks.

Figure 3. 16 Specimens molds, waffle blocks, and steel reinforcement.

3.8.1 Concrete Specimen Mixing and Casting

Concrete mixing was conducted inside the same laboratory. Rotary concrete mixer with a capacity ($0.25m^3$) was used for mixing the concrete cement and all dry ingredients mixed together (sand mixed alone with cement until they have been homogeneity before adding the other ingredient. Between (2.0-5.0 min) intervals were maintained between ingredients additions. Mixing water was added after (5.0 min) until the concrete mix became homogeneity in color and texture to avoid segregation of components. Mixing speed of rotary drum were also maintained almost steady for the same reason. The coarse aggregate was used in a saturated surface dry condition (SSD). Before mixing, the remaining concrete from the previous batch was carefully cleaned off from inside mixing drum. A damping cloth was used to wipe-out the interiors of mixing drum wall and blades before placing the dry components.

Freshly mixed concrete was placed directly (avoiding segregation) in casting molds (1000x1000x100mm) as shown in Figure (3.17). Total time, from adding water to mixture to finishing of mold surface shown in Figure (3.17), was kept under (30 min) in normal temperature environments. Electric vibrator was used directly after casting and leveling of freshly mixed concrete specimens as shown in Figure (3.17) in a period not more than 10 min and under same temperature conditions. The casted waffle slab has was carefully covered with plastic sheet for (24hr) to prevent evaporation of surface water and premature shrinkage cracks. In 2nd day (after 24 hours), waffle slabs and other specimens have been stripped from molds and covered with canvas sheets as curing technique as shown in the Figure (3.18).

Figure 3. 17 Specimens casting, vibrating, and finishing.

Figure 3. 18 Curing of waffle slab specimens.

3.8.2 Curing of Specimens

The 1st group of ten waffle slabs specimens (including reference samples) were cured with fully saturated canvas-sheets for 28 days, Figure (3.18), while the 2nd group of cubes, prisms and cylinders samples were submerged in water tank, as shown in Figure (3.19). The ten specimens were cured for 28 days. The same duration of curing was applied to the second group of samples. No visual appearance of surface cracks is monitored or recorded, since waffle slab samples weren't subjected to sever wet and dry cycles. Also, because of controlled environmental conditions (Temperature) inside the testing laboratory[69].

Figure 3. 19 Curing of concrete samples.

3.9 Testing of Fresh Concrete (Workability)

Standard slump tests were used to measure the workability of freshly mixed concrete. Cone mold dimensions according to ASTM C143-18 standards [70] have a height of 12-in (300 mm), a bottom diameter of 8-in (200 mm) and an upper diameter of 4-in (100 mm). Tests were applied to test the workability of normal strength concrete (NSC). The slump flow test has been performed according to, see Figure 3. 20.

Figure 3. 20 Workability tests, Slump.

3.10 Testing of Hardened Concrete

3.10.1 Compressive Strength (f_{cu}) and (f′c)

The compressive strength test is determined according to ASTM C109-18[71] where standard cubes (150x150x150mm) and cylinders (100x200mm). Concrete compressive strengths conducted using universal compression testing machine (Liya Co. Brand) of 2000 kN capacity, available inside the same laboratory building, as shown in Figure (3.21). Table (3.15) shows the mechanical properties of concrete.

Figure 3. 21 Compression strength test.

Table 3. 15 Tests of cube and cylinder specimens

Batch	Compressive strength F_{cu} (MPa)	Compressive Strength f′c (MPa)	Modulus of Elasticity (Ec)* (MPa)
Normal concrete	30.5	26	23965

* Ec = 4700 √ f′c In Map (ACI 318M -19)

3.10.2 Splitting Tensile Strength (f_t)

Splitting tensile strength (the indirect tensile strength) test has been carried out on standard concrete cylinders (100x200 mm) according to ASTM C496-18 [72], where the load has been applied perpendicular to the longitudinal axis of the cylinder using two steel plates one at bottom of the cylinder and the other at its top using the same universal compression testing machine (Liya Co. Brand) of 2000 kN capacity, available inside the same laboratory building, as shown in Figure (3.22). Cylindrical specimens were tested to failure occurrence as shown in Figure (3.22). The test results were the average of three specimens (1.96 MPa). The splitting tensile strength for three specimens is calculated by the following equation

$$ft = \frac{2P}{\pi DL} \qquad 3.1$$

where:

ft = splitting tensile strength (MPa).
P = failure load (N).
D = diameter of cylinder (mm).
L = length or height of cylinder (mm).

Figure 3. 22 Split tensile test machine

3.10.3 Flexural Strength (Modulus of Rupture fr)

Concrete prisms 100*100*500 mm have been cast for this test using flexural machine as shown in Figure (3.23), available inside the same laboratory building. Prisms were tested using two points loading according to ASTM C78-02 [73]. The test results were the average of three specimens (3.72 MPa). The modulus of rupture for three specimens is calculated by using the following formula:

$$fr = \frac{PL}{bd^2} \quad 3.2$$

Where:

fr = modulus of rupture (MPa).
P = failure load (N).
L = span length between supports center to center (mm).
b = width of prism cross section (mm).
d = depth of prism cross section (mm).

Figure 3. 23 Flexural testing machines.

3.11 Preparation of Concrete Surface and Bonding Process

It is crucial to properly prepare the concrete surface before applying the CFRP to create a strong bond between CFRP sheets and concrete [74]. The bond ensure that the force applied to the member of the structure is efficiently transferred to CFRP. For two days, at laboratory temperature, the model that was suggested for reinforcement with CFRP sheets was dried after being cured. For a suitable flat concrete surface for a good CFRP-Concrete bond, marked areas of the CFRP sheets were milled to remove layers of substrate or mortar defects, as shown in Figures (3.24). Cleaning the waffle slab samples and removing the grinding dust, off adhesion-impairing deposits dirt when attaching the CFRP sheets.

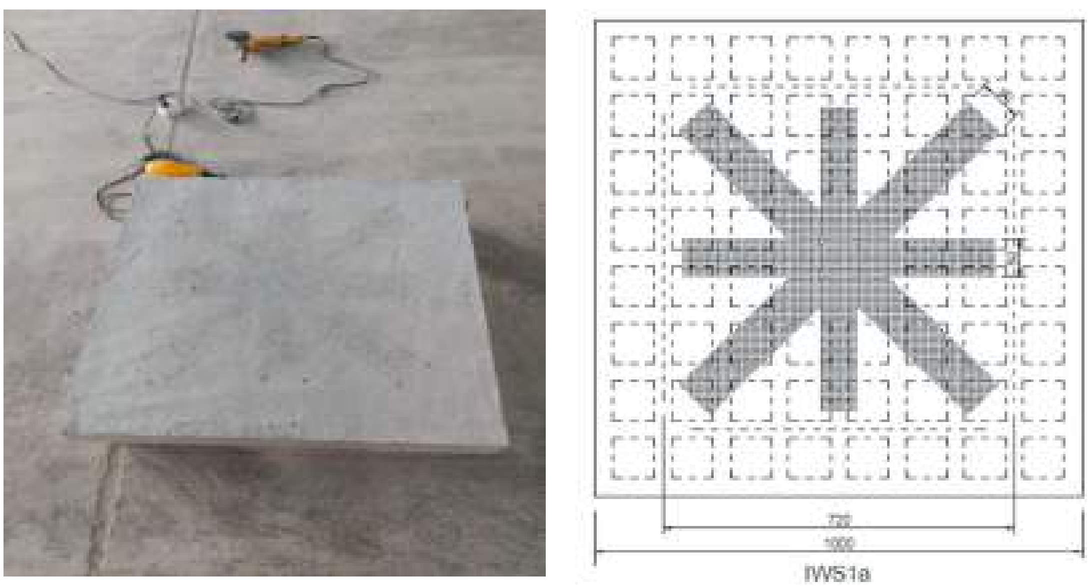


Figure 3. 24 Preparing of Surface of Concrete.

The next step was applying the adhesive material to both the CFRP sheets and the prepared concrete substrate. Then, the CFRP was placed at the specified positions. A roller was passed backward and forward over the CFRP sheets to squeeze the resin from the sides and eliminate air bubbles that could have weakened the CFRP–concrete bond in order to achieve the same level of adhesion throughout the CFRP sheets. Finally, after completing the CFRP installation, and prior to the testing date, the waffle slabs were painted with white color to facilitate the detection of the first crack and make crack patterns more visible, as shown in Figure (3.25) and (3.26).

The effect of following variables on the punching shear behavior and strength are investigated:

1. Solid head without strengthened
2. Solid head with strengthened
3. CFRP Configuration
4. Area of CFRP strips

For the first variable (Solid head without strengthened), the current study used only two categories of waffle slabs of each model (IWS1, IWS2). The waffle slab (IWS1), with a solid head of 275 mm, was supported on both edges of the x-direction and y-direction (the length of the solid head is less than 15% of the clear span between columns). The waffle slab (IWS2), with a solid head of 515 mm, was supported on both edges of the x-direction and y-direction (the length of the solid head larger than 15% of the clear span between columns or the solid section extends for a distance at least 2.5 times the slab effective depth from each column face).

While for the second variable (solid head with strengthened), two specimens are used in this study and they are (IWS1b and IWS2b). Same Configuration and CFRP area. For the third variable (configuration of CFRP), six configurations (IWS1a, IWS1b, IWS1c, IWS1d, IWS1e, and IWS1f) are used, with remain same area for all, and the CFRP sheet strip-width were changed according to each configuration, and were 40 mm, 80mm, 100 mm, 150mm, and 200 mm, respectively. as shown in Figure (3.25). The last variable (Area of CFRP), two areas are used in this study and they are (0.25 and 0.15, m^2).

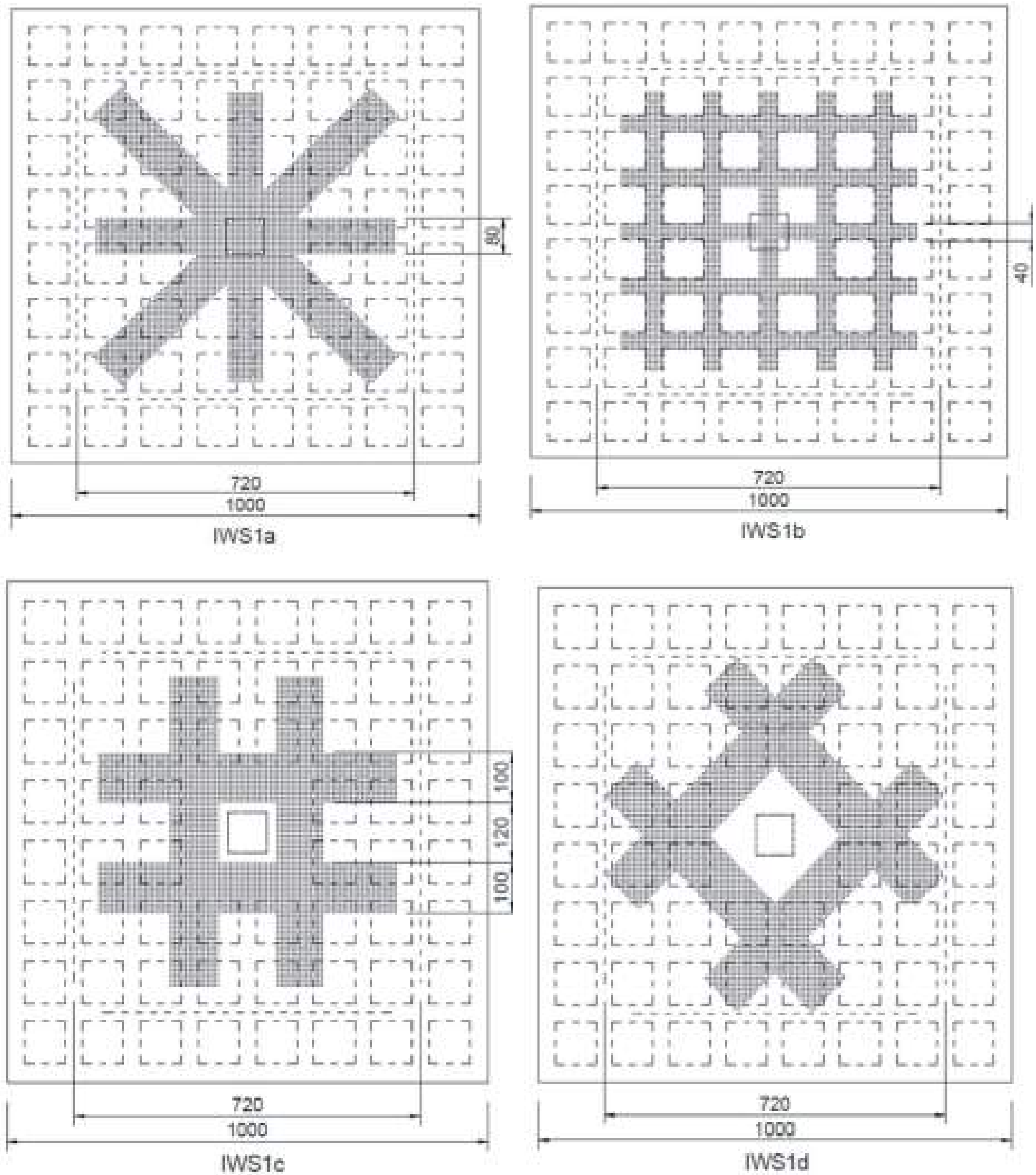


Figure 3. 25 Waffle slabs CFRP strengthening layouts

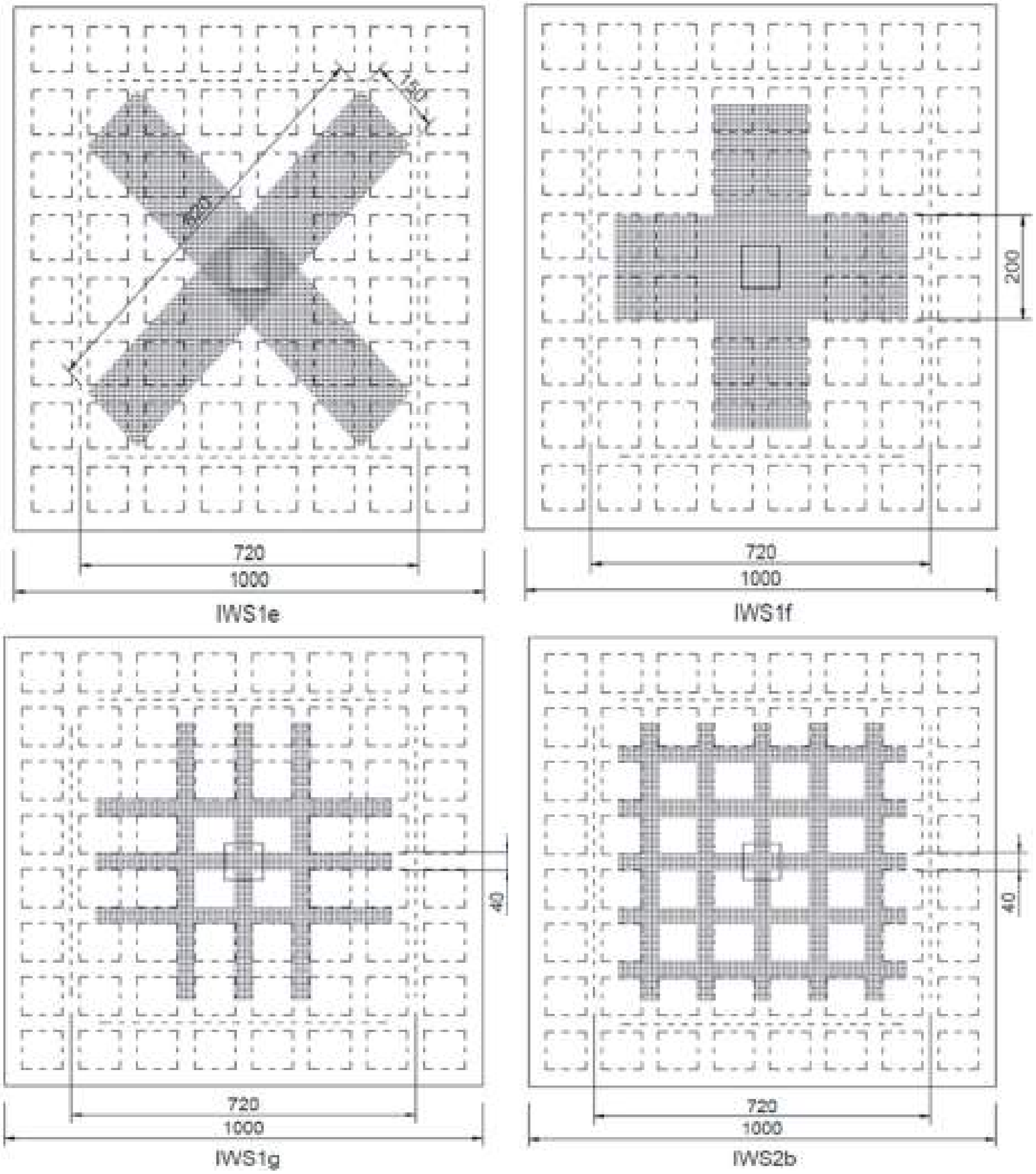


Figure (3.25) Continued

The normal strength concrete with a strength of (30) MPa was used in 28 days for all waffle slab samples. Use a plasticizer of 1% by weight of cement to facilitate the concreting of the narrow ribs, Steel reinforcement with 5.5 mm diameter were spaced at 28 mm(mesh) apart on the top surface of the slabs for flexural reinforcement ratio of (0.96 % ~ 1%), Each rib's both distribution reinforcement consisted of two steel rebars, each measuring 5.5 mm in diameter and running in a direction parallel to the x and y axes. was applied for all waffle slab specimens. No shear reinforcement in the ribs has been used for the sake of results clarity and research focusing.

Figure 3. 26 Specimens' paintings, CFRP bonding, and marking.

3.12 Waffle Slab Samples Preparations and Testing Procedure

All waffle slabs were tested using the hydraulic testing machine, as shown in Figure (3.27), with a maximum capacity of 600 kN. Firstly, slabs were seated on supported frame. To tests were performed in inverse manner (the top slabs faced down), and were loaded centrally were carried out under monotonic/static concentric loading, as shown in Figure (3.28). The reference waffle slabs were painted in white color to facilitate the detection of the first crack and make crack patterns more visible, as shown in Figure (3.29). The waffle slabs were labeled and marked according to designation mentioned in Table (3.2), location of the support lines and loading plate location accordingly. Waffle slab specimens were placed at the testing machine and adjusted so that the centerline, supports, and load arms were fixed at their locations. The slabs are tested under static loads, loaded in successive increments, up to failure. For each increment, the load is kept constant until the required readings are recorded, as shown in Figure (3.29). Waffle slabs were tested according to Load Incremental Procedure (LIP) so that the waffle slab deflect under constant loading rate a monotonic/static load to the point of failure. LIP was conducted to determine the first cracking loads, ultimate load and corresponding deflections on the basis of which the waffle slab would be subjected to a static loading. All results will be listed and presented in chapter four with their corresponding curves and tables.

Figure 3. 27 Testing Framed machine and waffle slab specimen.

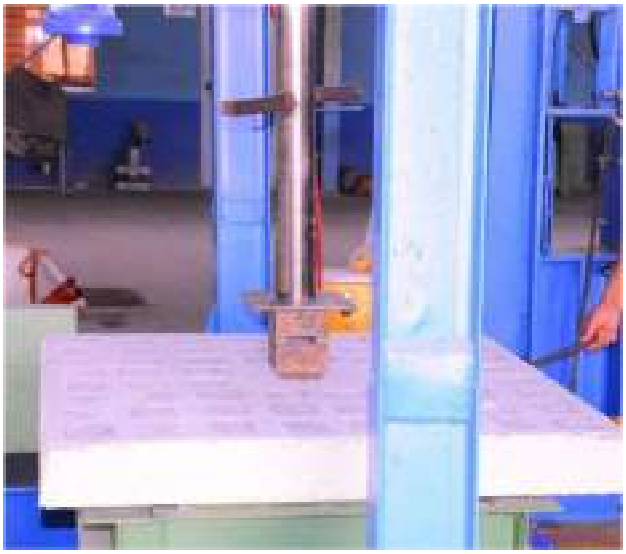


Figure 3. 28 Testing procedure.

Figure 3. 29 Dial Gauge Deflection.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the test results and a description of ten waffle slabs designed to failure in punching shear. So that the structural behavior and ultimate strength of waffle slabs with a solid region (solid head) could be assessed, ten waffle slabs supported were molded with dimensions of (1000x1000x100mm) (length x width x depth). Column idealized as a square column with sides of 80 x 80 mm positioned at the center of the slabs. By idealizing the negative bending distribution in the area around the column, where the largest bending moments and the maximum shear stresses occur, the slab dimensions were established.

4.2 General Behavior of Waffle Slabs Under Loading

The structural performance of strengthened waffle slabs using externally bonded CFRP strips is directly affected by boundary conditions (layout, configuration and alignment), and any alterations to these have a large impact on the final performance of the CFRP strengthened two-way waffle slabs. Therefore, parametric study based on five factors namely; CFRP area, CFRP width, CFRP distribution, and solid region dimension.

General behavior (crack pattern, vertical displacements, and failure mechanism) of all waffle slabs are almost identical. When the load is applied to the waffle slab sample, the first visible crack (bending cracks) is observed at the tension face of the tested slab vanged from 48% to 77% of the ultimate load as shown in Table (4.1). By installing CFRP strips on the tensile surface of the concrete slab, the effective tension area and the tensile resistance of the strengthened section increased compared with those of the control specimen. The strengthened most samples showed more brittle failure than the control specimens, which can be seen in their load deflection curves in Figures (4.1) and (4.2). However, CFRP strengthening increases the slab stiffness while enhancing the load capacity, which may reduce a specimen's deflection, and energy absorption of some specimens. None of the samples failed due to CFRP rupture, which shows that the CFRP strips did not reach maximum tensile strength.

