IMPROVEMENT OF PUNCHING SHEAR STRENGTH OF REINFORCED CONCRETE SLABS USING ALUMINUM SHEET STIFFENERS

A THESIS

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(Structures)

BY

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بسم الله الرحمن الرحيم

فَدَعَا رَبَّهُ أَنِّي مَغْلُوبٌ فَانْتَصِرْ ۞

فَفَتَحْنَا أَبْوَابَ السَّمَاءِ بِمَاءٍ مُنْهَمِرٍ ۞

وَفَجَّرْنَا الْأَرْضَ عُيُونًا

صدق الله العظيم

سورة القمر الجزء السابع والعشرون

To my mother …

To my brothers…

To my sisters…

To my wife …

And all my friends

With entire my honorary and my respect

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Haidar Hassan Haidar

2016

Certification

I certify that this thesis entitled "**Improvement of Punching Shear Strength of Reinforced Concrete Slabs Using Aluminum Sheet Stiffeners"** was prepared by **Haidar Hassan Haidar** under my supervision at University of Basrah / College of Engineering – Department of Civil Engineering, in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering (Structures).

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Examining Committee's Report

We certify that we have read this thesis titled **"improvement of punching shear strength of reinforced concrete slabs using aluminum sheet stiffeners"** which is being submitted by **Haidar Hassan Haidar** and as Examining Committee, examined the student in its contents. In our opinion, the thesis is adequate for award of Master Degree of Science in Civil Engineering.

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ABSTRACT

The aim of this study is to investigate the potential effect of externally bonded aluminum sheets to improve punching shear strength of reinforced concrete slabs and compare the results with design codes.

The experimental program includes testing a total of 16 slabs (800 x 800 x 100) mm. The slabs are divided into two groups according to compressive strength; the first group consists of nine normal concrete slabs and second group consists of seven high strength concrete slabs. In each group, one slab is left without strengthening as a control slab, while the remaining slabs have a different aluminum sheets distribution.

The effect of amount of aluminum sheets (0.16, 0.24, 0.32) m^2 (plan area), width of aluminum sheets (100 and 50) mm, and location of aluminum sheets in addition to concrete strength on the punching shear strength of slabs are studied. All slabs in this study are designed to fail in punching shear.

During the test, the slabs are simply supported on all four edges and loaded centrally by a (80 x 80) mm column. Load deflection curves, cracking patterns and effect of variables on the test results are discussed.

Experimental results showed that, the strengthening by aluminum sheets increased the ultimate punching load of the slabs by (5-41) %, the first cracking load by (11.58-53.57) %. The strengthened slabs showed less deflection during loading by about 40% compared to the control slabs.

Also, the results showed that the increase in ultimate punching load for normal strength concrete (fcu=30) MPa, is between (25-41)% more than for high strength concrete (fcu=65) MPa, which is between (5-29)%.

increasing the plan area of aluminum sheets lead to increase of the ultimate punching load, whereas with constant area of aluminum (plan area), the

width of sheets 100 mm or 50 mm was found to have no effect on the slabs punching strength.

Slabs strengthened with plan area of aluminum sheets (0.16) m^2 for three different locations (0.5d, 1.5d and 2d) from column face are investigated. The distance (0.5d) gives high punching load.

The results are compared with predicted punching shear strength by design models of the **ACI 318-11Code**, **the BS8110-1997** and **Eurocode 2-2004.** The design codes provide very conservative for predicted punching shear strength.

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Nomenclature

Symbol	Description
Afp	Cross-sectional area of CFRP sheets.
As	Cross-sectional area of internal ordinary steel.
b	Perimeter of the loaded area
bo	Perimeter of critical section
c or r	Side length of the square column
d	Effective depth of the slab
Ec	Modulus of elasticity of concrete
Ef	Modulus of elasticity of CFRP fibers.
Es	Modulus of elasticity of steel
f_{fu}	Ultimate strength of CFRP sheets.
$f'c$	Concrete cylinder compressive strength
$f_{0.1}$	Stress at 0.1% offset strain for aluminum.
$f_{0.2}$	Stress at 0.2% offset strain for aluminum
f_{cu}	Concrete cube compressive strength
ft	Minimum tensile strength (or ultimate stress) for aluminum
fy	Yield strength of steel reinforcement
h	Slab thickness.
m	flexural moment per unit width of CFRP strengthened slab (N m/m)
n	Total number of CFRP strips per slab width of b.
P	Any applied force on the structure.
P_{flex}	The load that causes flexural failure in slab (N)
Pu	Ultimate punching shear load that causes punching shear failure
pvs	Punching shear strength by Rankin and Long.

$ß_C$	Ratio of long side to short side of the column
Vu	Ultimate punching strength of the concrete slab
W/C	Water to cement ratio
ά	Concrete strength factor .
v	Poisson's ratio.
ρ_b	Balanced steel ratio
ρ_{max}	Maximum steel ratio at insure tension failure
ρs	Steel reinforcement ratio
φ	Strength reduction factor

Abbreviations

Abbreviations	Description
ACI	American Concrete Institute.
AFRP	Aramid Fiber Reinforced Polymer.
ASTM	American Society for Testing and Materials.
B.S	British Standards
CFRP	Carbon Fiber Reinforced Polymer.
CRCA	Coarse recycled concrete aggregates
FEM	Finite Element Method
FRP	Fiber Reinforced Polymer.
GFRP	Glass Fiber Reinforced Polymer.
HM	High Modulus of elasticity.
HS	High Strength.
HSC	High Strength Concrete
LWAC	light weight aggregate Concrete
NCA	Natural coarse aggregates
NSC	Normal Strength Concrete
NSM	Near Surface Mounted.
RC	Reinforced Concrete.

CHAPTER ONE

INTRODUCTION

1.1 General

The reinforced concrete flat plate is an economical and popular structural system. It consists of a two-way slab of uniform thickness cast monolithically with columns. Beams, drop panels, and capitals are not used [1].

Flat plate can be built relatively rapidly because the absence of drop panels results in simpler formwork arrangements, enabling rapid floor construction, and giving maximum flexibility to the occupants. In addition, flat slab helps minimizing floor-to-floor heights. This provides advantages in terms of lower building height and reduced installation costs [2]. The disadvantages of flat plat are high shear stress near column and excessive long term deflection.

Punching shear failure is one of most popular failure modes in flat slabs. It occurs around concentrated load on a slab or a column. This failure is accompanied with a special mechanism of collapse in which sudden and an inverted conical plug of concrete slab above the column is isolated. Punching shear failure occurs with almost no warning signs because deflections are small and cracks at the top side of the slab are usually not visible [3].

In flat slabs the load transfer between the slab and the column induces high stresses near to this last that incite to cracking and even failure. The punching shear failure is associated to the formation of a cone-shaped element. This shape is a result of the interaction between the shear effects and flexion in a region close to the column. In a flat slab under uniformly distributed loads, cracks will first appear near the columns. With the increase of the load, other cracks will appear parallel to the columns sides forming what know as tangential cracking.

There will be radial cracks as well starting from the columns forming several radial parts. When in failure, tangential cracks propagate in an inclined surface from the slab side in tension until the intersection between the column with the slab side in compression. This will then form the already mentioned cone-shaped element [4].

The punching shear strength in a flat slab depends on the slab geometry, loaded area, slab thickness, concrete strength and amount of reinforcement (either flexural or punching shear reinforcement). The transferred moments between the slab and the column, the slab particularities (e.g.: openings), and the position of the column (center, edge or corner) influence the punching shear force as well [4]. The punching shear failure of flat slab is demonstrated in Fig. (1.1) [4].