It is noted that the first crack loads increase in vanyed from 4.26 % to 67.02 % compared to the value of the crack load in the reference waffle slab. While the increase in the final load vanged from 2 % to 47.1 % compared to the final load in the reference waffle slab as shown in Table (4.1). It was observed that all waffle slab samples were punched in the snap position. In case of failure, the slab could no longer bear additional load. The general structural behavior of waffle slabs is different in terms of crack patterns when a concentrated load is gradually applied over the upper surface of the waffle slab sample.

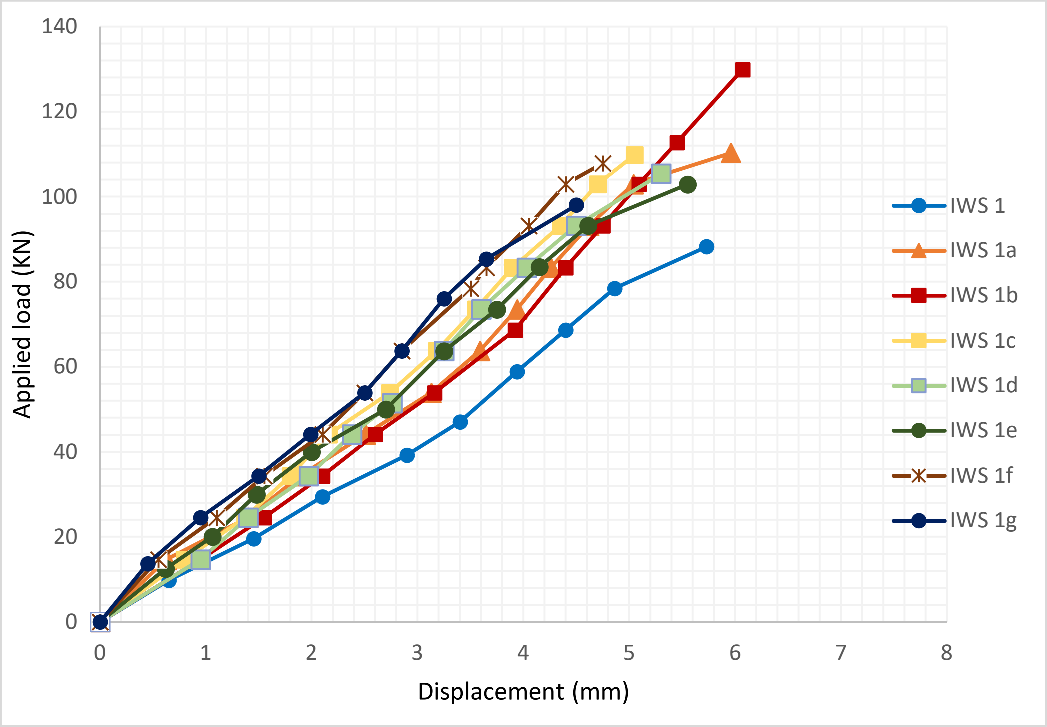


Figure 4. 1 Comparison of Load-Central Deflection Curves

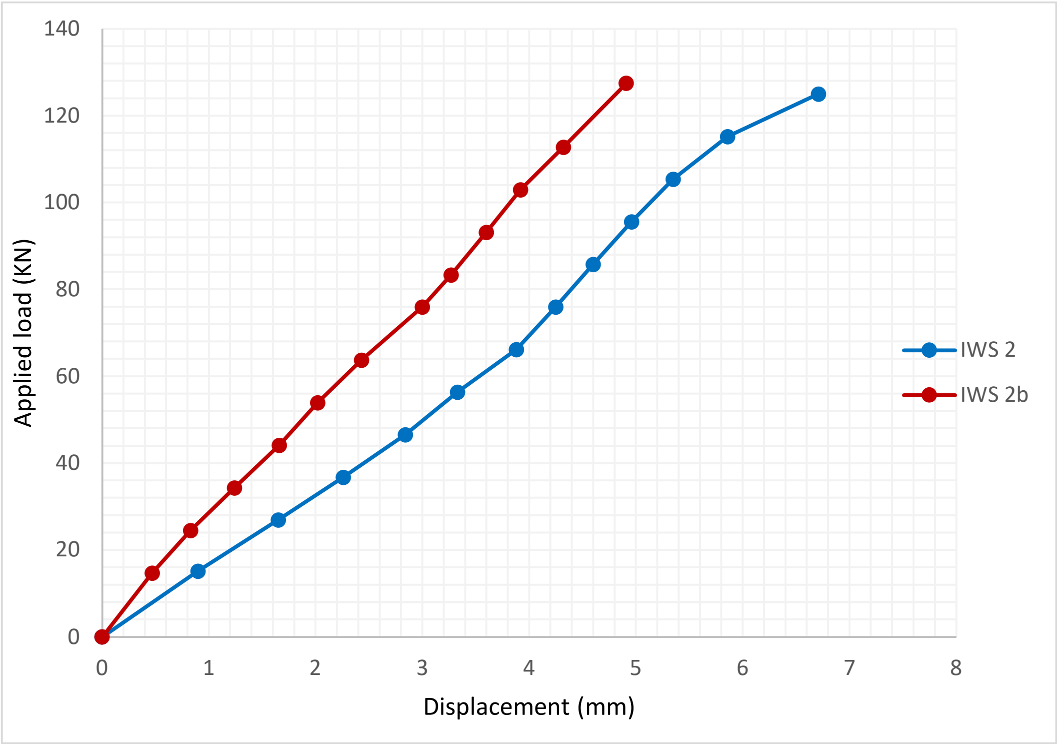


Figure 4. 2 Comparison of Load-Central Deflection Curves

Table 4. 1 Testing results of waffle slabs and mode of failures

Specimen category	Specimen	First crack load (Pcr) (kN)	Ultimate Load (Pu) (kN)	Ultimate deflection (mm)	Pcr/P_u %	Failure mode
IWS1	IWS1*	47.00	88.30	5.73	53.22	Flexural punching
	IWS1a	54.00	110.30	5.96	48.95	Flexural punching
	IWS1b	68.60	129.90	6.07	53.80	Flexural punching
	IWS1c	63.70	109.80	5.05	58.00	Flexural punching
	IWS1d	51.48	105.40	5.30	48.84	Flexural punching
	IWS1e	49.00	103.00	5.55	47.57	Flexural punching
	IWS1f	78.50	107.90	4.75	72.75	Flexural punching

	IWS1g	76.00	98.10	4.50	77.47	Flexural punching
IWS2	IWS2 *	66.20	125.00	6.71	52.96	Flexural punching
	IWS2b	76.00	127.50	4.91	59.60	Flexural punching

* Reference waffle slabs.

4.2.1 Stiffness

Stiffness refers to the ability of a material, component, or structure to resist deformation under external force. In order to find the stiffness of the reinforced concrete members, there is one type of stiffness which will be measured in this study namely secant stiffness. According to Sullivan, Calvi, & Priestley [75], in the inelastic range, the secant stiffness, relates between the ultimate load (Pu) and its corresponding ultimate displacement, Δu. The equations used are shown below:

$$\text{Secant stiffness} = \frac{\text{Pu}}{\Delta \text{u}} \qquad 4.1$$

The stiffness for all reinforced concrete waffle slabs was offered in Table (4.2). the stiffness of the reference waffle slabs without CFRP strips (IWS1, IWS2) was (15.41, 18.62 KN/mm) respectively. The results showed that for the unstrengthened waffle slab when the solid area was reduced from (515x515 mm) to (275x275mm), the waffle slab stiffness decreased by (19.31%). Also, the test data displayed in the table exhibited that the reinforced concrete waffle slabs containing CFRP strips stiffness increases compared to the reference waffle slabs. Where CFRP strengthening layout (configuration or arrangement) play a role in increasing the stiffness of concrete slabs, where the rate of increasing vanged from 19.93 % to 47.37 % compared to the reference waffle slab (IWS1). Also, for the waffle slab (IWS2), when strengthening, its stiffness increased by a percentage (39.41%).

Table 4. 2 Stiffness of the tested waffle slabs.

Specimen category	Specimen	Secant Stiffness (kN/mm)	Increasing ratio of Secant stiffness (%)
IWS1	IWS1*	15.41	/
	IWS1a	18.50	19.93
	IWS1b	21.40	38.87
	IWS1c	21.74	41.07
	IWS1d	19.88	29.00
	IWS1e	18.55	20.37
	IWS1f	22.71	47.37
	IWS1g	21.80	41.46
IWS2	IWS2 *	18.62	/
	IWS2b	25.96	39.41

4.2.2 Energy Absorption

Energy absorption is a measure of a material's ability to absorb energy and undergo plastic deformation without fracturing. The area under the load-displacement curve represents the total energy absorbed by the material during the deformation process [76]. Therefore, the larger the area under the curve, the greater the energy absorption capacity of the material. Table (4.4) presents the energy absorption results for all tested waffle slabs.

The results indicate that the Energy absorption decreased with reducing the size of the solid section, it was observed that the size of the solid section has a pronounced influence on Energy absorption, in comparison with Specimen IWS2, with a 515 mm solid section, the specimen IWS1 provided a decrease in Energy absorption of 28.76% with a decrease solid section to 275 mm, as given in Table (4.3).

Table 4. 3 Energy absorption for all waffle slabs.

Specimen category	Specimen	Energy absorption (kN.mm)	ratio in energy absorption (%)
IWS1	IWS1*	292.13	/
	IWS1a	337.00	15.35
	IWS1b	342.12	17.11
	IWS1c	280.80	-3.87
	IWS1d	272.18	-6.82
	IWS1e	302.27	3.47
	IWS1f	253.3	-13.29
	IWS1g	239.10	-18.15
IWS2	IWS2 *	410.07	/
	IWS2b	312.96	-23.68

It was observed that all samples of waffle slabs strengthened with CFRP showed a decrease in their energy absorption capacity by a percentage ranging between 3.87% and 23.68%. However, three specific specimens (IWS1a, IWS1b, and IWS1e) exhibited a positive outcome with an increase in their energy absorption percentage by 15.35%, 17.11%, and 3.47%, respectively, compared to the unstrengthened waffle slab. This means that the CFRP distribution technique on the surface of the waffle slab for these specimens was effective and the best in increasing the energy absorption compared to other specimens that have the same CFRP area but with a different configuration. It was concluded that the best arrangement of CFRP sheet strips to increase energy absorption depends on two major factors, distributed area, and orientation. As shown in the results (Plus & cross and grid) were the best configuration for increasing the energy absorption and also (cross) was the least preferred due to the limitation of the stiffening area and orientation (45 with the direction of reinforcement).

4.3 Effect of Solid Head

4.3.1 Ultimate Load

It is significant to notice that waffle slab specimen self-weights were not taken into account. It was observed that waffle slab specimens IWS1 and IWS2 were punched in a sudden mode of failure (brittle failure). When a slab failure, it is no longer able to support further weight. The punching failure ultimate load from the tests is shown in Table (4.1). The results indicate that the overall punching shear strength decreases with reducing the size of the solid section. It was observed that the size of the solid section has a pronounced influence on punching strength, in comparison with specimen IWS2, with a 515 mm solid section, specimen IWS1 provided a decrease in ultimate punching load of 29.36% with a decrease solid section to 275 mm, as given in Figure (4.3). This would be expected because of the decreasing portions of the potential failure surface of the failure formed and discharged within the solid sections. due to losses on the failure surface, as it extended into the waffle portion, there was an incomplete failure. When the solid region is small at the periphery of the column, the compression strut of the ribs outside the rigid region may reach its ultimate capacity first. This situation results in punching failure being initiated outside the solid area for specimen IWS1, as shown in Figure (4.4). 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.

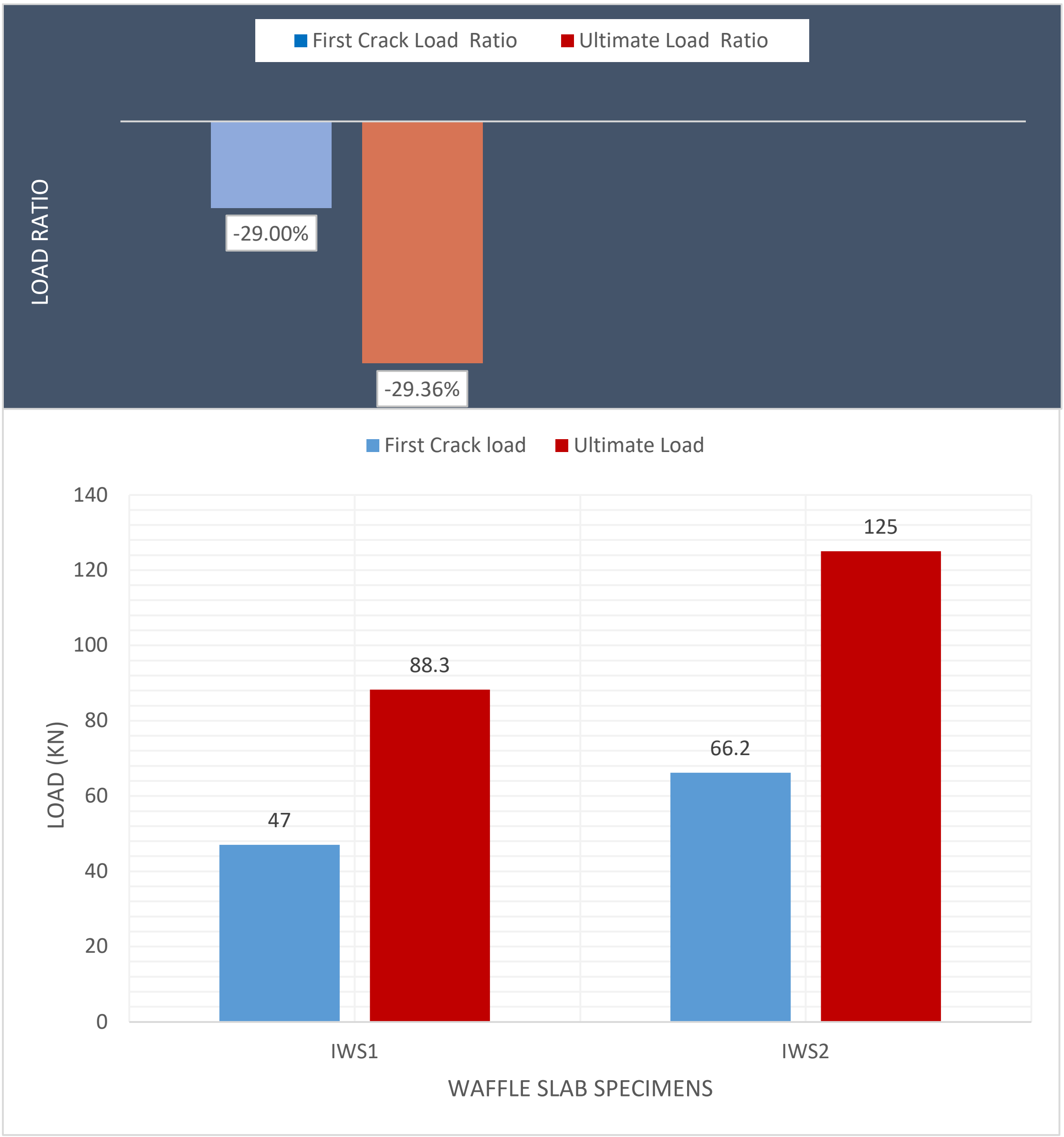


Figure 4. 3 First Crack Loadings Vs Ultimate Failure Loadings.

The reduction of the punching capacity depends on the loss of the shear area, which depends on the size of the solid section. A decrease in punching force will not occur if the solid area is large, as shown in Figure (4.4).

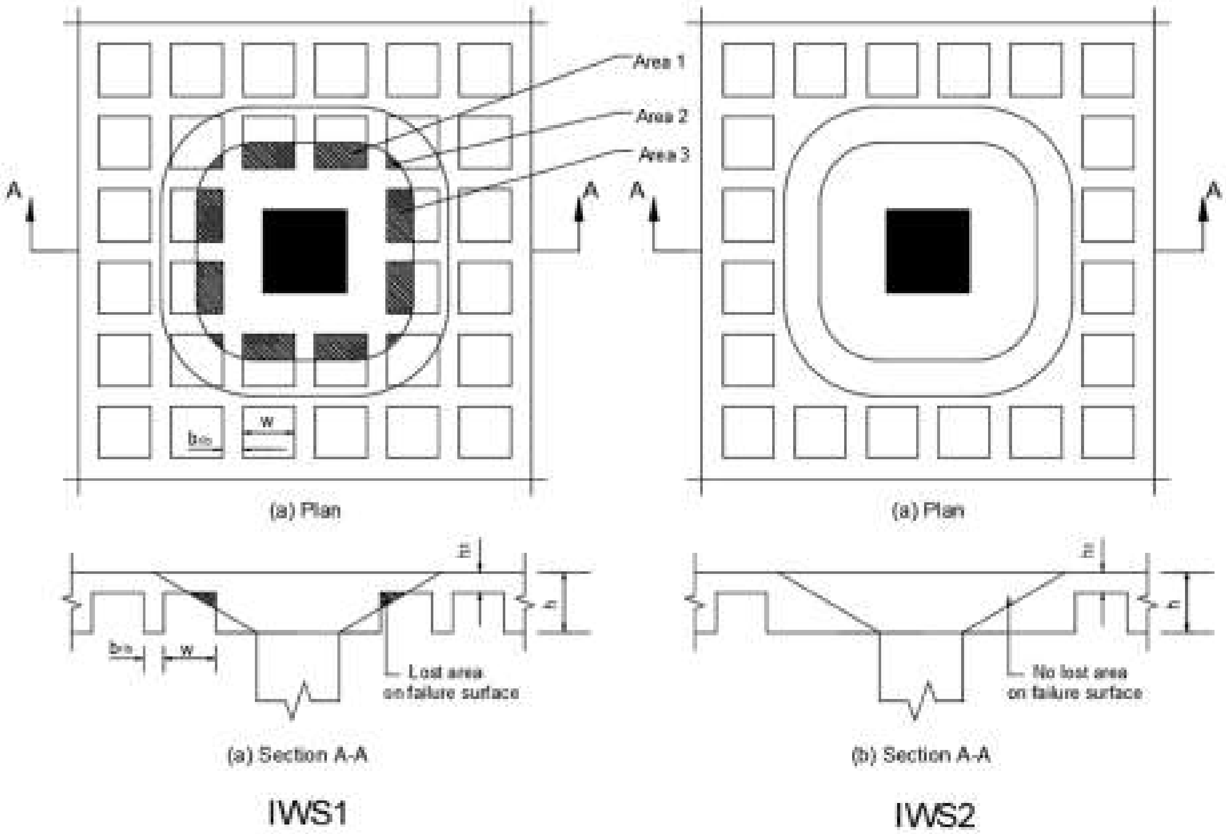


Figure 4. 4 Proposed punching failure surfaces with losses.

4.3.2 Vertical Displacements

The typical load and deflection curve recorded in tests is shown in Figure (4.5). The deflection is measured at the center of the waffle slabs. Note that the slope of the load–deflection curves indicate stiffer behaviour in the sample IWS2 compared with the specimen IWS1 as shown in Figure (4.5). The load and deflection curve can be thought of as two straight lines inclined at two different angles. The slope of the first line segment is steeper slope compared to the second line segment. It is believed that this phenomenon is due to the stiffness of the section because of the ribs and the thickness of the waffle slab the stiffness of the uncracked part is represented by the first slope, and the second slope represents the cracked part. These lines are parallel to the two models, and the difference between them is in the starting point related to the first part. This means less effect of the solid head on the slabs after the first crack when the solid section (solid head) extends for a distance at least 2.5 times the slab's effective depth from each column face. It is clear from these curves that sample IWS1 with the smallest solid area is the weakest compared to sample IWS2 with the largest solid area. Sample IWS1 had 14.6% less displacement than sample IWS2, as shown in Figure (4.6). However, had a smaller slope for the same level of loading.

It was found that slab IWS2, which had a broader solid head, had greater displacements than the reference waffle slab IWS1, this may be due to its resistance to the larger load.

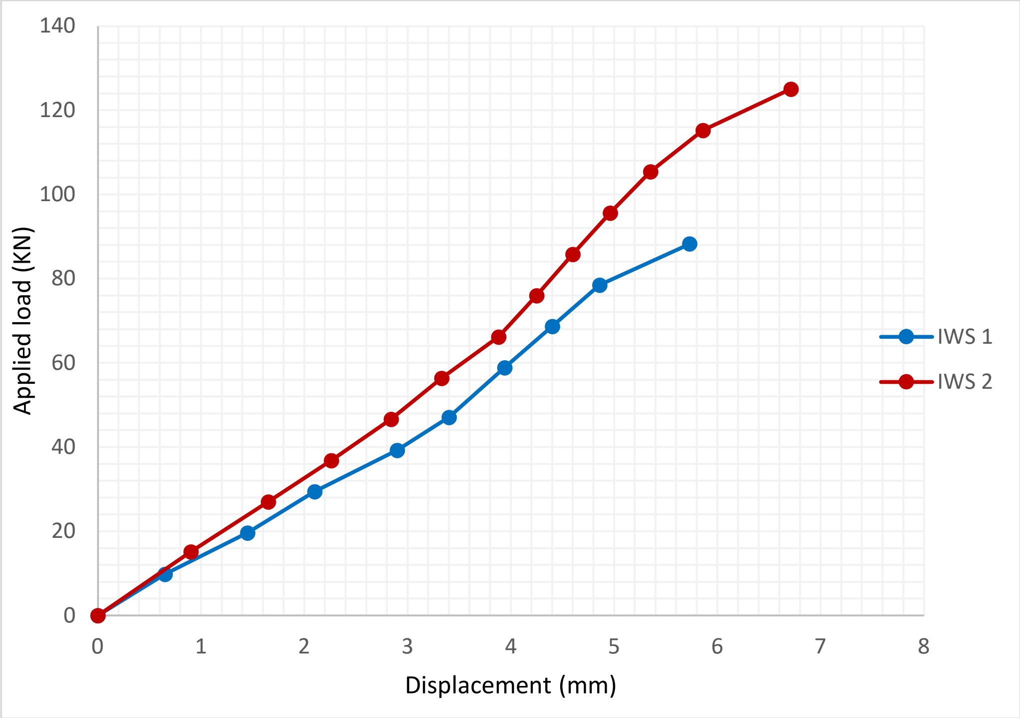


Figure 4. 5 load-deflection curves of IWS1 vs IWS2

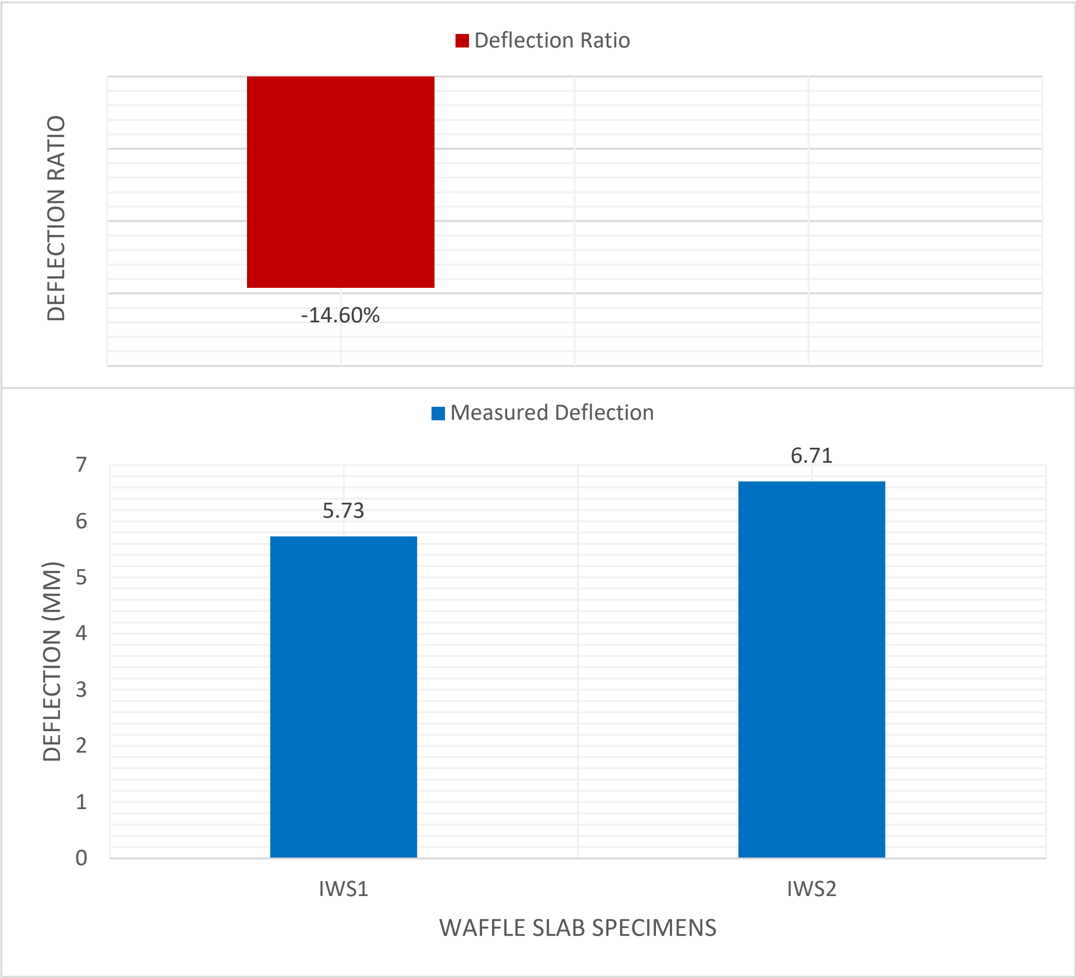
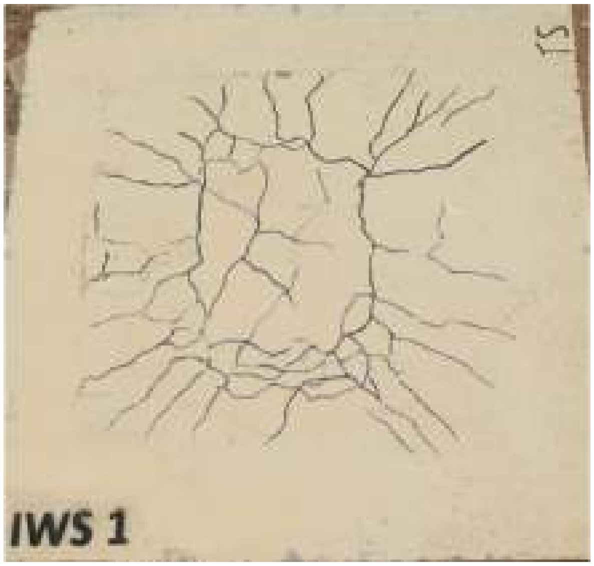


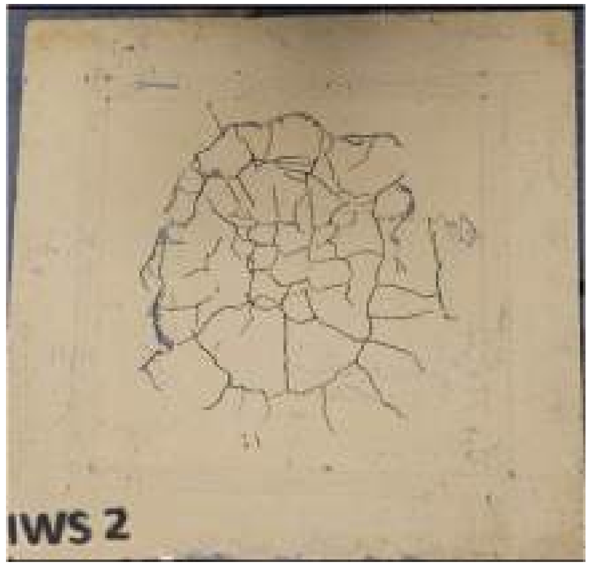
Figure 4. 6 Measured Deflection IWS1 Vs IWS2

4.3.3 Cracking Patterns

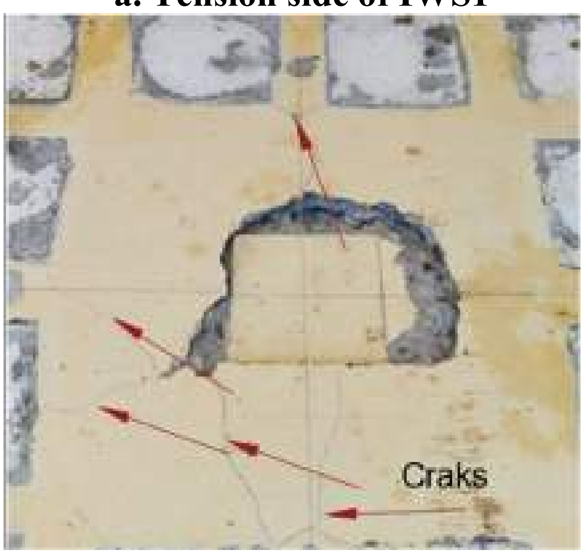
In general, the presence of flexural cracks was observed above of the column in the slab when the load was applied to the waffle slab sample. The cracking pattern in sample IWS1 showed a different behavior from sample IWS2. It was observed that the cracks are formed around the column in radial envelopes in the tensile zone, it intersects approximately with shear cracks at a distance of 1.75 times the overall depth of the slab from the column faces and then spread in a radial pattern to the outside near the supports. This cracking configuration in the top surface of the waffle slab (the compression side) was also observed when subjected to column concentrated loading, with Fine cracks observed on the solid region (solid head) spread to the outside toward the edges. which differs from the pattern of reference waffle slab IWS2, a localized (very limited) cracking pattern occurred at the perimeter of the column loading area. with no cracks observed in the compression face, as shown in Figure (4.7).



a. Tension side of IWS1



b. Tension side of IWS2



c. Compression side of IWS1

d. Compression side of IWS2

Figure 4. 7 Punching Failure Mechanism of Waffle slab specimen

In addition, the first visible crack (bending cracks) was also observed at the tensile surface of the tested waffle slabs at a load level equal to 53% of the ultimate load, which differs from the sample IWS2 with the greater solid area, which behaved like flat slabs so that the cracking started on the tensile face near the center, radiates towards the edges in radial and circular envelopes, it intersects approximately with shear cracks at a distance of 2.2 times the overall depth of the slab from the column faces. with the formation of minute cracks that are dense near the center. The spread of cracks and the failure area was not observed near the supports, as in the sample IWS1. However, the first visible crack was also observed at a loading level equal to 52%, and it is very close to the sample with the smaller solid area IWS1. However, it is noticed that the first crack loads increased in value by (40.85) % compared to the value of the first crack load in IWS1. Compared to the waffle slab that contains a smaller solid area and because the failure surface in sample IWS1 extends outside the solid area and fails due to shear in the ribs. These are attributed to the that the surface cracks are as a result of invisible cracks that formed inside the sample IWS1 of the smaller solid area from the column faces and extended into the waffle section.

4.4 The Effect of The Configuration of CFRP

4.4.1 Ultimate Load

By installing CFRP strips on the tensile surface of the concrete waffle slab, the effective tension area and the tensile resistance of the strengthened section increased compared with those of the control specimen. When the overall tensile reinforced ratio (due to contributions from both steel reinforcement and the CFRP strips) exceeded a critical value (balanced reinforced), compressive plastic strains could have developed in the compression zone before the propagation of tensile cracks. This resulted in a descending of the neutral axis to a lower level (compared with IWS1) to balance the compressive and tensile forces, and the reinforced concrete might have failed in compression rather than tension. This process can increase the maximum load capacity in the CFRP-strengthened area and decrease the ductility of the failure mode. It was observed that all waffle slab specimens CFRP-strengthened gave greater results than the unstrengthened. However, it was observed that all waffle slab specimens were punched in a sudden mode of failure (brittle failure), When a waffle slab failure, it is no longer able to support further load. It is noticed that the ultimate load is increased in value of (16.6-47.1) % compared to the value of the ultimate load in reference waffle slabs, as shown in Figure (4.8).

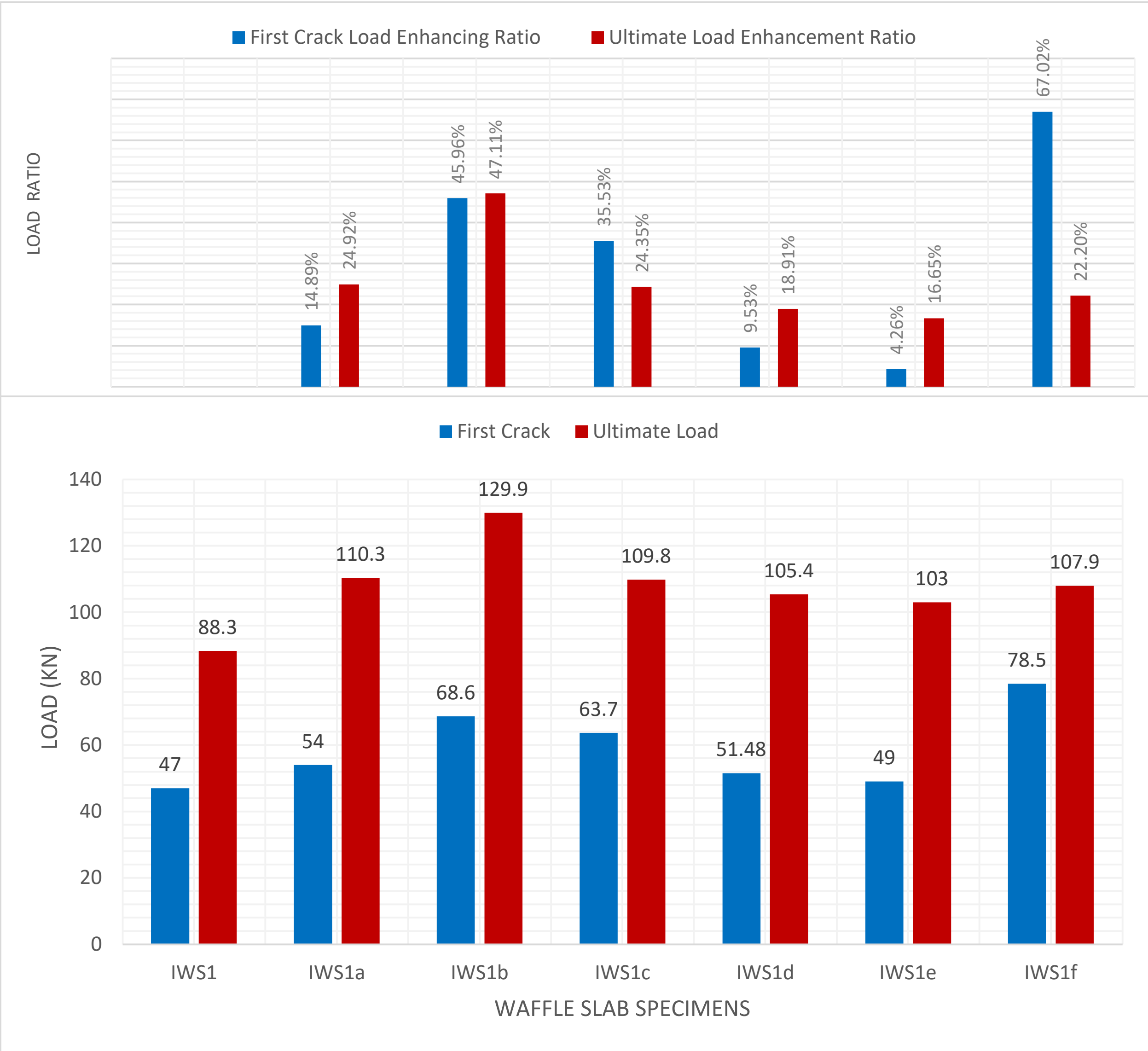


Figure 4. 8 First Crack Loadings Vs Ultimate Failure Loadings for IWS1

However, it was noted that the IWS1b specimen of the waffle slab gave higher strength than the other specimens (IWS1C and IWS1f) Which have the same directions of strengthening and the same area of strengthening. but with the technology of distributing CFRP in the form of strips/grids and separate spaces, the IWS1b gave greater resistance because the space is distributed over the ribs on the tensile side, The increase in shear strength is attributed to the uniform distribution of CFRP strips of specimen IWS1b. It was also observed that the skewed form of strengthening CFRP gave good results and was higher than the reference waffle slab as in the specimens (IWS1a, IWS1d, and IWS1e) and it can be noted that the samples (IWS1a, IWS1c, IWS1d, IWS1e, and IWS1f) gave convergent results.

4.4.2 Vertical Displacements

Figure (4.9) shows the load-deflection curves of the control waffle slab and the strengthened CFRP strips waffle slab, and the load-deflection curves show that the behavior of the RC control waffle slab is Less stiffness than the reinforced samples. (IWS1c, IWS1d, IWS1e, and IWS1f) and their behavior is close to each other. However, presented smaller displacements for the same loading level when compared to slab IWS1. Difference in load-deflection behavior may be associated with the CFRP strips width, and alignment angle relative to the ribs of the waffle slab. However, the slab deflection decreased, which could be due to the enhanced waffle slab stiffness. It was interesting to notice that specimen (IWS1a) had abnormal (more) deflection than the specimen reference slab IWS1. In addition, the greatest discrepancies were observed in the specimen (IWS1b), which had the highest vertical displacements and the ultimate resistance for all slabs. with a more brittle load-deflection curve, it is two straight lines inclined at two different angles. The first slope corresponds to the stiffness of an uncracked section, while the second slope corresponds to the stiffness of a cracked section. The slope of the second line segment is slightly steeper compared to the first line segment, as shown in Figures (4.9) and (4.10).

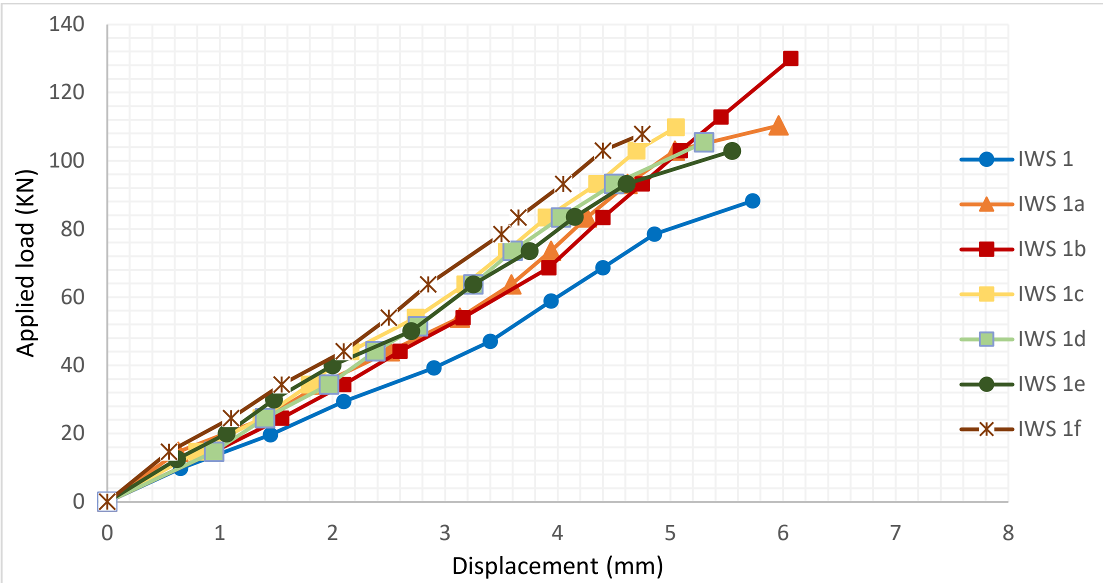


Figure 4. 9 Comparison of Load - Central Deflection Curves of Group First

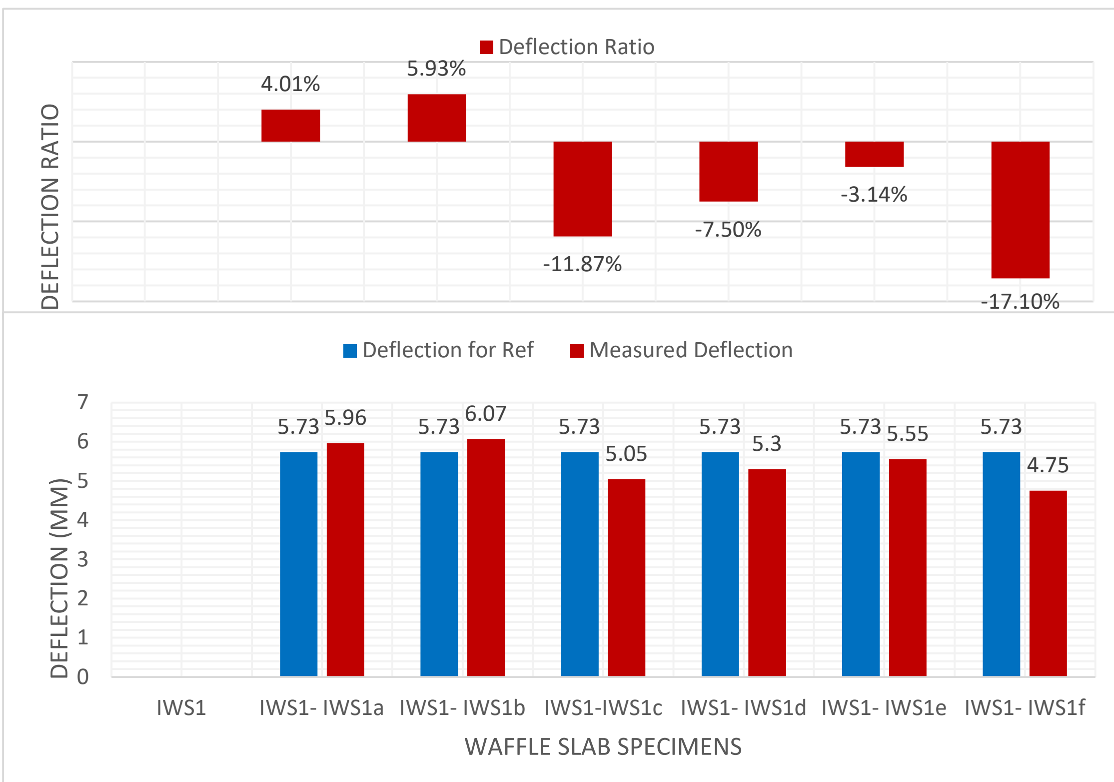


Figure 4. 10 Measured Deflection Vs Ref Slab

It is believed that such a phenomenon is due to the fact strengthening the ribs in the form of a grid on the tensile side becomes fully mobilized and effective. However, the CFRP-strengthened samples' behavior is more brittle than those of the non-strengthened. This is due to the stiffness of the specimens when strengthened.