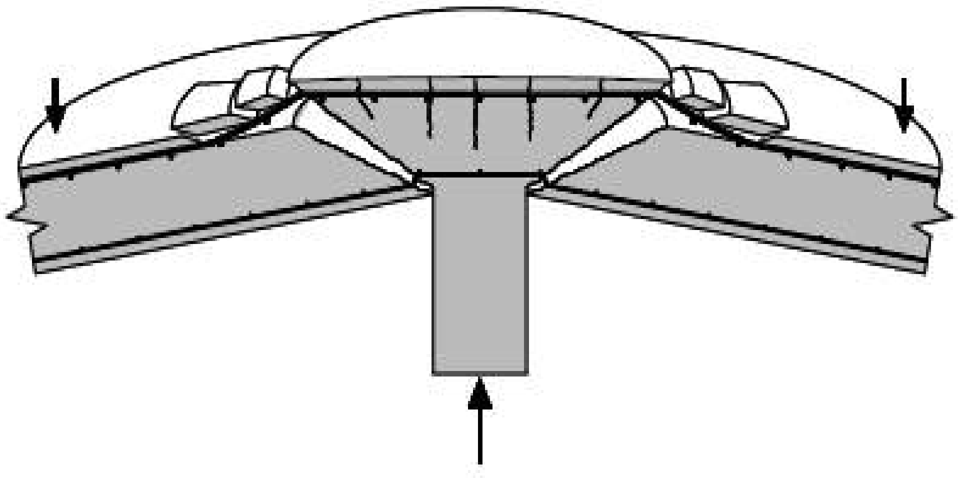


Figure (1.1) Punching failure of flat slab near the vicinity of column[4].

Popular reasons that cause punching shear failure are the following [5]:

- Bad details and unsuitable design for punching shear capacity.
- Loading of structure early before the concrete reaches sufficient strength or poor quality of construction or quick construction causing low concrete strength.

- Additional loading such as wind loading, earthquakes, big effect of fire and extent of building by increase number of stories or change of building uses.

Figure (1.2) show typical punching shear failure in Piper's Row Car Park, Wolverhampton, UK, 1997 (built in 1965).

Figure (1.2) punching shear failure in Piper's Row Car Park, Wolverhampton, UK, 1997.

1.2 Aluminum

Aluminum is the third most popular element in the earth's crust it is coming after silicon and oxygen. Aluminum is the most plentiful metal and makes up 8% of the crust total mass [6].

Pure aluminum is not suitable for structural applications because of the low values of its mechanical characteristics. In order for aluminum to be useful as a structural metal, it was essential to develop suitable alloys. However, many alloys are available with a large variety of excellent mechanical and physical qualities. The appropriate alloy depends on the specific application. The (6xxx series alloys) are the most useful for structural applications because of their combination of strength, corrosion resistance, and weldability [6].

Generally the advantages of aluminum alloys are [7]:

a. Low density, of approximately one third of steel.
b. Good strength and toughness properties.
c. Large variety of possible cross-sectional shapes of profiles and connection elements.
d. Good workability.
e. High corrosion resistance due to a tough oxide-layer.
f. Excellent to recycle without a decrease in quality.

To increase strength of aluminum alloys, a cold working process is used, this process slightly increase strength ($f_{0.2}$ = 100 MPa) and reduce of ductility. Another way of increasing the strength of the material is to alloy aluminum with another element (AlMg alloys) and the high strength can be obtained if heat treatment is applied. The strength goes up to ($f_{0.2}$ =250 MPa) in AlMgSi alloy, and can reach ($f_{0.2}$=350-400 MPa) in AlZn and AlCu alloys[8].

A comparison of the stress – strain curves of AlMgSi alloy which are used in this study and Fe360 steel in Fig. (1.3) it can be observed that aluminum alloys have a strain–hardening portion without a horizontal line corresponding to yielding. It is clearly shown that the ultimate elongation is lower than that of steel and the (f_t / $f_{0.2}$) ratio is lower than that of steel (1.2 against 1.5). Both materials behavior linearly elastic up to the elastic limit. They differ in inelastic behavior. On other hand Aluminum is lighter than steel, the specific weight is (2700 kg/m^3) for aluminum and (7800 kg/m^3) for steel [8].