4.4.3 Cracking Patterns

For the strengthened waffle slabs, cracking pattern showed an almost similar behavior to that without CFRP strengthening. 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 intersects approximately with shear cracks at a distance of (2.5-2.9) times the overall depth of the waffle slab from the column faces. As the load is increased the already formed cracks get widen while new cracks started to form, around the column in radial and circular envelopes and occurred in the tension surface of the waffle slab. In the case of waffle slabs with CFRP strengthening, by installing CFRP strips on the tensile surface of the concrete slab, the effective tension area and the tensile resistance of the strengthened section increased compared with those of the control specimen. the first cracks appeared tangentially to the column loaded area in the unstrengthened (interior areas) and then the radial cracks propagated and more fines cracks combined at higher rate, particularly in waffle slabs IWS1d, IWS1e, and IWS1f. The flexural-shear cracks in the concrete were initiated by flexural cracks, and developed due to the shear stresses. The crack propagation caused concrete fracture, which in turn led to the de-bonding of the CFRP strips. The slabs' cracking pattern is shown in Figure (4.11).

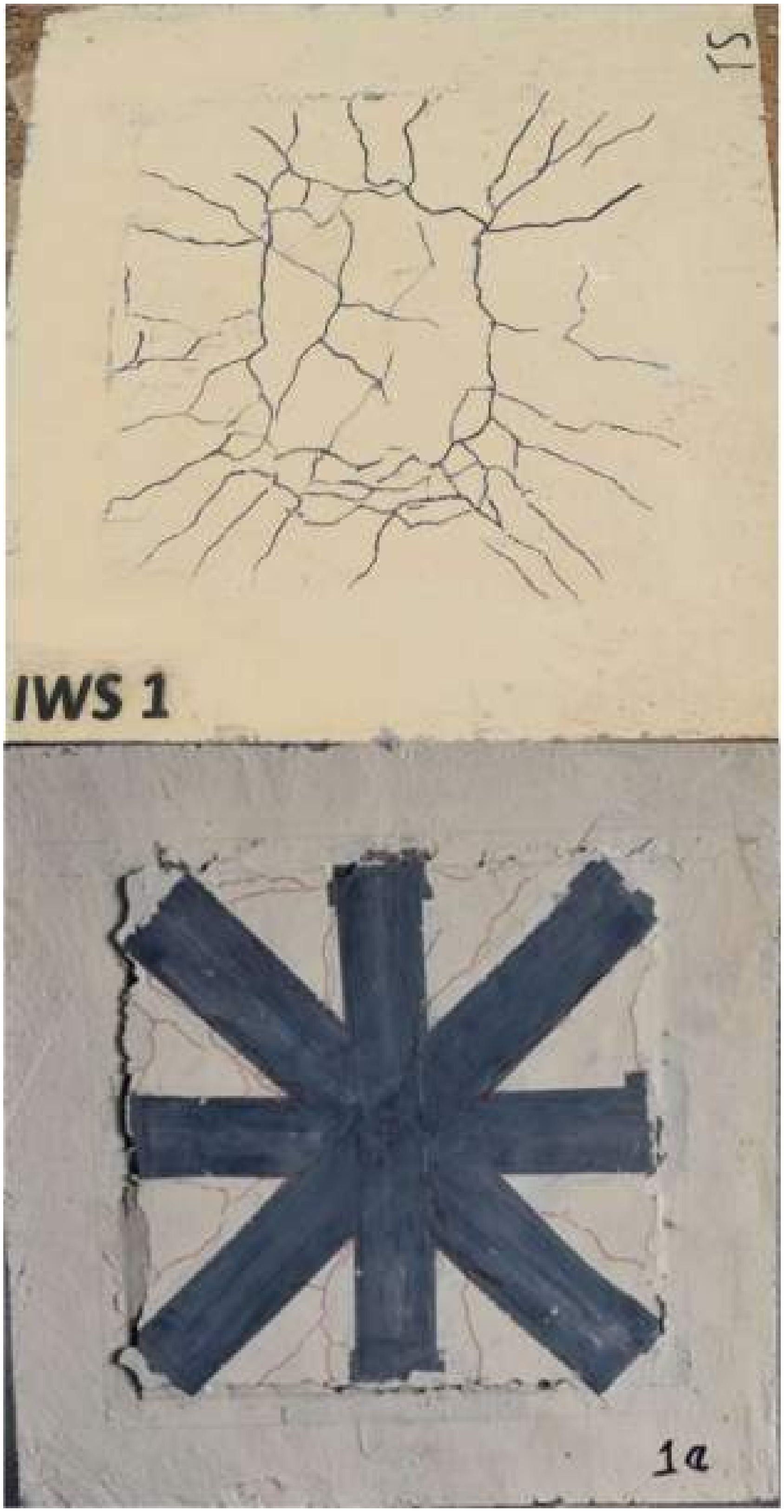


Figure 4. 11 Failure crack pattern of (IWS1, a, b, c, e, and f)

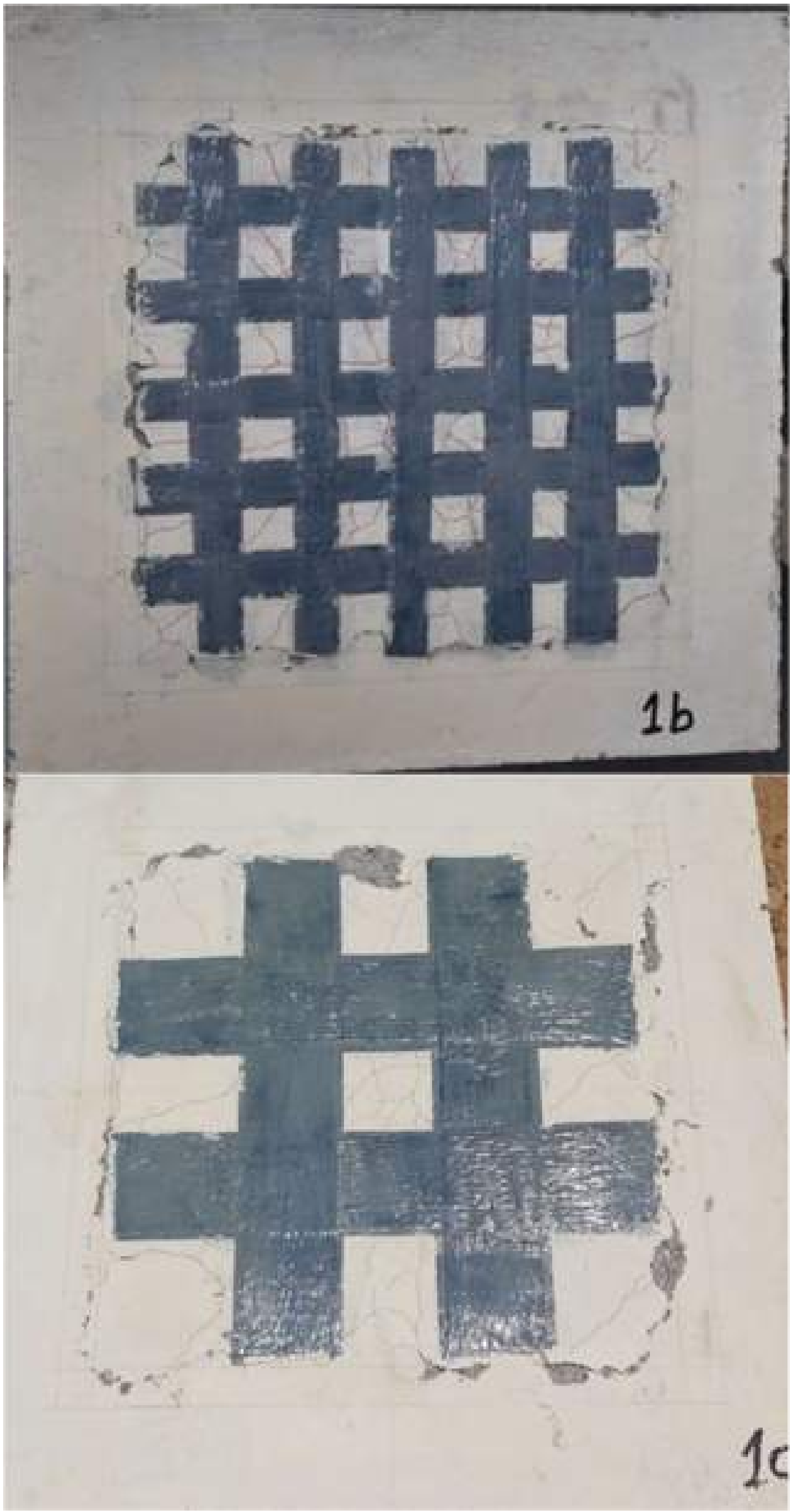


Figure (4.11) Continued

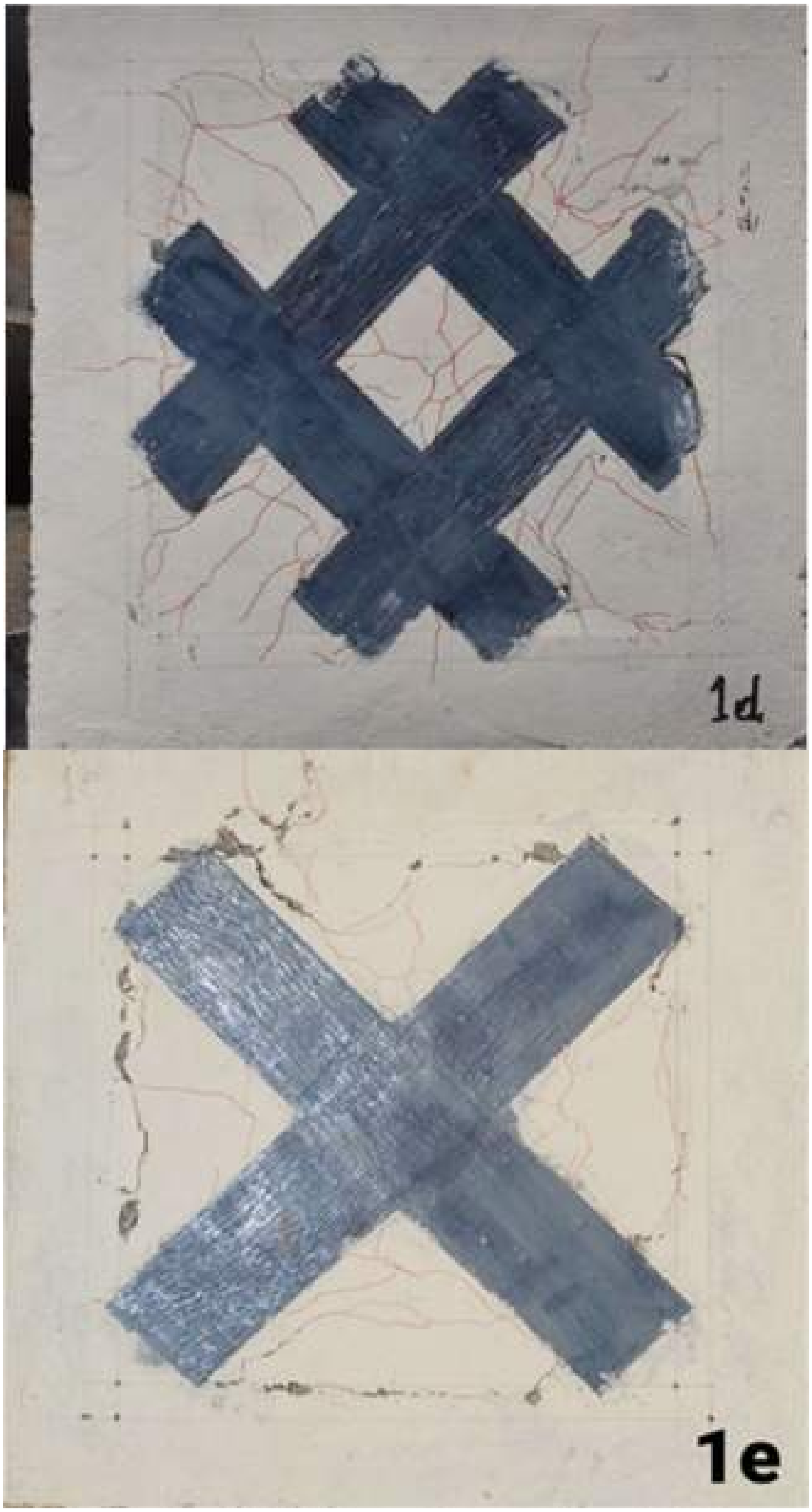


Figure (4.11) Continued

Figure (4.11) Continued

No cracks are observed in the compression face of any waffle slab, except IWS1b Fine cracks are observed in the form of a plus sign as shown in the figure (4.12). This cracking configuration in the top surface of the waffle slab (the compression side) was also observed when subjected to column concentrated loading. which differs from the pattern of reference waffle slab IWS1, a localized (very limited) cracking pattern occurred at the perimeter of the column loading area as shown in Figure (4.12). None of the samples failed due to CFRP rupture, which shows that the CFRP sheets did not reach their maximum tensile strength, failure progression outside the CFRP-strengthened area.

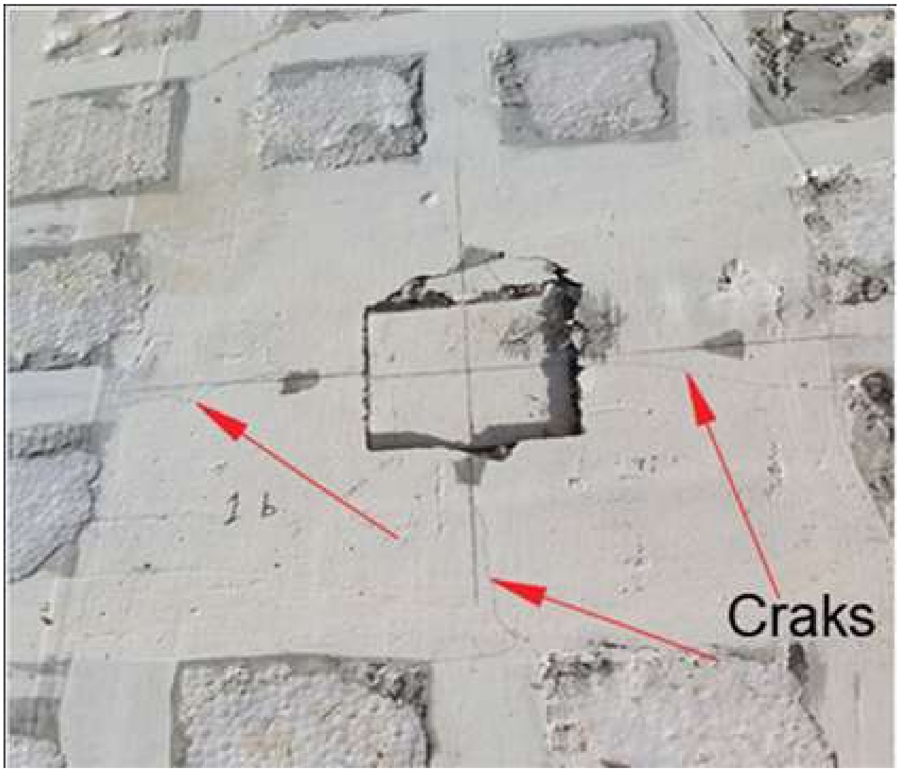


Figure 4. 12 Punching Failure crack pattern of IWS1b

4.5 The Effect of The Area of Strengthening with Same Configuration.

4.5.1 Ultimate Load

The waffle slab specimens (IWS1g) were punched in a sudden mode of failure (brittle failure) while the other samples with the largest CFRP area were also failed. When a waffle slab failure, it is no longer able to support further load. However, it is noted that when reducing the CFRP strips area ratio by (40) %, It is noticed that the ultimate load for IWS1g increased in value by (11.09) % than for the reference waffle slabs, as shown in Figure (4.13). but it is interesting that the first crack load increased by 61.7% respectively.

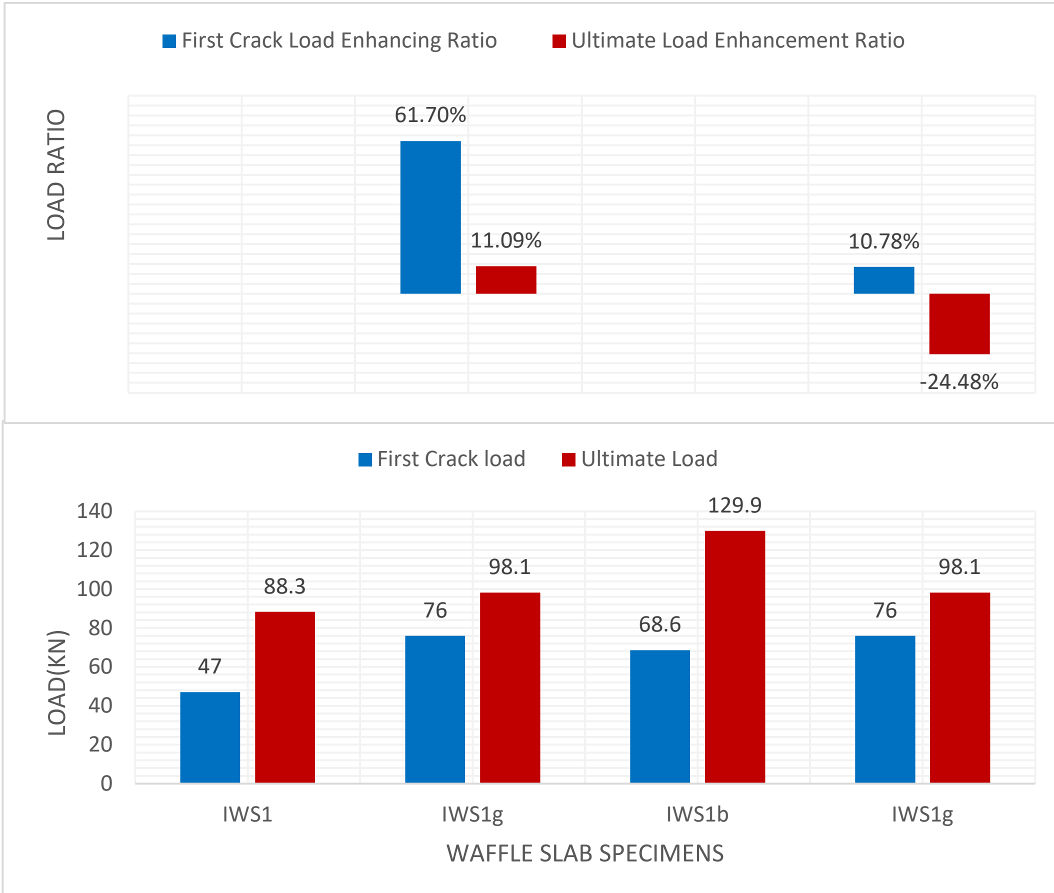


Figure 4. 13 First Crack Loadings Vs Ultimate Failure Loadings

and this means that when strengthening in the same configuration CFRP and with a smaller area, it had a clear effect and gave good results, especially for the first crack load. it gave a higher rate of 10.78% when compared with sample IWS1b that the same configuration CFRP and with a larger area, but for the ultimate load, it decreased by 24.48%. This indicates that the strengthening of the ribs in the tensile region near the column obviously increases the punching force and especially for the first crack load.

4.5.2 Vertical Displacements

As shown in Figure (4.14), even if the CFRP area is reduced by (40%), the load-deflection curves show that the behavior of the control waffle slab is least stiffness than the strengthened sample. However, the strengthened waffle slabs

(IWS1g) tested have an upper limit for the first crack load in addition to a higher slope with a decrease in vertical displacement by (21.46) %. This may be due to the increase in the initial stiffness of the sample IWS1g, compared with reference waffle slabs IWS1, as shown in Figure (4.15).

However, when compared with the sample (IWS1b) with a larger CFRP area, it was found that the shape of the load-deflection curve is different, and less sharp than the shape of the curve load-deflection of the specimen (IWS1b), with the deflection decreased by (25.9) %. This shows CFRP strips area has an obvious effect on the load-deflection curve, as shown in Figure (4.14). That is, when the CFRP area is reduced this reduces the energy absorption, with a reduction in the Ultimate load. However, this means that the reduced CFRP area for specimen IWS1g is better in improving the elastic behavior of the waffle slab when strengthening the ribs.

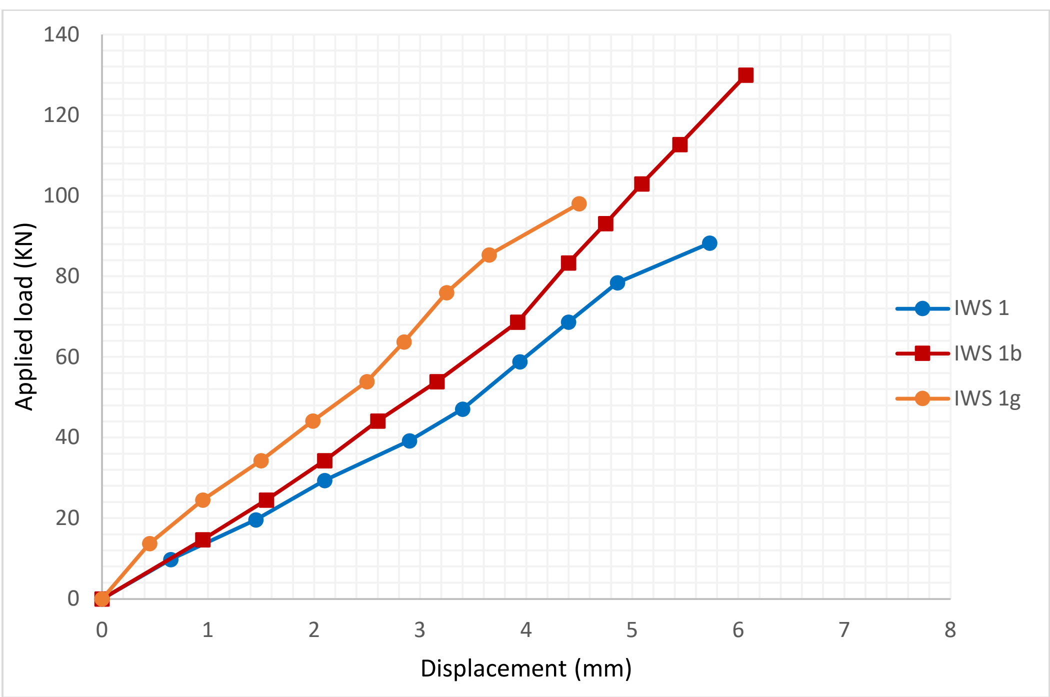


Figure 4. 14 load-deflection curve of IWS1 vs IWS1b and IWS1g

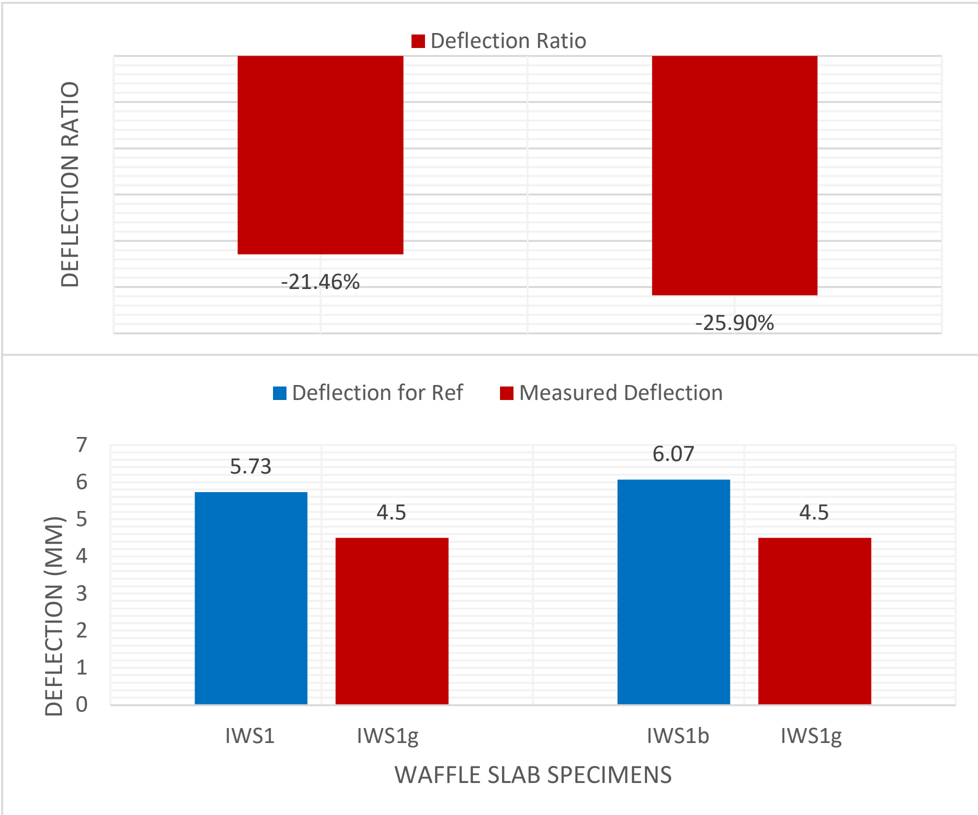


Figure 4. 15 Measured Deflection Vs Ref Slab and IWS1g

4.5.3 Cracking Patterns

The specimen (IWS1g) compared with the control specimen, there was no significant difference in the crack distribution. Flexural cracks on the tensile face began near the center (semi-random phenomena) and radiated toward the edges, of the supports. It intersects approximately with shear cracks at a distance of (2.7) times the overall depth of the waffle slab from the column faces. As the load is increased the already formed cracks get widen while new cracks started to form, around the column in radial and circular envelopes and occurred in the tension surface of the waffle slab. The first cracks appeared tangentially to the column loaded area in the unstrengthened (interior areas) and then the radial cracks propagated and more fines cracks combined at higher. However, when compared with the sample (IWS1b) it was noticed that there is a little difference in the crack pattern. It was noted that in the sample (IWS1g) the crack had extended a greater distance than that in the sample (IWS1b) as shown in Figure (4.16). This is due to a reduction in the CFRP area. The low concrete resistance in tension and shear stresses caused the tensile cracks to propagate and join the compression crushing area in the column vicinity to form long cracks that caused flexural punching failure. But the strengthened sample (IWS1b) showed more brittle failure than the strengthened sample (IWS1g), which can be seen in their load deflection curves in Figure (4.14).

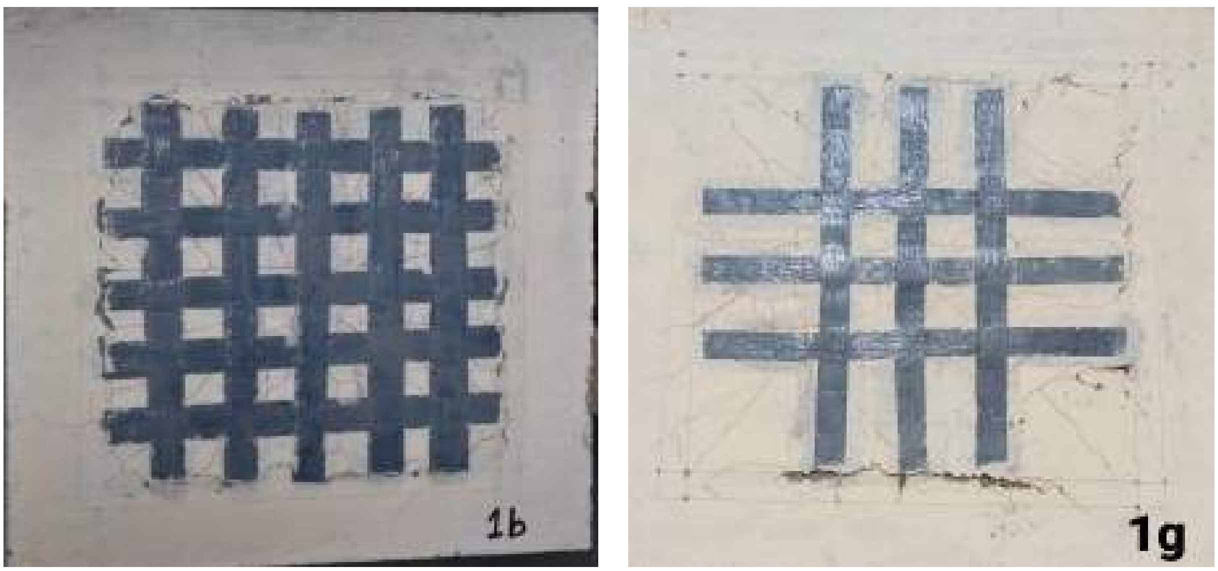


Figure 4. 16 Failure crack pattern

4.6 Effect of Strengthening on Size of Solid Section

4.6.1 Ultimate Load

Depending on the fact that the strengthened in the form of grid strips gave the largest percentage increase in the ultimate load in the category with the smallest solid area (IWS1), it was applied to the second category with the largest solid area (IWS2), but it was not effective and did not give a good result. It is noticed that the ultimate load for (IWS2b) increased in value by (2 %) compared to the value of the ultimate load for the reference waffle slab (IWS2), as shown in Figure (4.17), and this percentage is almost unnoticeable. However, it was observed that the first crack load increased by 14.80%. The flexural punching failure in (IWS2) was due to partial CFRP strengthening on the tension surface of the waffle slab in the column vicinity, The strengthened sample showed more brittle failure than the control specimen, which can be seen in their load deflection curves in Figure (4.18). This result can be explained by the increase in the solid area (solid head), and thus this affects the behavior of the waffle slabs, which leads to its behavior in a manner similar to solid slabs, and the strengthening in the form of grid tapes did not find any benefit in that.

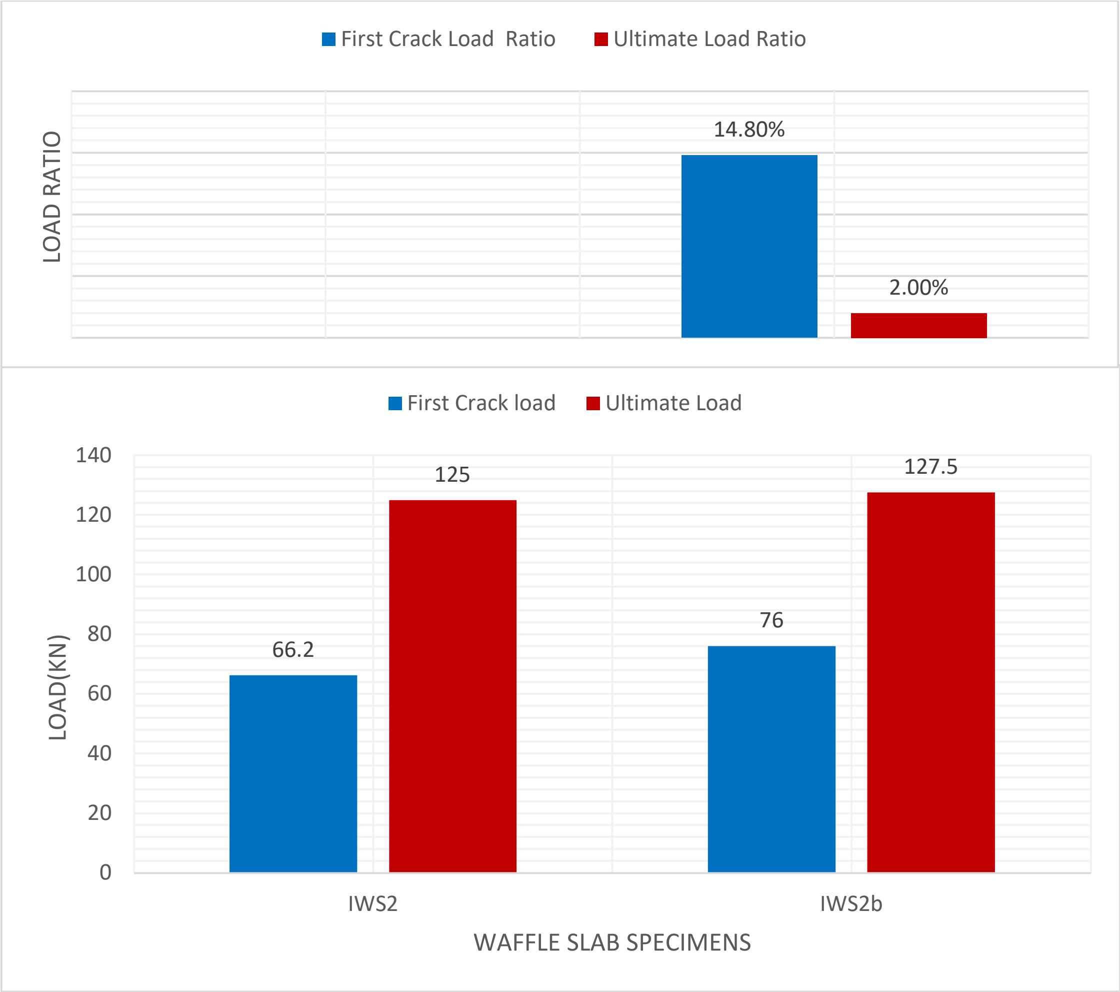


Figure 4. 17 First Crack Loadings Vs Ultimate Failure Loadings

4.6.2 Vertical Displacements

The load–deflection curves in Figure (4.18) demonstrate less stiffness of the control waffle slab (IWS2), which caused considerable waffle slab deflection. Greater slab deflection may increase the energy absorption ability, which is the area below the load-deflection curves. which differs from the load-deflection curves of strengthened CFRP waffle slab (IWS2b), load–deflection curve demonstrated a brittle punching failure as there was a sudden drop after the ultimate load capacity of the slab was reached. This resulted in a decrease in the deflection ratio by (26.82) %, as shown in Figure (4.19). However, the slab deflection decreased, due to an increase in the stiffness of the waffle slab when strengthen with CFRP strips.

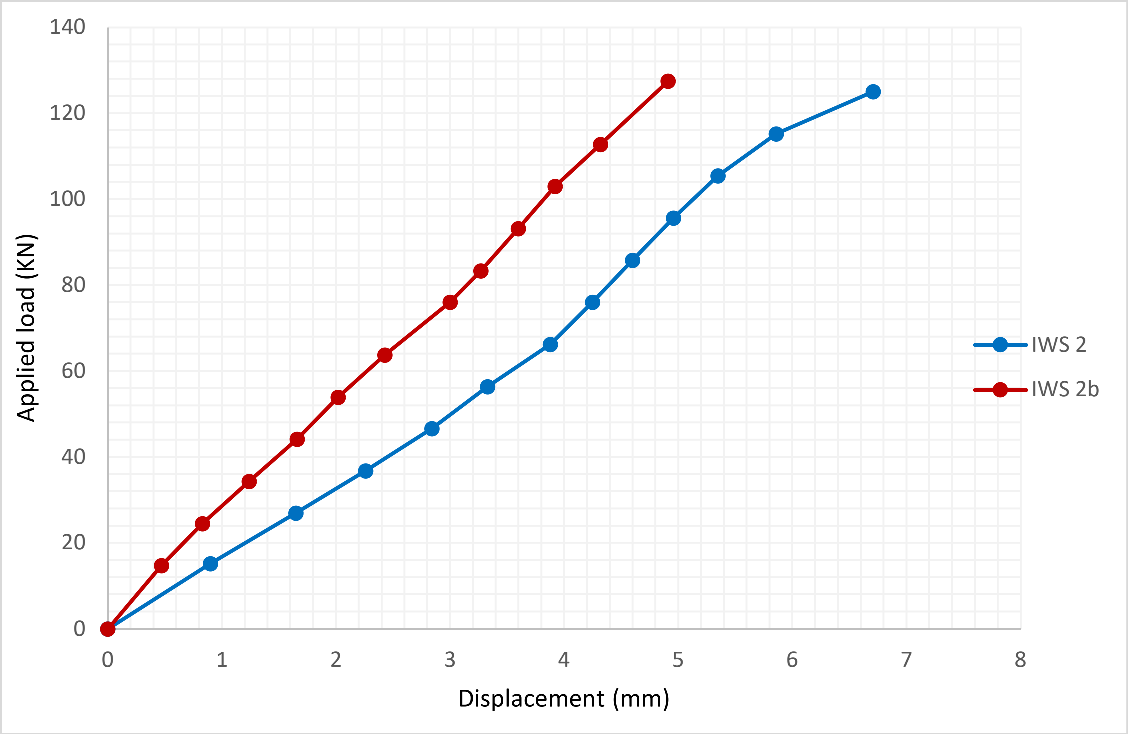


Figure 4. 18 load-deflection curves of IWS2 vs IWS2b

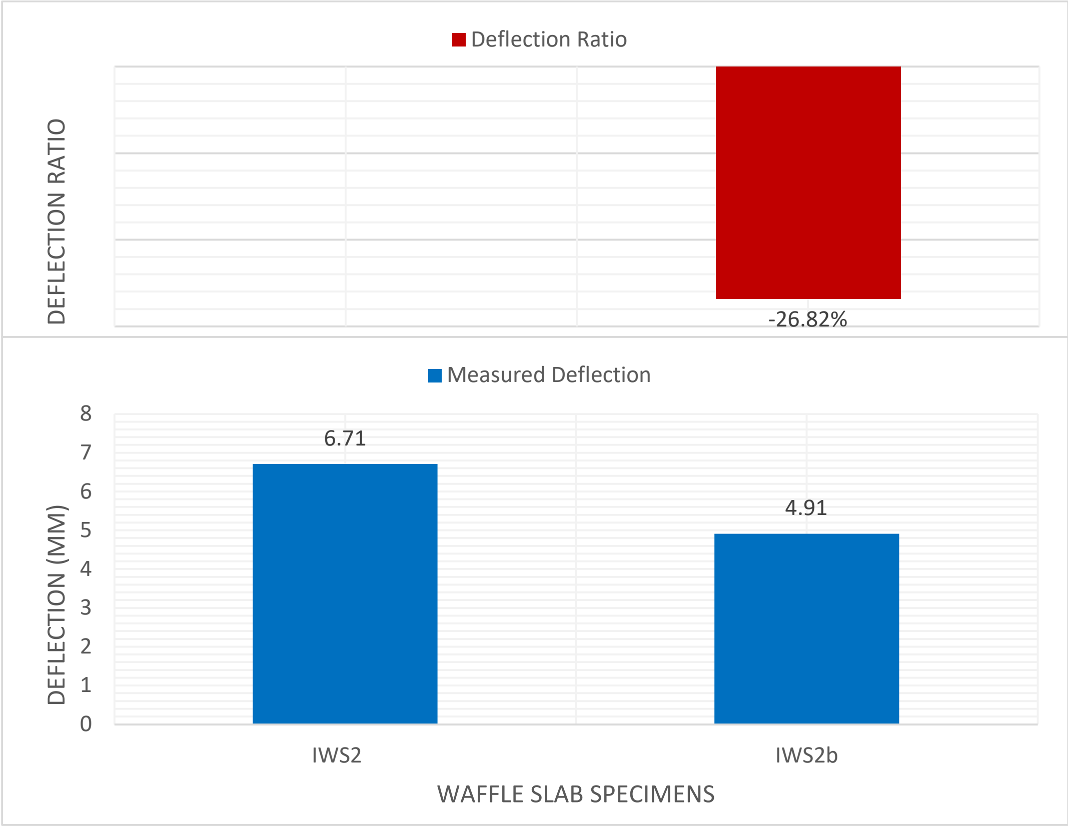


Figure 4. 19 Measured Deflection Vs Ref Slab

4.6.3 Cracking Patterns

For the strengthened waffle slabs (IWS2b), the cracking pattern showed almost similar behavior to that without CFRP strengthening (IWS2), flexural cracks on the tensile face began near the center (semi-random phenomena).it intersects approximately with shear cracks at a distance of (2.5) times the overall depth of the waffle slab from the column faces. The crack propagation caused concrete fracture, which in turn led to the de-bonding of the CFRP strips. The slab cracking pattern is shown in Figure (4.20). No cracks are observed in the compression face.

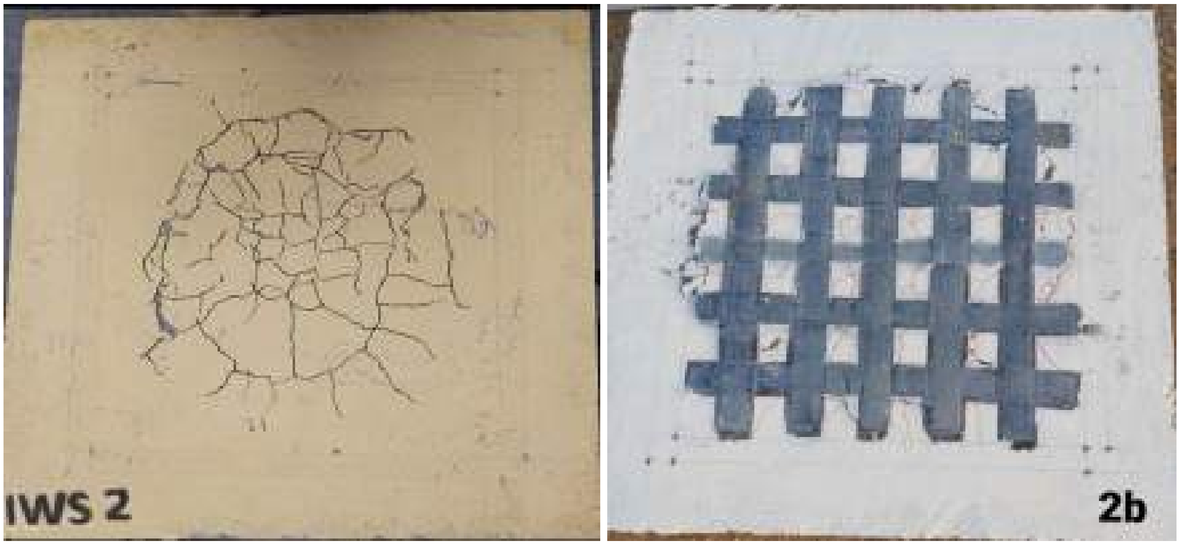


Figure 4. 20 Failure crack pattern

4.7 The Effect of The Same Configuration on Different Solid Section

4.7.1 Ultimate Load

The areas of the RC waffle slabs that were covered by the CFRP strips in strengthening were the same. This enables a direct comparison of different samples in the solid area (solid head). a considerable improvement in the load capacity of IWS1b (with a solid head of 275 mm) was observed due to the enhancement of the tensile resistance of the critical section in the column vicinity by CFRP strengthening. It is noted when applying the same configuration of CFRP to sample IWS2b (with a solid head of 515 mm). The results indicate that when increasing the solid area with strengthening, the ultimate load decreased by (1.84) % compared with IWS1b, while the first crack load increased by (10.78) % respectively, as shown in the Figure (4.21). The strengthening did not improve satisfactorily, and the result is almost unnoticeable, and the results are close to each other despite the increase in the solid area.