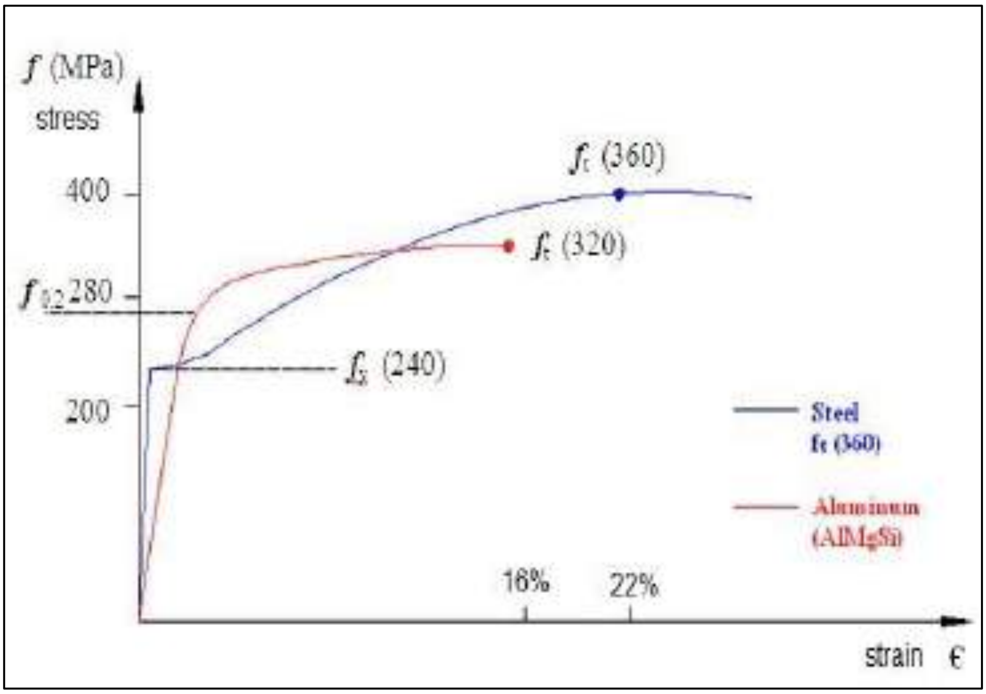


Figure (1.3) Stress-strain curves for (AlMgSi alloy and Fe360 steel).

1.3 Strengthening and Retrofitting Techniques of Existing Reinforced Concrete Elements

The strengthening of reinforced concrete structures is often required due to design stage errors, construction stage errors, inadequate maintenance, over loading at service stage, accidental damages and reduction of capacity due to aging and environmental effect. Some sort of upgrading is required for those structures to overcome the problem [9].

Also, one of the challenges to Improvement and strengthening of concrete structures is the choice of a method that can enhance the strength and treatment limitatione such as building operations, constructability and cost. Strengthening and rehabilitation are accomplished either by reducing the magnitude of the internal forces or by enhancing the resistance of the existing structure to them

[10]. A common strengthening method and retrofitting technique for upgrading punching shear capacity of existing concrete flat slabs are strips or laminates of CFRP (carbon fiber reinforced polymer), steel plates and shear studs or shear bolts. Strips of CFRP are constructed by adhesively bonding to the surface of concrete member in order to repair them or increase their capacity [11].

The steel plates are bonded to the concrete members by use of epoxy adhesives and in some cases additional fastening is provided by bolts glued to the holes drilled in the concrete members [12]. Shear studs or bolts are inserted vertically through the holes which are made in concrete slabs around the columns [13].

1.4 Strengthening of Concrete Flat Slab by Using Aluminum sheets

To select a particular structural material for a given application, its properties are evaluated and compared with other competing materials. The following points reflect powerful properties of aluminum which will be active when utilizing those materials in this study.

1. High strength to weight ratio.
2. Corrosion resistance.
3. Good workability and ease of application. Aluminum can also be recycled, which gives environmental advantages.

The disadvantages of aluminum can be summer as follows:

1. Aluminum does not rust and can normally be used unpainted. However, the strongest alloys will corrode in some hostile environments due to chemical reaction.
2. Aluminum is difficult to weld, the use of adhesive bonding is well established as a valid method for making structural joints in aluminum.

3. Strain values of concrete, steel and aluminum are (0.0035, 0.003 and 0.016) respectively.

1.5 Adhesive bonded connections

The use of epoxy-resins could be profitable tools for optimizing some connection problems as well as for maximizing economy.

Generally the advantages of using adhesion bonded connections are:.

- Eliminating concentrated stresses.
- Eliminating the risk of fatigue damage in connector.
- Avoiding the reduction of aluminum strength due to the heat of connectors welding.

1.6 Objectives of the Study

The main objective of this study is to investigate the behavior of concrete flat slab strengthened with aluminum sheet under punch loading. For this purpose, experiments have been performed on reinforced concrete slabs strengthened externally with different configuration of aluminum sheets subjected to concentrated loadings.

The effect of the variables: the amount of aluminum (number of strip layers, width of strip and location of aluminum strip) and compressive strength of concrete (two target strengths), are varied to assess their effects on the punching strength of RC flat slabs.

1.7 Thesis Layout

The thesis is organized in five chapters. The current chapter is being the ***first***.

Chapter two presents literature review concerning the experimental and theoretical studies of the strengthened concrete slabs failed in punching shear.

Chapter three illustrates the details of the experimental work.