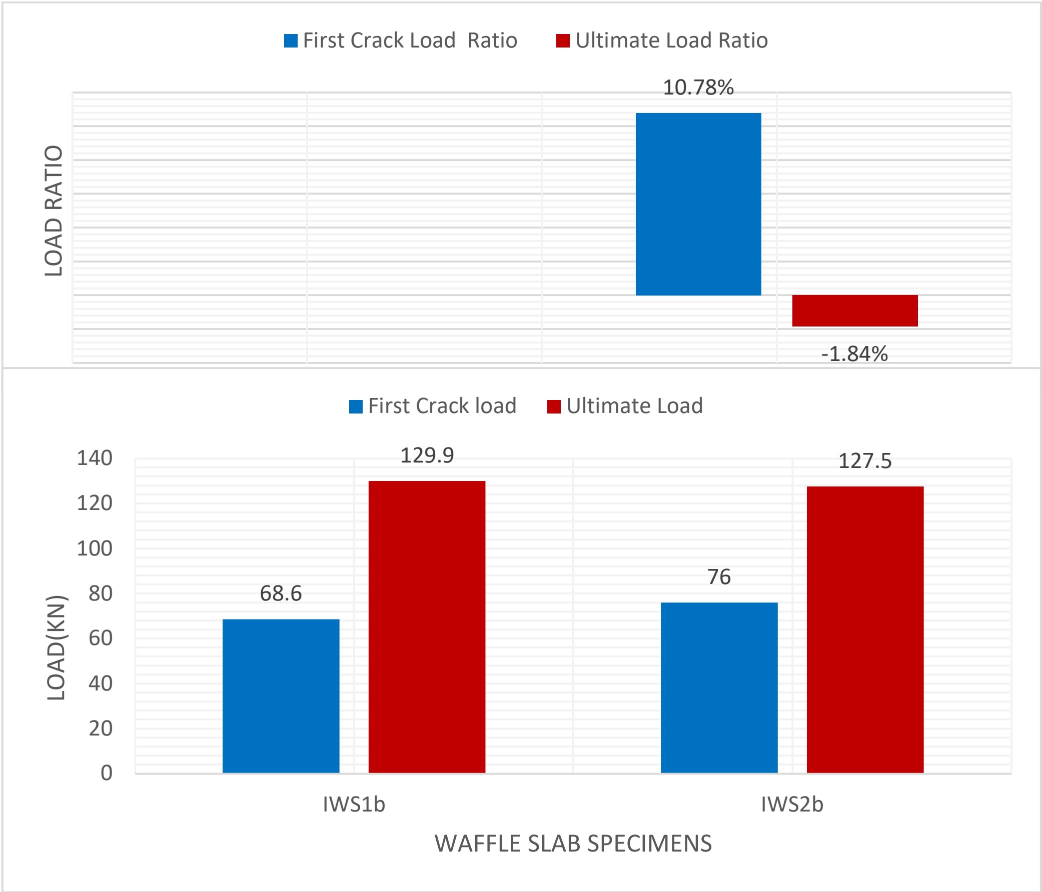


Figure 4. 21 First Crack Loadings Vs Ultimate Failure Loadings

The reason may be due to the fact that the method of strengthening the ribs in the tensile area of the reinforced concrete waffle slab with the dimensions of 275 mm solid area is more effective compared to the waffle slabs of the dimensions of the 515 mm solid area. or due to the stiffness of the unstrengthening waffle slab (IWS2). It was observed that waffle slab specimens IWS1b and IWS2b were punched in a sudden mode of failure (brittle failure), when a waffle slab failure, it is no longer able to support further load.

4.7.2 Vertical Displacements

Figure 4.22 shows the load–deflection curves for the strengthened waffle slab (IWS1b) and (IWS2b). The experimental load–deflection curve demonstrated a brittle punching failure as there was a sudden drop after the ultimate load capacity of the waffle slab was reached. The load-deflection curve can be considered as two straight lines inclined at two different angles. The first slope corresponds to the stiffness of an uncracked section, while the second slope corresponds to the stiffness of a cracked section, as indicated in Figure (4.22). The slope of the second line segment is slightly steeper compared to the first line segment. Note that the slope of the load–deflection curves indicates stiffer behavior in the CFRP strengthened samples. It is very clear from these curves that the strengthened waffle slab IWS2b has a higher limit for the first cracking load and a higher slope compared with IWS1b. However, the deflection decreased by (19.11) % compared with specimen IWS1b, as shown in Figure (4.23). which could be due to the enhanced waffle slab stiffness from the CFRP strengthening with the bigger concrete section (equivalent) has an increased moment of inertia and, by extension, greater stiffness for displacement.

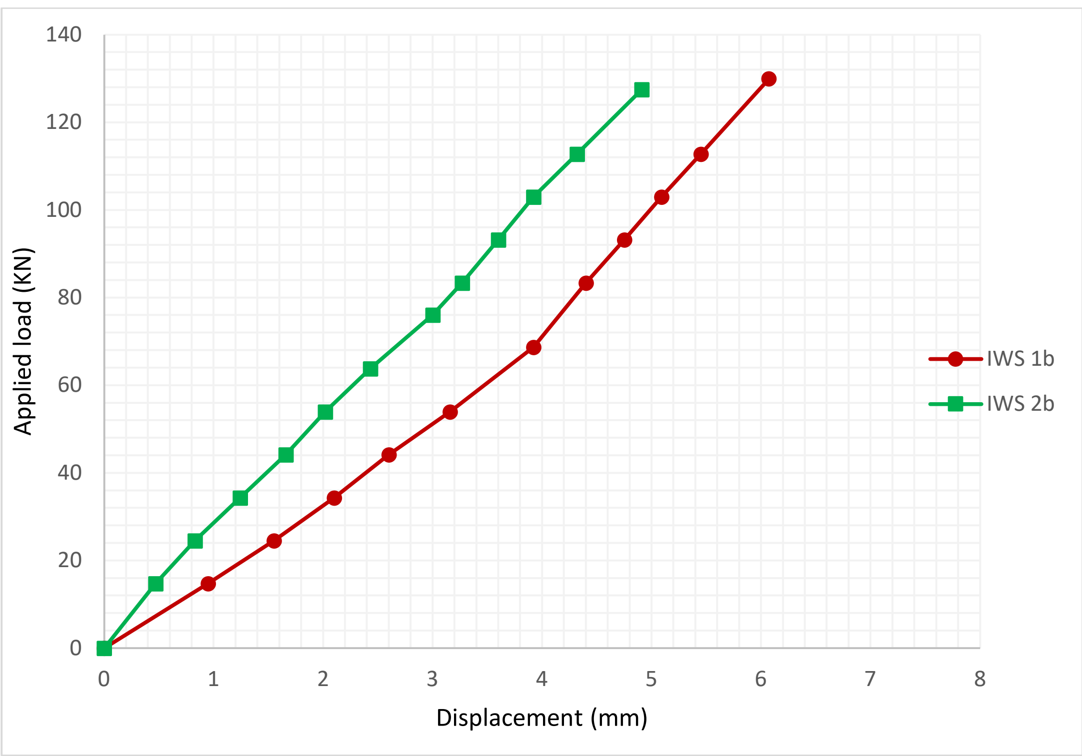


Figure 4. 22 load-deflection curve of IWS1b vs IWS2b

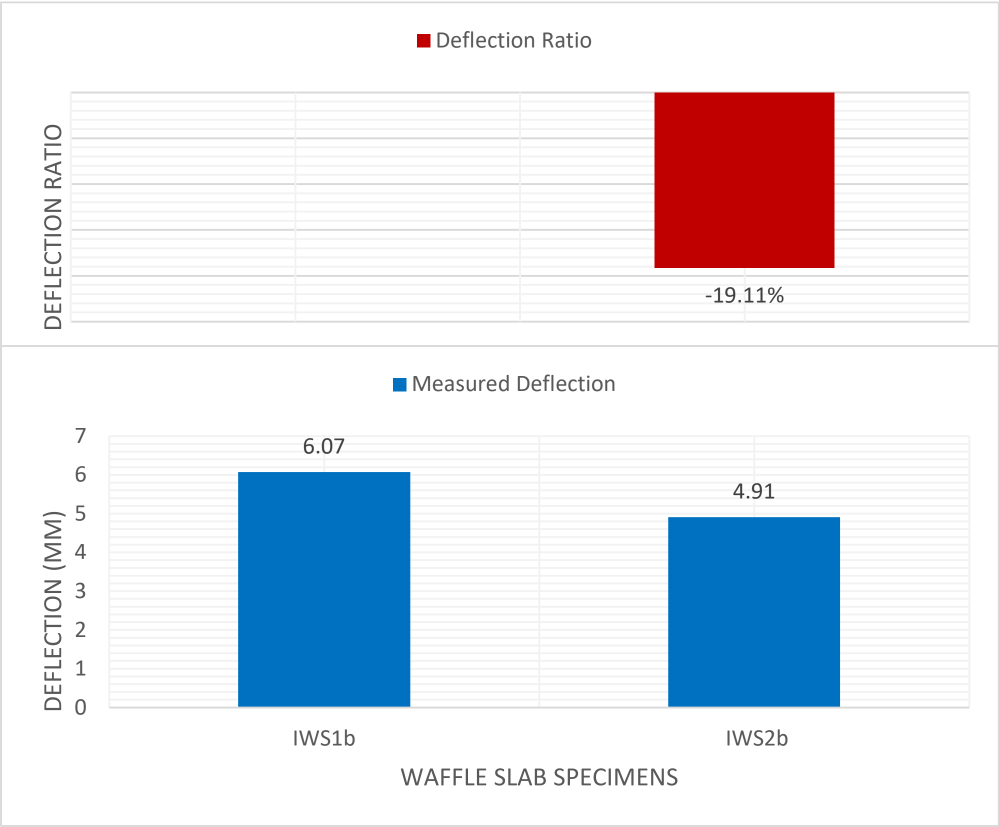
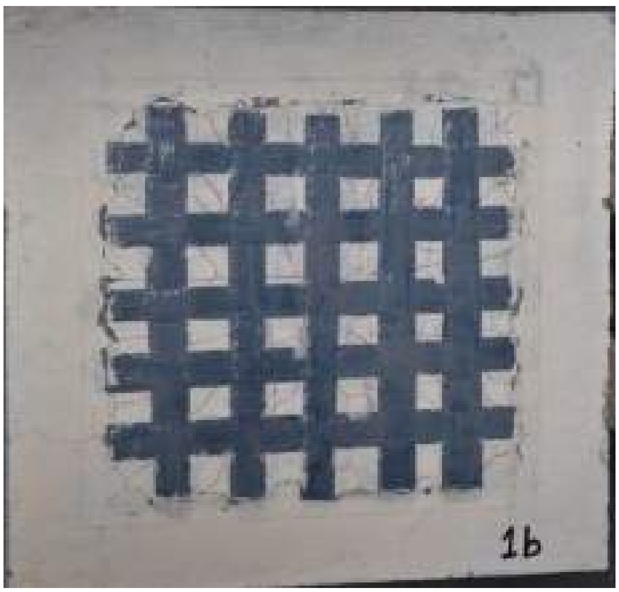


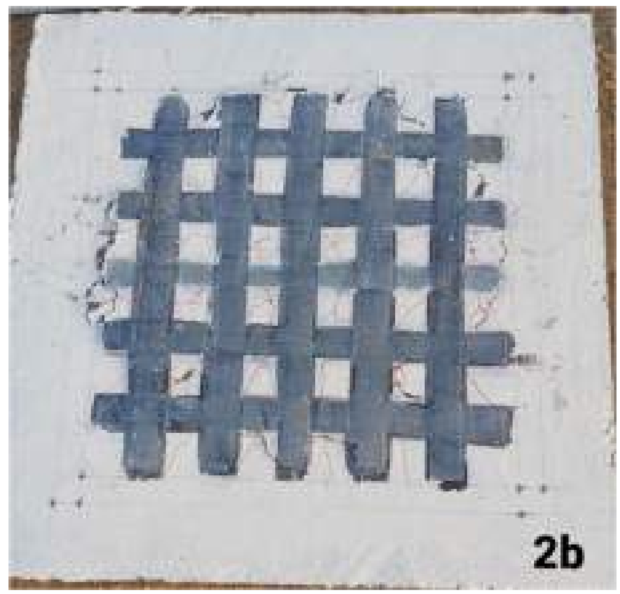
Figure 4. 23 Measured Deflection Vs IWS1b

4.7.3 Cracking Patterns

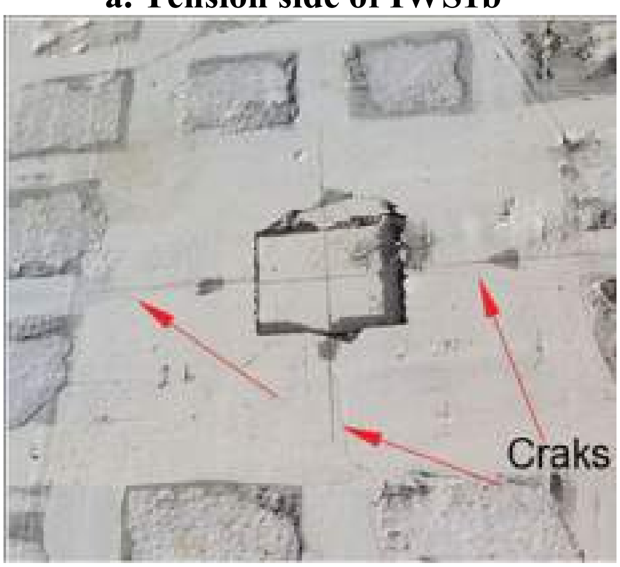
The strengthened waffle slab IWS2b cracking pattern showed an almost different behavior to that strengthened waffle slab IWS1b, as shown in Figure (4.24). flexural cracks on the tensile face began near the center (semi-random phenomena) and radiated toward the edges, it intersects approximately with shear cracks at a distance of (2.5) times the overall depth of the waffle slab from the column faces. The flexural-shear cracks in the concrete were initiated by flexural cracks, and developed due to the shear stresses. The crack propagation caused concrete fracture, which in turn led to the de-bonding of the CFRP strips in waffle slab IWS2b. In addition, no cracks are observed in the compression face. a localized (very limited) cracking pattern occurred at the perimeter of the column loading area. which differs from the pattern of the waffle slab IWS1b which flexural cracks intersects with shear cracks at a distance of (2.8), with the concrete compressive crushing that caused punching shifted from the column vicinity to outside the strengthening region. When the compressive strut in the column vicinity is strengthened, an un-strengthened compressive strut outside the strengthened region may reach its ultimate capacity first.



a. Tension side of IWS1b



b. Tension side of IWS2b



c. Compression side of IWS1b

d. Compression side of IWS2b

Figure 4. 14 Punching Failure crack pattern

This situation results in punching failure being initiated outside the strengthening zone as shown in Figure (4.24) in the waffle slab IWS1b. However, fine cracks are observed in the compression face. with a localized partial cracking pattern occurred at the perimeter of the column loading area as shown in Figure (4.24). None of the samples failed due to CFRP rupture, which shows that the CFRP strips did not reach their maximum tensile strength.

4.8 Failure Angles

The angles of punching shear failure were measured and documented as shown in Figures (4-25) and (4-26). Angles represent the inclined sides of punched conical pyramid part. Angles are measured by indicating the dimensions of the pushed-out zone at the center line passing through the loaded area.

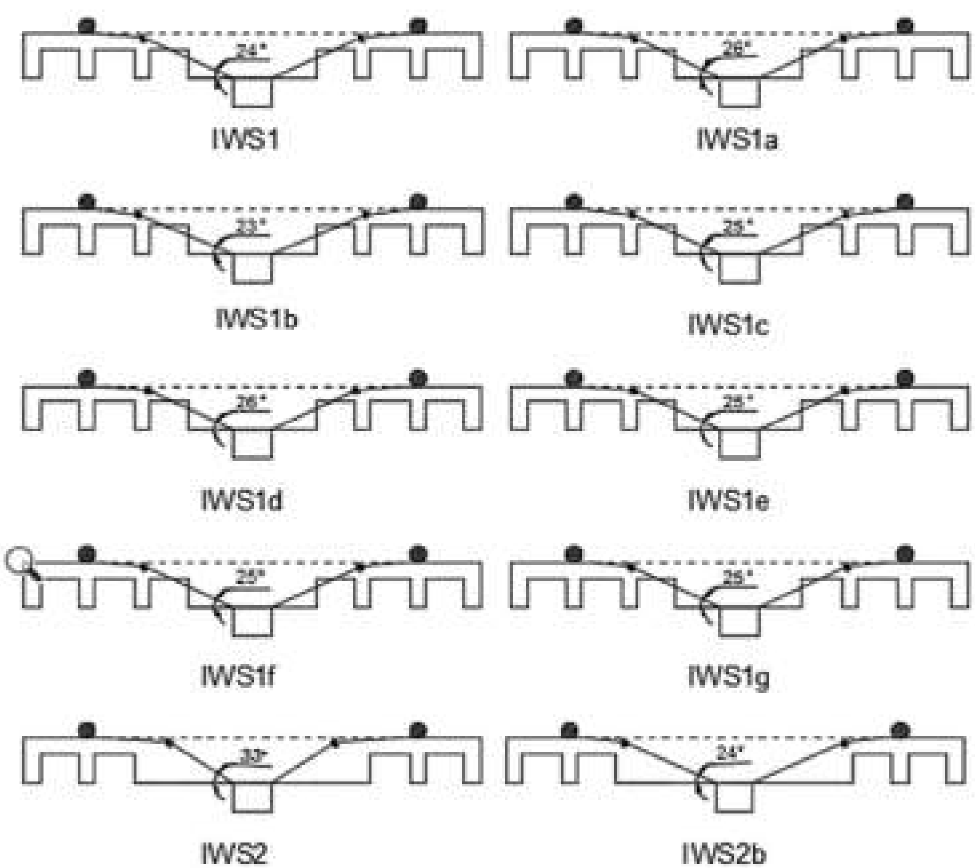


Figure 4. 25 Punching Shear Failure Angles of each specimen
[IWS1, a, b, c, d, e, f, g, and IWS2, b].

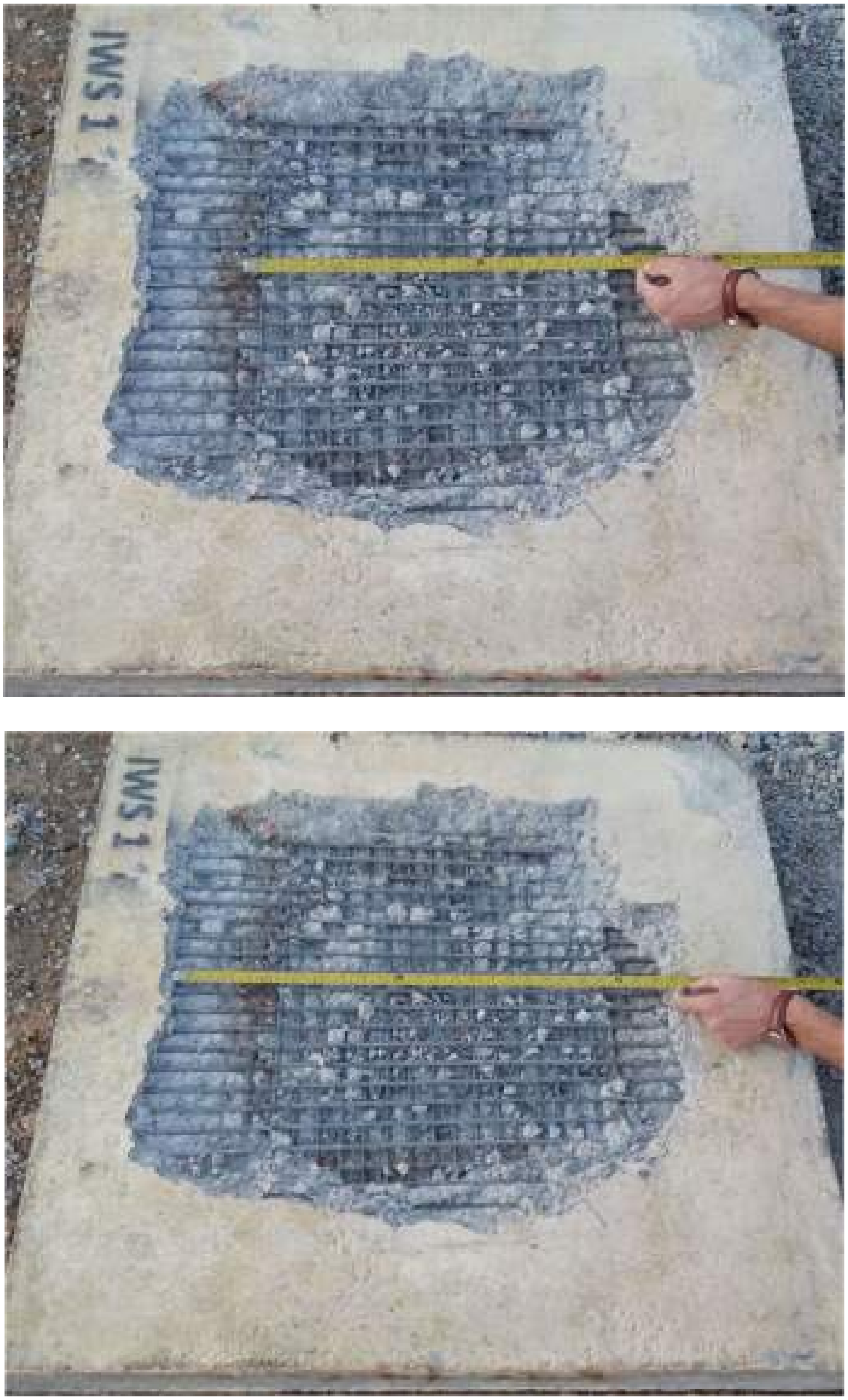


Figure 4. 26 Punching Shear Failure Angle measurements of control specimen [IWS-1].

4.9 Waffle Slab Punching Shear Strength (Unstrengthened Types)

It was found that tested waffle slabs, did not meet the design codes in terms of control perimeter, The European code was more conservative for specimen IWS2 through control perimeter see Figure (4.25). It was observed that the ultimate failure loads for specimen IWS1 are less than the punching shear strength estimated by the codes [CAN-CSA, Eurocode, and ACI-318M]. The comparison shown in Table (4.4), with the test results of specimen IWS1 revealed that Eurocode overestimated the punching capacities, whereas ACI and CAN-CSA prediction was conservative and accepted. Demonstrating that the findings of these codes' calculations, which treat the waffle slab as solid, are accepted. The specimen IWS2 the waffle slabs with a larger solid region behaved like a flat, entirely solid slab, and the codes' predictions of the punching shear were accepted, but the ACI code was very conservative. All equations and calculations are available in Appendix (I). For the waffle slab IWS1 the computed shear strength (nominal/ultimate) of the European code [Eurocode-1992], the punching shear with a ratio Vexp/Vcomp (74.4%), secondly the Canadian code [CAN-CSA-A23.3] with ratio Vexp/Vcomp (85.4%), and lastly provided the most conservative predictions of nominal punching shear resistance is ACI-318M with ratio Vexp/Vcomp (99.1%). Additionally punching Shear for strengthened waffle slabs design equations are yet to developed and require extensively thorough studies.

Table 4.4 Testing Results of Waffle Slabs and International Design Code Estimated Punching Shear Strength.

Slab	P_{Exp} (kN)	$P_{n\text{-}ACI}$ (kN)	P_{ACI} / P_{exp}	P_{EC} (kN)	P_{EC} / P_{exp}	P_{CAN} (kN)	P_{CAN} / P_{exp}	Imp.
IWS1	88.3	89.13	1.00	118.64	1.34	103.43	1.17	min
IWS2	125.0	89.13	0.71	118.64	0.95	103.43	0.83	

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This thesis presents an experimental investigation undertaken to evaluate the punching shear behavior of concrete waffle slabs strengthened by externally bonded CFRP sheets. This study chose to analyze the strengthening performance of waffle slabs using only two categories of waffle slabs (IWS1&IWS2) that have a solid head of (275x275mm) and (515x515mm), respectively. Ten slab specimens were cast and tested until failure by punching. The experimental results were analyzed and also compared with code provisions. The following conclusions can be listed as follows:

1. Unstrengthened waffle flat slab with a small solid area of 275x275 mm (the length of the solid area is less than 15% of the clear span between columns) had a reduced ultimate load about of 29.36% than the waffle flat slab with a larger solid area of 515x515 mm. Also, the stiffness and energy absorption of were decreased by 40.63% and 28.76% respectively were decreased.
2. Unstrengthened waffle slab with the solid area 515x515 behaved like solid flat slabs.
3. Punching shear cones on unstrengthened waffle flat slabs with small solid areas exceeded to the ribs area.
4. The increase in the dimensions of the solid head can be dispensed with as much as the emphasis is placed on the configuration CFRP strip.
5. The CFRP-strengthened concrete waffle slabs exhibited increased stiffness, ranging from 19.93% to 47.37%, compared to the reference waffle slabs. Moreover, all slabs strengthened with CFRP strips demonstrated a higher final

load carrying capacity, with an increase ranging from 2% to 47.11%, compared to the unstrengthened reference waffle slab. Strengthening reinforced concrete slabs with CFRP has been shown to significantly enhance load carrying capacity and stiffness.

6. Applying CFRP to the tension surface of waffle slabs has a significant effect on the crack pattern of the waffle flat slabs. This is because it delays the crack appearance and reduces the crack width, and results in an increase in cracking loads of about (4.26-67.02) % compared with the unstrengthened slab.
7. CFRP strengthening layout (configuration or arrangement) play a key role in enhancing the punching shear capacity of concrete slabs. It was concluded that the best arrangement of CFRP strips depended on two major factors, distributed area, and orientation. The successful increasing in punching shear capacity, stiffness, and energy absorption were by 47.11%, 38.87%, and 17.11%, respectively compared to control specimen.
8. CFRP strips to the negative steel reinforcement orientation was also a key factor in strengthening. This is clearly shown by comparing the results of the cross configuration and the plus configuration. The increasing of ultimate load with an orientation angle of (45°) reached about of (16.65%), while the latter with an orientation angle of (0.0°) reached about of (22.2%) of punching shear enhancement.
9. Waffle slab with a strengthening (Plus & cross) configuration have a more ductile punching failure mode owing to the development of wide tensile cracks on the strengthening waffle slab compared with the reference waffle slab.
10. Applying CFRP to the tension surface of waffle slabs with a small solid area is an efficient method for increasing load capacity, stiffness, and energy

absorption, with proportions about (11.09-47.11%), (19.93-47.37%) and (3.47-17.11%) respectively. However, slab deflection may be reduced about (3.14-21.46%).

11. Decreasing of strengthening area of CFRP from (0.15 m2) to (0.25 m2), grid configuration, led to an improved punching shear capacity and stiffness of about 11.09% and 41.46% respectively, with a decrease in energy absorption by as much as 18.15 %, for waffle slabs with a small solid area compared with reference slab.
12. Applying the grid configuration in a waffle slab with the solid area largest (515x515mm) does not considerably change slab behavior, and cannot be assumed to be an efficient strengthening technique, where led to an improved punching shear capacity of (2%).
13. The most common failure mode for reinforced waffle slabs, is brittle punching failure.
14. Regarding the computational results, comparisons with test results revealed that the punching design procedures for solid flat slabs of Eurocode overestimated the punching failure loads of waffle slab specimens, whereas the punching design procedures for flat slabs of both ACI and CAN-CSA remained conservative.

5.2 Recommendations For Further Studies

More research is needed to fully comprehend the punching behavior of two-way slabs made of reinforced concrete and repaired by CFRP sheets. Here are some of the key aspects that need to be prioritized:

1. Additional tests of reinforced concrete slabs strengthened considering different areas different strengthening patterns and different types of load as uniformly distributed load.
2. Studying the structural response of EB CFRP-waffle slab (or repaired reinforced concrete waffle slabs) subjected to loading of dynamic nature like repeated, cyclic, and impact.
3. Studying the effect of High temperature on that carbon fiber reinforced plastic (CFRP) sheets bonded to waffle slab. And their effects on the structural overall integrity of reinforced concrete waffle slabs.
4. Studying the effect of concrete compressive strength of the waffle slab. effects on the structural performance of strengthened concrete waffle slabs.
5. Future research could also focus on the longer-term performance/behavior of two-way waffle slabs that have been strengthened or repaired using CFRP sheets, or that have been exposed to extreme salt water impregnation cycles and its fluctuations through expected service design life.

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APPENDIX A

A.1 Effective length of FRP Sheet Bonded to Concrete

The required CFRP length to transfer the stresses properly was estimated based on Monti and Liotta's [65]. Effective bonded length is;

$$l_e = \sqrt{\frac{E_f t_f}{2 f_{ctm}}} \qquad \text{[length in } mm\text{]} \qquad \text{A-1}$$

where:

E_f = FRP sheet elastic modulus,
t_f = sheet thickness,
$f_{ctm} = 0.27 \cdot R_{ck}^{2/3}$ = concrete mean tensile strength
R_{ck} = concrete characteristic cubic strength.

A.2 International Codes Punching Shear Design Recommendations

The ACI-318M-19, Eurocode 1992-04 and CAN CSA A23.3-14 formulations are presented below, with the safety factors removed, in order to compare the calculated values to the computational results.

A.2.1 ACI 318M-19

According to the American code, the estimated punching shear load (V_{ACI}, p), for slabs without shear reinforcement, is the lowest among Equations A-2, A-3 and A-4.

$$V_{ACI,\,p} = 0.33\sqrt{fc'}\ u_1 d \qquad \text{A-2}$$

$$V_{ACI,p} = 0.17\left(1 + \frac{2}{\beta_c}\right)\sqrt{f'_c}\ u_1 d \qquad \text{A-3}$$

$$V_{ACI,p} = 0.083\left(2 + \frac{\alpha_s d}{u_1}\right)\sqrt{f'_c}\ u_1 d \qquad \text{A-4}$$

Where

f'_c = compressive strength of concrete limited to 70 MPa;

$\beta_c =$ ratio between the largest and smallest column dimensions;
$\alpha_s =$ constant that assumes a value equal to 40 for internal columns, 30 for edge columns and 20 for corner columns
$d =$ section effective depth;
$u1 =$ control perimeter according to ACI 318 (Figure A. 1).

For waffle slabs, the American code recommends that the ribs should have a minimum width (b_w) of 100 mm, a maximum height (h_b) of 3.5 times the minimum width of the rib and a maximum spacing between the faces of the ribs (s) of 750 mm. The thickness of the topping slab (hf) must be at least 37.5 mm and at most s/12 ratio (Figure A.1). For ribs without shear reinforcement, ACI 318 allows the shear strength to be estimated by Equation (A-5).

$$V_{ACI,s} = \frac{1}{6}\sqrt{f_c'}b_w d \qquad \text{A-5}$$

Where;

f_c' = compressive strength of concrete limited to 70 MPa
b_w = rib width considered
d = rib effective depth

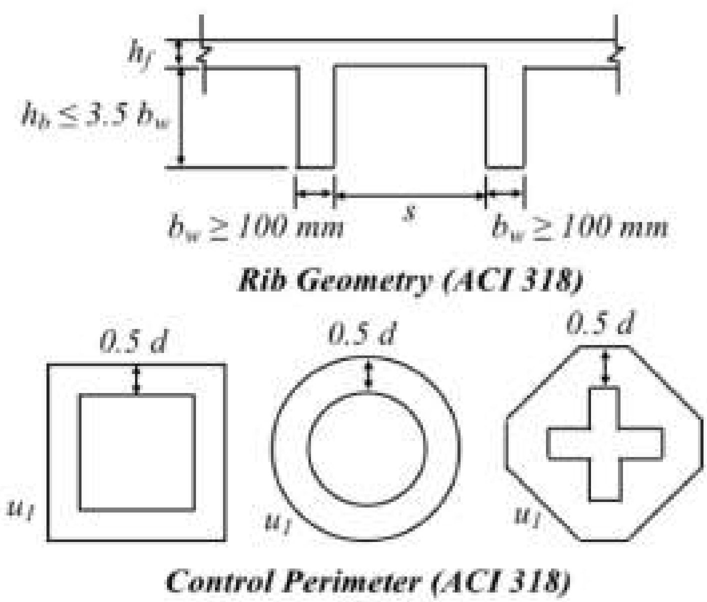

Figure A.1 Rib geometry and control perimeter according to ACI 318M

A.2.2 EUROCODE-1992-1 [2004]

According to the European code, the estimated punching shear load (V_{EC}, p) for slabs without shear reinforcement is given by Equation (A-6).

$$V_{EC,p} = 0.18\,\xi(100\rho_1 f_{ck})^{\frac{1}{3}} u_1 d \qquad \text{A-6}$$

Where;

f_{ck} = compressive strength of concrete in MPa.
ρ_1 = longitudinal reinforcement rate, not greater than 0.02.
$\xi = (1 + \sqrt{200/d})$
$\xi = (1 + \sqrt{200/d}) <= 2.0$.
d = section effective depth.
u_1 = control perimeter according to Eurocode.
For waffle slabs, EC2 recommends that the topping slab and the ribs do not need to be analyzed separately when there is sufficient torsional stiffness between these two elements, and the waffle slab can be analyzed as solid slab. However, this condition is only acceptable if the spacing between the faces of the ribs (s) does not exceed 1500 mm, if the height of the rib (h) does not exceed 4 times its width (bw) and if the height of the table (hf) is at least the greater of these two factors: (s/10) or (50 mm) (Figure 2). For ribs without shear reinforcement, EC2 allows the shear strength to be estimated using Equation (A-7).

$$V_{EC,s} = 0.18\,\xi(100\rho_1 f_{ck})^{\frac{1}{3}} b_w d \qquad \text{A-7}$$

f_{ck} = compressive strength of concrete in MPa.
ρ_1 = longitudinal reinforcement rate, not greater than 0.02.

$\xi = (1 + \sqrt{200/d}) <= 2.0$.

d = rib effective depth.
b_w = rib width considered.

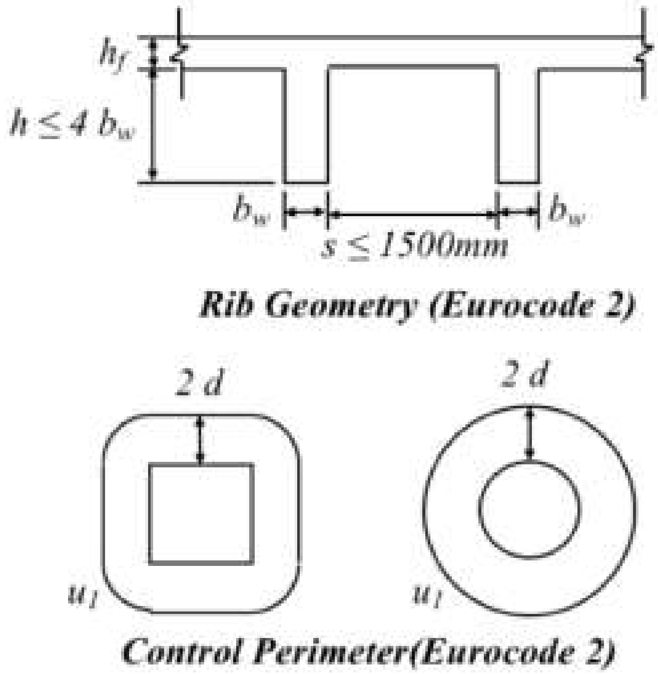

Figure A.2 Rib geometry and control perimeter according to Eurocode

A.2.3 CAN CSA S23.3- [2014]

According to the Canadian code, the estimated punching shear load (V_{CAN}, p) for Waffle slabs without shear reinforcement is given by Equation (A-8).

$$V_{CAN,p} = v_c = \gamma_c \lambda_t \sqrt{f_c'}\ .bo\ .d \qquad \text{A-8}$$

$$\gamma = \text{Min}\ \left[0.38\ , 0.19 + \frac{0.38}{\beta_c}, 0.19 + 4\frac{d}{b_o}\right] \qquad \text{A-9}$$

Where;

$f_c' =$ compressive strength of concrete in MPa.

$\sqrt{f_c'} \leq 8.0\ MPa$

d = section effective depth.

b_o = control perimeter according to CAN CSA S23.2, fig (A.3).

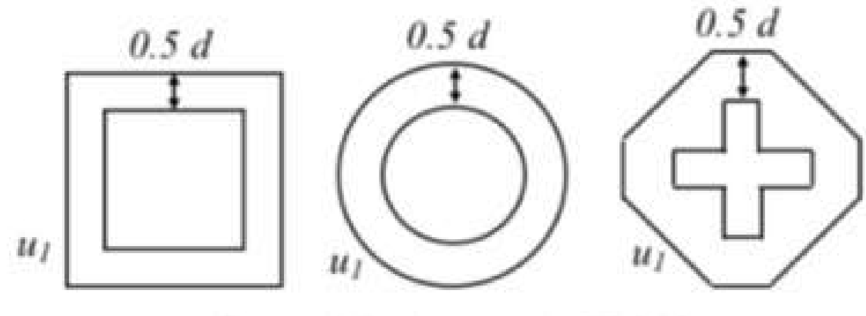

Figure A.3 Flat plat slab punching circumference according to CAN CSA S23.3-14

A.3 CALCULATIONS

1. Waffle Slab Design:

Design problem of an interior waffle slab with bay dimensions (1000 x1000 mm) center to center with total depth of (100 mm) supported on equally spaced column of (hw x S, 80 x 80 mm). Each slab consists of (h = 35 mm) deck flange thickness and (bw = 35 mm) rib width, and (85 x 65 mm) slab voids. Each waffle slab is constructed with (f_c' = 24.4 MPa) concrete compressive strength.

According to ACI 318 design code of waffle slab geometrical limitations, as shown in Figure (A.4), the following criteria should be applied;

Deck slab thickness ≥ 50 mm → assumed thickness = 175 ≥ 50 … ok.

Rib width ≥ 100 mm → assumed width = 175 ≥ 100 … ok.

Rib depth ≤ 3.5 bw → assumed rib depth = 325 ≤ 3.5x100 =350 … ok.

Rib spacing ≤ 750mm → assumed rib spacing = 425 ≤ 750 … ok.

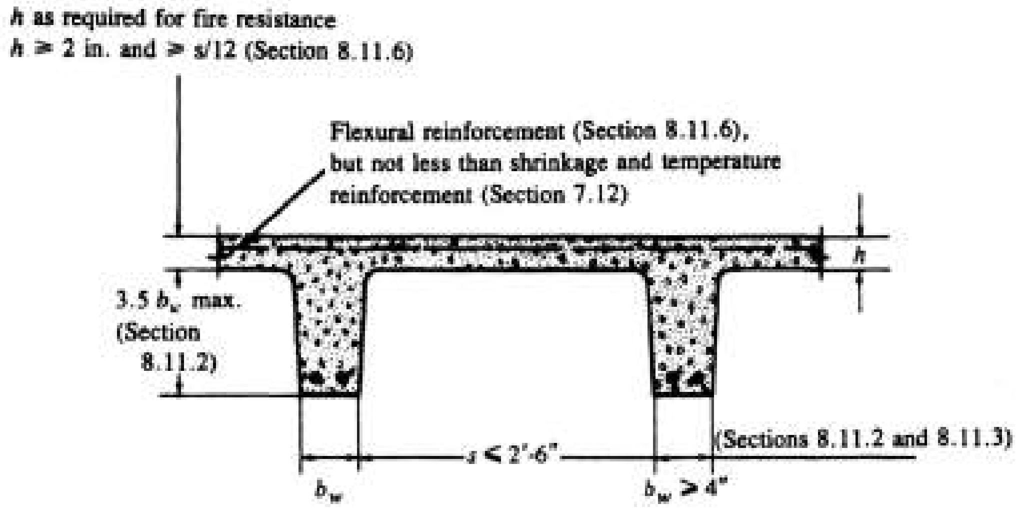

Figure (A.4) Limiting dimensions of concrete waffle slab, joist construction, and removable filler forms.

Applying the laboratory specimen testing scaled factor of 1/5th yields;

Deck slab thick = 35 mm

Rib width = 35 mm

Rib depth = 65 mm

Rib spacing = 85 mm

2. Punching Shear Calculations:

Strengthening mechanisms consistent with the rib's layout using sika-Wrap sheet with average thickness (0.167mm), tensile strength of (3000 MPa), elastic modulus (220 GPa), poisons ration (0.3).

Applying American Code of Concrete design, where punching shear load (VACI, p), for waffle slabs without shear reinforcement, is the lowest among Equations A-2, A-3 and A-4 as following.

$$V_{ACI,\,p} = 0.33\sqrt{fc'}\ u_1 d$$

$$V_{ACI,p} = 0.17\left(1 + \frac{2}{\beta_c}\right)\sqrt{f_c'}\ u_1 d$$

$$V_{ACI,p} = 0.083\left(2+\frac{\alpha_s d}{u_1}\right)\sqrt{f_c'}\ \ u_1 d$$

$$u_{1,ACI} = 4(c_1 + d)$$

$$u_{1,ACI} = 4(80+85) = \ 656\ mm$$

$$V_{ACI,\ p} = 0.33\sqrt{24.4}\ x\ 656\ x\ 85x10^{-3} = \ \ 89.83\ kN$$

$$V_{ACI,p} = 0.17\left(1+\tfrac{2}{1}\right)\sqrt{24.4}\ \ x656\ \ \ x85\ x10^{-3} = 138.81\ kN$$

$$V_{ACI,p} = 0.083\left(2+\frac{40_{\times}85}{656}\right)\sqrt{24.4}\ \ x\ 656\ \ \ x85\ x10^{-3} = 160.89\ kN$$

➔ Punching Shear Load (VACI, p) = 89.83 kN

Applying European Code of Concrete design Eq(A-6) and (A-7) as follows.

$$V_{EC,p} = 0.18\ \xi(100\rho_1 f_{ck})^{\frac{1}{3}} u_1 d$$

$\xi = (1+\sqrt{200/d})$ <= 2.0

$\xi = (1+\sqrt{200/85})$ = (> 2.0) ➔ use 2.0

$$u_{1,EC} = 4(c_1 + \pi d)$$

$$u_{1,EC} = 4(80 + 3.14\ \mathrm{x}\ 85) = 1376\ mm$$

$$V_{EC,s} = 0.18\ x2\ x\ (100\ \mathrm{x}\ 0.0095\ \mathrm{x}\ (24.4)\ \ )^{\frac{1}{3}}\ x\ 1376x\ 85\ x10^{-3} = 118.25$$

➔ Punching Shear Load (V_{EC2}, p) = 118.64 KN

Applying Canadian Code of Concrete design, where punching shear load (V_{CAN},p), for waffle slabs without shear reinforcement, is the lowest among Equations as following.

$$V_{CAN,p} = \ \ (0.19+\frac{0.38}{\beta_c})\ \ .\lambda_t\sqrt{f_c'}\ .bo\ .d$$

$$V_{CAN,p} = \left(0.19 + \frac{0.38}{1}\right) \text{ x1 x } \sqrt{24.4}\, x\, 656\, x\, 85\, x10^{-3} = 154.39\, kN$$

$$V_{CAN,p} = 4\frac{d}{b_o} \;.\lambda_t\sqrt{f_c'}\;.bo\;.d$$

$$V_{CAN,p} = 4\frac{85}{656} \; x\; 1\; x\; \sqrt{24.4}\, x\, 656\, x\, 85\, x10^{-3} = 138.73\, kN$$

$$V_{CAN,p} = 0.38\;.\lambda_t\sqrt{f_c'}\;.bo\;.d$$

$$V_{CAN,p} = 0.38 \text{ x } 1\; x\; \sqrt{24.4}\, x\, 656\, x\, 85\, x10^{-3} = 103.43\, kN$$

Where;

$b_{o,\text{CAN}} = 4(c_1 + \text{d})$
$b_{\text{o, CAN}} = 4(80 + 85) = 656\, mm$
$\lambda_t = 1$ {$normal\ weight\ concrete$}

➔ Punching Shear Load (V_{CAN}, p) = 103.43 kN

Strengthening Calculations:

the effective bonded length (l_e).

$$l_e = \sqrt{\frac{E_f t_f}{2 f_{ctm}}}$$

$f_{ctm} = 0.27 \cdot R_{ck}^{2/3}$

$f_{ctm} = 0.27 \cdot (30.5)^{2/3} = 2.63$ MPa

$$l_e = \sqrt{\frac{220 \text{x } 10^3 x\ 0.167}{2 \text{ x } 2.63}} = 84 \text{ mm}$$

Required CFRP length = Le + 4d + colum length

84 + 4 x 85 + 80

= 504 mm

Actual CFRP length = 620 > 504 mm

BUILDING TRUST

PRODUCT DATA SHEET

SikaWrap®-300 C

Woven unidirectional carbon fibre fabric, designed for structural strengthening applications as part of the Sika® strengthening system

DESCRIPTION

SikaWrap®-300 C is a unidirectional woven carbon fibre fabric with mid-range strengths, designed for installation using the dry or wet application process. Suitable for use in hot and tropical climatic conditions.