The results and behavior of the tested concrete slabs are demonstrated and discussed in ***chapter four.***

Finally, the main conclusions drawn from the study and recommendations for future works are demonstrated in ***Chapter five***.

CHAPTER TWO

REVIEW OF LITERATURE

2.1 Introduction

The aim of this chapter is to present a brief review for the available information concerning the behavior of reinforced concrete flat slabs that fail in punching shear with a special emphasis on the commonly strengthening techniques used for these slabs to increase their punching shear capacity.

The review considers the following aspects:

1. Punching shear resistance of concrete slab.
2. Punching shear resistance of concrete slab strengthened with CFRP, steel plates and steel bolts.
3. Building codes approaches for predicting punching shear.

2.2 Punching Shear Resistance of Flat Slabs

Graf (1933) [14] investigated the shear strength of slabs loaded by concentrated loads near the supports. The main conclusion was the shear strength increases with the increase of concrete strength.

Whitney (1957) [15] carried out a series of tests for slabs supported around its perimeter and loaded through a column stub in the center. The primary test parameters were strength of steel and concrete, size and spacing of bars, position of loading, depth to span ratios, and column size. Based on analysis of experimental results obtained from tests on slabs, it was concluded that all of these variables greatly influenced on the shear strength of slabs.

Long and Bond (1967) [16] conducted a theoretical analysis of the punching shear problem for round slabs without shear reinforcement. They concluded that punching strength in slab was strongly dependent on the flexural strength especially for slabs having factual amount of reinforcement.

Long (1975) [17] derived a formula to predict the punching shear resistance of slabs at interior columns. The predicted load for a slab was taken from the following equation (in imperial units):-

$$Vu = 16(r+d)d(100\rho)^{0.25}\sqrt{f'c}/(0.75+4r/l) \quad \text{..... (2.1)}$$

where; *L* is the span between center to center of columns(mm).
r: column width or length of side square of load region (mm).
d: distance from reinforcement of tension to upper compression zone (mm) .
For previous equation, he assumed the critical section to be located at a distance (d/2) from column face.

Rankin and Long (1987) [18] proposed an equation for estimating the punching shear strength of conventional slab-column connections the proposed formula was:

$$P_{vs}=1.66\sqrt{f'c}(c+d)d*d\sqrt[2]{100\rho} \quad \text{.....(2.2)}$$

where : f′c: is the cylindrical compressive strength in MPa

ρ: is the reinforcement ratio, As/bd.

P_{vs}: is the punching shear strength in N.

The influence of concrete compressive strength and reinforcing steel ratio on punching shear of RC slabs were investigated by **Grander (1990)** [19]. The test results showed that the shear capacity was proportionate to the cubic root of concrete strength and steel ratio as shown in equation below:

$$Vu = 0.99(\rho fc')^{1/3}(400/d)^{1/4} \quad \text{..... (2.3)}$$

where; Vu: ultimate shear load in N.

ρ: The reinforcement ratio.

d: The effective depth of slab (mm).

Marzouk and Hussein (1991) [20] investigated the structural behavior of flat slabs casted by high strength concrete (HSC) by an experimental program for seventeen square specimens. The variables were the reinforcement ratio, concrete strength, slab depth and column size. The test results showed that the two main modes of punching failure of HSC slabs can be classified as flexure-punching and punching shear. The deformations of HSC slabs that failed due to flexure-punching were larger than those that failed due to punching shear. When steel reinforcement ratio increases, slab stiffness and ductility were increased. Also, they observed that the angles of the failure surface were ranged from 32 to 38 degrees with the horizon for HSC slabs.

Tomaszewicz (**1993) [**21] tested nineteen square flat slabs witout reinforcement for shear. A concentrated load at center was used for all slabs to reach the failure by punching shear. All edges of slabs were simply supported. Concrete strength, flexural reinforcement ratio and slab thickness were considered as the variables. The results showed that the increase of slab thickness, concrete strength and column size increases punching shear capacity.

Munahey (1995) [22**]** experimentally Investigate**d** the action of the amount of flexural reinforcement, size of column and compressive strength on the punching shear capacity of reinforced concrete flat slabs. The dimensions of twelve specimen slabs were (850 x850) mm with constant depth (75) mm and all slabs were loaded by concentrically a square column. The test results showed that the increase in size of column or concrete compressive strength leads to increasing a ultimate load, first crack load and detraction the deflection under load. Also, he concluded that the number of cracks reduces when the ratio of flexural reinforcement increase.