USES

SikaWrap®-300 C may only be used by experienced professionals.

Structural strengthening of reinforced concrete, masonry, brickwork and timber elements or structures, to increase flexural and shear loading capacity for:

- Improved seismic performance of masonry walls
- Replacing missing steel reinforcement
- Increasing the strength and ductility of columns
- Increasing the loading capacity of structural elements
- Enabling changes in use / alterations and refurbishment
- Correcting structural design and / or construction defects
- Increasing resistance to seismic movement
- Improving service life and durability
- Structural upgrading to comply with current standards

CHARACTERISTICS / ADVANTAGES

- Multifunctional fabric for use in many different strengthening applications
- Flexible and accommodating of different surface planes and geometry (beams, columns, chimneys, piles, walls, soffits, silos etc.)
- Low density for minimal additional weight
- Extremely cost effective in comparison to traditional strengthening techniques

APPROVALS / CERTIFICATES

- Poland: Technical Approval ITB AT-15-5604/2011: Zestaw wyrobów Sika CarboDur do wzmacniania i napraw konstrukcji betonowych.
- Poland: Technical Approval IBDiM Nr AT/2008-03-0336/1, Płaskowniki. pręty, kształtki i maty kompozytowe do wzmacniania betonu o nazwie handlowej: Zestaw materiałów Sika CarboDur® do wzmacniania konstrukcji obiektów mostowych.
- USA: ACI 440.2R-08, Guide for the Design and construction of Externally Bonded FRP Systems for strengthening concrete structures, July 2008.
- UK: Concrete Society Technical Report No. 55, Design guidance for strengthening concrete structures using fibre composite material, 2012.

PRODUCT INFORMATION

Construction	Fibre orientation Warp Weft	0° (unidirectional) Black carbon fibres 99 % White thermoplastic heat-set fibres 1 %
Fibre type	Selected mid-range strength carbon fibres	
Packaging	**Fabric length per roll** ≥ 100 m	**Fabric width** 500 mm

Product Data Sheet
SikaWrap®-300 C
June 2023, Version 01.03
020206020010000011

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Shelf life	24 months from date of production		
Storage conditions	Store in undamaged, original sealed packaging, in dry conditions at temperatures between +5 °C and +35 °C. Protect from direct sunlight.		
Dry fibre density	1.82 g/cm³		
Dry fibre thickness	0.167 mm (based on fibre content)		
Mass per area	304 g/m² ± 10 g/m² (carbon fibres only)		
Dry fibre tensile strength	4 000 N/mm²		(ISO 10618)
Dry fibre modulus of elasticity in tension	230 000 N/mm²		(ISO 10618)
Dry fibre elongation at break	1.7 %		(ISO 10618)

TECHNICAL INFORMATION

Design nominal thickness	0.167 mm		
Design nominal cross section	167 mm² per m width		
Laminate tensile strength	**Average** 3 500 N/mm²	**Characteristic** 3 200 N/mm²	(EN 2561*) (ASTM D 3039*)
Laminate modulus of elasticity in tension	**Average** 225 kN/mm²	**Characteristic** 220 kN/mm²	(EN 2561*)
	Average 220 kN/mm²	**Characteristic** 210 kN/mm²	(ASTM D 3039*)
	* modification: sample with 50 mm Values in the longitudinal direction of the fibres Single layer, minimum 27 samples per test series		
Laminate elongation at break in tension	1.56 % 1.59 %		(EN 2561) (ASTM D 3039)
Tensile resistance	**Average** 585 N/mm	**Charactorstic** 534 N/mm	(EN 2561) (ASTM D 3039)
Tensile stiffness	**Average** 37.6 MN/m 37.6 kN/m per ‰ elongation	**Characteristic** 36.7 MN/m 36.7 kN/m per ‰ elongation	(EN 2561)
	Average 36.7 MN/m 36.7 kN/m per ‰ elongation	**Characteristic** 35.1 MN/m 35.1 kN/m per ‰ elongation	(ASTM D 3039)

SYSTEM INFORMATION

System structure

The system build-up and configuration as described must be fully complied with and may not be changed.

Concrete substrate adhesive primer	Sikadur®-330
Impregnating / laminating resin	Sikadur®-330 or Sikadur®-300
Structural strengthening fabric	SikaWrap®-300 C

For detailed information on Sikadur®-330 or Sikadur®-300, together with the resin and fabric application details, please refer to the Sikadur®-330 or Sikadur®-300 Product Data Sheet and the relevant Method Statement.

APPLICATION INFORMATION

Consumption	**Dry application with Sikadur®-330**	
	First layer including primer layer	1.0 - 1.5 kg/m²
	Following layers	0.8 kg/m²
	Wet application with Sikadur®-300	
	Primer layer	0.4 - 0.6 kg/m²
	Fabric layers	0.6 kg/m²
	Note: Consumtion is for standard application only. Rough or uneven substrate surfaces, loss and wastage may lead to a higher consumption. Please refer to the relevant Method Statement for further information.	

BASIS OF PRODUCT DATA

All technical data stated in this Data Sheet are based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.

FURTHER INFORMATION

Please refer to the Method Statement of SikaWrap® manual dry application, SikaWrap® manual wet application or SikaWrap® machine wet application for further information, guidelines and limitations.

IMPORTANT CONSIDERATIONS

- SikaWrap®-300 C shall only be applied by trained and experienced professionals.
- A specialist structural engineer must be consulted for any structural strengthening design calculation.
- SikaWrap®-300 C fabric is coated to ensure maximum bond and durability with the Sikadur® adhesives / impregnating / laminating resins. To maintain and ensure full system compatibility, do not interchange different system components.
- SikaWrap®-300 C can be over coated with a cementitious overlay or other coatings for aesthetic and / or protective purposes. The over coating system selection is dependent on the exposure and the project specific requirements. For additional UV light protection in exposed areas use e.g. Sikagard®-550 W Elastic (G).

ECOLOGY, HEALTH AND SAFETY

This product is an article as defined in article 3 of regulation (EC) No 1907/2006 (REACH). It contains no substances which are intended to be released from the article under normal or reasonably foreseeable conditions of use. A safety data sheet following article 31 of the same regulation is not needed to bring the product to the market, to transport or to use it. For safe use follow the instructions given in the product data sheet. Based on our current knowledge, this product does not contain SVHC (substances of very high concern) as listed in Annex XIV of the REACH regulation or on the candidate list published by the European Chemicals Agency in concentrations above 0,1 % (w/w).

APPLICATION INSTRUCTIONS

SUBSTRATE QUALITY

Minimal substrate tensile strength: 1.0 N/mm² or as specified in the strengthening design.
Please also refer to the relevant Method Statement or further information.

SUBSTRATE PREPARATION

Concrete must be cleaned and prepared to achieve a laitance and contaminant free, open textured surface.
Please also refer to the relevant Method Statement for further information.

APPLICATION METHOD / TOOLS

The fabric can be cut with special scissors or a Stanley knife (razor knife / box-cutter knife). Never fold the fabric.
SikaWrap®-300 C is applied using the dry or wet application process.
Please refer to the relevant Method Statement for details on the impregnating / laminating procedure

LOCAL RESTRICTIONS

Note that as a result of specific local regulations the declared data and recommended uses for this product may vary from country to country. Consult the local Product Data Sheet for exact product data and uses.

LEGAL NOTES

The information, and, in particular, the recommendations relating to the application and end-use of Sika products, are given in good faith based on Sika's current knowledge and experience of the products when properly stored, handled and applied under normal conditions in accordance with Sika's recommendations. In practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The user of the product must test the product's suitability for the intended application and purpose. Sika reserves the right to change the properties of its products. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms of sale and delivery. Users must always refer to the most recent issue of the local Product Data Sheet for the product concerned, copies of which will be supplied on request.

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BUILDING TRUST

PRODUCT DATA SHEET

Sikadur®-330

2-component epoxy impregnation resin

DESCRIPTION

Sikadur®-330 is a 2-component, thixotropic epoxy based impregnating resin and adhesive.

USES

Sikadur®-330 may only be used by experienced professionals.

Sikadur®-330 is used as:
- Impregnation resin for SikaWrap® fabric reinforcement for the dry application method
- Primer resin for the wet application system
- Structural adhesive for bonding Sika® CarboDur® plates into slits

CHARACTERISTICS / ADVANTAGES

- Easy mix and application by trowel and impregnation roller
- Manufactured for manual saturation methods
- Excellent application behaviour to vertical and overhead surfaces
- Good adhesion to many substrates
- High mechanical properties
- No separate primer required

SUSTAINABILITY

- Conformity with LEED v4 MRc 4 (Option 2): Building Product Disclosure and Optimization - Material Ingredients
- Conformity with LEED v2009 IEQc 4.1: Low-Emitting Materials - Adhesives and Sealants

APPROVALS / CERTIFICATES

- Avis Technique N° 3/16-875 (annule et remplace N° 3/10-669) Sika® CarboDur®, SikaWrap®
- CIT n°290 18/07/2017 (certificato di idoneità tecnica all'impiego) ; Sika ® CarboDur®, SikaWrap®, Sikadur®
- Road and Bridges Research Institute (Poland): IBDiM No AT/2008-03-336/1
- Adhesive for structural bonding tested according to EN 1504-4, provided with the CE-mark

PRODUCT INFORMATION

Composition	Epoxy resin	
Packaging	5 kg (A+B)	Pre-batched unit
	Not pre-dosed industrial packaging:	
	Component A	24 kg pails
	Component B	6 kg pails
Colour	Component A: white paste Component B: grey paste Components A + B mixed: light grey paste	

Shelf life	24 months from date of production
Storage conditions	Store in original, unopened, sealed and undamaged packaging in dry conditions at temperatures between +5 °C and +30 °C. Protect from direct sunlight.
Density	1.30 ± 0.1 kg/l (component A+B mixed) (at +23 °C)
Viscosity	Shear rate: 50 /s

Temperature	Viscosity
+10 °C	~10 000 mPas
+23 °C	~6 000 mPas
+35 °C	~5 000 mPas

TECHNICAL INFORMATION

Modulus of elasticity in flexure	~ 3 800 N/mm² (7 days at +23 °C)	(DIN EN 1465)
Tensile strength	~ 30 N/mm² (7 days at +23°C)	(ISO 527)
Modulus of elasticity in tension	~ 4 500 N/mm² (7 days at +23 °C)	(ISO 527)
Tensile strain at break	0.9 % (7 days at +23 °C)	(ISO 527)
Tensile adhesion strength	Concrete fracture (> 4 N/mm²) on sandblasted substrate	(EN ISO 4624)
Coefficient of thermal expansion	4.5×10^{-5} 1/K (Temperature range −10 °C – +40 °C)	(EN 1770)

Glass transition temperature (EN 12614)

Curing time	Curing temperature	TG
30 days	+30 °C	+58 °C

Heat deflection temperature (ASTM D 648)

Curing time	Curing temperature	HDT
7 days	+10 °C	+36 °C
7 days	+23 °C	+47 °C
7 days	+35 °C	+53 °C

Resistant to continuous exposure up to +45 °C.

Service temperature	−40 °C to +45 °C

SYSTEMS

System structure	Substrate primer - Sikadur®-330. Impregnating / laminating resin - Sikadur®-330. Structural strengthening fabric - SikaWrap® type to suit requirements.

APPLICATION INFORMATION

Mixing ratio	Component A : component B = 4 : 1 by weight When using bulk material the exact mixing ratio must be safeguarded by accurately weighing and dosing each component.
Consumption	See the "Method Statement for SikaWrap® manual dry application" Ref 850 41 02. Guide: 0.7 - 1.5 kg/m²
Ambient air temperature	+10 °C min. / +35 °C max.
Dew point	Beware of condensation. Substrate temperature during application must be at least 3 °C above dew point.
Substrate temperature	+10 °C min. / +35 °C max.

Substrate moisture content	< 4 % pbw			
Pot Life	Temperature	Pot life	Open time	(EN ISO 9514)
	+10 °C	~90 minutes (5 kg)	~90 minutes	
	+23 °C	~60 minutes (5 kg)	~60 minutes	
	+35 °C	~30 minutes (5 kg)	~30 minutes	

The pot life begins when the resin and hardener are mixed. It is shorter at high temperatures and longer at low temperatures. The greater the quantity mixed, the shorter the pot life. To obtain longer workability at high temperatures, the mixed adhesive may be divided into portions. Another method is to chill components A+B before mixing them (not below +5 °C).

BASIS OF PRODUCT DATA

All technical data stated in this Product Data Sheet are based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.

IMPORTANT CONSIDERATIONS

Sikadur®-330 must be protected from rain for at least 24 hours after application.
Ensure placement of fabric and laminating with roller takes place within open time.
At low temperatures and / or high relative humidity, a tacky residue (blush) may form on the surface of the cured Sikadur®-330 epoxy. If an additional layer of fabric or a coating is to be applied onto the cured epoxy, this residue must first be removed with warm, soapy water to ensure adequate bond. In any case, the surface must be wiped dry prior to application of the next layer or coating.
For application in cold or hot conditions, pre-condition material for 24 hours in temperature controlled storage facilities to improve mixing, application and pot life limits.
For further information on over coating, number of layers or creep, please consult a structural engineer for calculations and see also the "Method Statement for SikaWrap® manual dry application" Ref 850 41 02.
Sikadur® resins are formulated to have low creep under permanent loading. However due to the creep behaviour of all polymer materials under load, the long term structural design load must account for creep. Generally the long term structural design load must be lower than 20-25% of the failure load. Please consult a structural engineer for load calculations for the specific application.

ECOLOGY, HEALTH AND SAFETY

For information and advice on the safe handling, storage and disposal of chemical products, users shall refer to the most recent Safety Data Sheet (SDS) containing physical, ecological, toxicological and other safety-related data.

APPLICATION INSTRUCTIONS

SUBSTRATE QUALITY

Substrate must be sound and of sufficient tensile strength to provide a minimum pull off strength of 1.0 N/mm² or as per the requirements of the design specification.
See also the "Method Statement for SikaWrap® manual dry application" Ref 850 41 02.

SUBSTRATE PREPARATION

See the "Method Statement for SikaWrap® manual dry application" Ref 850 41 02.

MIXING

Pre-batched units:
Mix components A+B together for at least 3 minutes with a mixing spindle attached to a slow speed electric drill (max. 300 rpm) until the material becomes smooth in consistency and a uniform grey colour. Avoid aeration while mixing. Then, pour the whole mix into a clean container and stir again for approx. 1 more minute at low speed to keep air entrapment at a minimum. Mix only that quantity which can be used within its pot life.

Bulk packing, not pre-batched:
First, stir each component thoroughly. Add the components in the correct proportions into a suitable mixing pail and stir correctly using an electric low speed mixer as above for
pre-batched units.

APPLICATION METHOD / TOOLS

See the "Method Statement for SikaWrap® manual dry application" Ref 850 41 02.

CLEANING OF EQUIPMENT

Clean all equipment immediately with Sika® Colma Cleaner. Cured material can only be removed mechanically.

LOCAL RESTRICTIONS

Please note that as a result of specific local regulations the declared data for this product may vary from country to country. Please consult the local Product Data Sheet for the exact product data.

LEGAL NOTES

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الخلاصة

قدمت هذه الرسالة بحثًا تجريبيًا تم إجراؤه لتقييم سلوك القص الثاقب لبلاطات الوافل الخرسانية المقواة بألياف الكربون البولمرية (CFRP) الملصقة خارجيًا. الهدف الأساسي من هذه الدراسة هو إنشاء منهجية عملية لتعزيز قدرة القص لبلاطات الوافل الخرسانية المسلحة دون إحداث تغيير كبير في الهيكل الداخلي لبلاطة الوافل. اختارت هذه الدراسة تحليل أداء تقوية بلاطات الوافل باستخدام فئتين فقط الاولى ذات المساحة الصلبة بابعاد (275 × 275 مم) والثانية (515 × 515 مم) على التوالي. تتكون الفئة الاولى من ثمانية بلاطات ، وكانت بلاطة واحد بدون تقوية كبلاطة مرجعية ، وتم تقوية البلاطات المتبقية. بينما تتكون الفئة الثانية من بلاطتين فقط. تم إجراء الاختبارات الإنشائية على عشر عينات من بلاطات الوافل بأبعاد (1000 × 1000 مم) وسمك (100 مم) ، ومقطع عرضي للفراغات (65 × 85 مم) لجميع عينات الوافل تحت التحميل الأحادي المركز ، لمحاكاة الظروف في لوح الوافل المدعوم على وصلات الأعمدة الداخلية. كما تم إجراء سلسلة من الاختبارات على المواد. المتغيرات التي تم النظر فيها هي: المساحة الصلبة بدون تقوية ، المساحة الصلبابة مع التقوية ، شكل و مساحة CFRP.تم صب جميع العينات في وضع رأسي لمحاكاة موضع الصب للنموذج الأولي ولكن تم اختبارها بطريقة عكسية ، والعينات مدعومة على مساند عند أربعة جهات ، وتم تحميلها مركزيًا. على الرغم من أن آلية فشل التثقيب الملحوظة لبلاطات الوافل كانت مشابهة لتلك الموجودة في البلاطات التقليدية ، فقد تم ثقب جميع بلاطات الوافل في وضع مفاجئ. أظهرت النتائج أن بلاطة الوافل الفئة الاولى الغير المقوى قد عانى من القص الثاقب وتصرف بطريقة مماثلة للبلاطات التقليدية ، مما يشير إلى الامتثال للقوانين فيما يتعلق بأحكام مقاومة القص الثاقب. أظهرت النتائج أن مساحة مربعة صلبة يقل طولها عن 15٪ من الامتداد الكلي لفضاء البلاطة. يتم تقليل سعة القص نسبيًا لأن بعض سطح الفشل المحتمل يتم فقده عندما يمتد إلى قسم الوافل. تم تقوية الفئة الأولى بمساحة صلبة (275 × 275) بالياف CFRP ومقارنتها بالبلاطة المرجعية. تظهر نتائج الاختبارات أن بلاطات الوافل ذات المساحات الصلبة الصغيرة يمكن تقويتها بألواح CFRP الملصقة خارجيًا. حيث أظهرت النتائج التجريبية أن تقوية CFRP زادت من حمل التثقيب النهائي للبلاطات الوافل بنسبة (11.09- 47.11)٪ ، كما زاد حمل التكسير الأول بنسبة (4.26-67.02)٪.أيضاً أظهرت البلاطات المقواة انحرافًا أقل أثناء التحميل بحوالي (21.46)٪ مقارنة بالبلاطة المرجعية غير المقواة. يعزز تقوية بلاطات الوافل بالياف الكاربون البوليمرية من قدرتها على التحميل في كلتا الفئتين. ومع ذلك ، فإن تطبيق شكل الشبكة ، في الفئة الأولى ، يحسن بشكل كبير من سلوك بلاطة الوافل. في المقابل ، لا يؤثر نفس شكل التقوية بشكل كبير على سلوك الفئة الثانية مع نسبة تقوية تكاد تكون غير محسوسة تقريبًا. تظهر النتائج أن تطبيق

تقوية CFRP على بلاطات الوافل بمساحة صلبة والتي يقل طولها عن 15٪ من الامتداد للفضاء من سنتر العمود، يمكن أن يزيد من سعة التحميل القصوى ويعزز صلابة بلاطات الوافل المقواة ، وبالتالي يقلل من انحراف ألواح الوافل. وضع الفشل الأكثر شيوعًا لبلاطات الوافل المقواة هو فشل التثقيب الهش.

جمهورية العراق

وزارة التعليم العالي والبحث العلمي

كلية الهندسة/جامعة ميسان

قسم الهندسة المدنية

دراسة تجريبية للقص الثاقب لبلاطات الوافل الخرسانية المقواة بألياف الكاربون البولمرية

من قبل

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رسالة

مقدمة الى كلية الهندسة – جامعة ميسان

كجزء من متطلبات الحصول على درجة الماجستير في علوم الهندسة المدنية / الانشاءات

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