Ramadane (1996) [23] studied the effect of concrete strength on the punching shear strength of 18 square slabs. The concrete strength varied from (30 to 100) MPa. All slabs were without shear reinforcement but have equal flexural reinforcement in two directions. Under the center of the slabs punching load was applied by column. The test results showed that increasing concrete compressive strength produces increases punching shear resistance.

Tuan (2001) [24] compared the value of punching shear calculated from Australian standard for concrete structures (AS3600) 1994, with twenty nine test results from four research studies. slab reinforcement ratio, slab depth and concrete strength were the variable presented in these four approaches. It was concluded that the punching shear resistance improved and allowed higher forces to transport through the column-slab connection when using high strength concrete. Also, it was found that the comparison of experimental results shows that AS3600 formula is applicable up to 100 MPa.

Povilas et al. (2002) [25] depending on computer modeling of slab-column joint, conducted a theoretical investigation for behavior of punching shear. Ratio of bending moment to shear force, ratio of slab thickness to column depth and ratio of span to slab thickness and flexural reinforcement were the variables. The result showed that the slabs were punched out as pyramid having plane slope angle change from 33° for reinforced slabs to 45° for slabs without reinforcement. Also that the magnitude of punching load depended on ratio of bending moment and shear forces influential within critical section. They also found that the punching shear capacity increases if the ratio of flexural reinforcement increases in punching shear region.

Zhang (2003) [26] studied the effect of concrete strength, reinforcement ratio, slab depth and column size on the punching shear strength of seventeen high strength concrete slabs (HSC). The test results indicated that punching shear strength depends on a power of the concrete compressive strength. He assumed the perimeter of critical section located at (0.5d) from the loaded area, and the reinforcement ratio had a great influence on punching shear resistance especially when the slab depth was at a high value. Also, he concluded that punching shear capacity increases if size of the column increases too.

Ahmed (2005) [27] experimentally investigated the punching shear resistance by testing twenty seven normal and high strength concrete slabs. He divided the experimental results to three groups and analysis it. These groups were based on three variables which include the slab thickness, size and shape of column and concrete strength. One of conclusions was the size of the failure zone increases when increases column dimension or compressive strength. Also, the punching shear strength increases and deflections decreases at all phase when the concrete compressive strength increases.

Guandalini et al. (2009) [28] studied behavior of punching shear strength for slabs by molding and testing set of slabs. Size of aggregate, slab dimensions and flexural reinforcement were the variables. They compare the results with design codes. They concluded that the formula of (ACI 318-08) is more conservative for evaluated punching load for low ratio of reinforcement and thick slabs. They obtained satisfying results when they use (Euro code 2).

Al khafaji et al. (2009) [29] inspected sixteen reinforced concrete flat slabs propped by couple columns to investigate the behavior of the punching shear capacity. All specimens with normal concrete were tested and restrained on all sides as simply supported. The slabs dimensions were (850*470*50) mm. Net distance between columns and column shape were considered in a parametric study. Specimens were divided into two series depending on column shape, every series had eight specimens. The first series had couple square column with (75x75) mm dimensions and (0.05 d to 9.30 d) net distance between columns. The second series had couple circular columns with (85) mm diameter with same clear distance between columns were used as in first series. The results showed that at (9.3 d and 9 d) net distance between columns, zone of failure was split up into two zones and the ultimate load approaches the upper rate, and when the net distance is equivalent to (0.05 d to 7 d), the failure zone was split up into one zone decreasing the maximum ultimate load by (6.5 to 33.9 %) and by (16.4 to 35.9 %) for first series and second series respectively. Slabs with circular columns were found to have punching shear capacity greater than the slabs with square columns, when the area of cross section for square and circular columns are similar and the net distance between columns are the same.

Hoang (2011) [30] studied the effect of first crack of reinforced concrete slabs on the punching shear strength. Square specimens with dimensions (1050 x1050 x 150) mm were casted and tested. The patterns of initial crack were formed by mechanistic tension, uniaxial as well as biaxial. Widths of cracks at the maximum of the tension applied were (0.20 - 0.55) mm. After occurrence of the cracks and prior to punching shear testing the axial force was removed. Results showed no considerable strength decrease compared with strength of non-cracked slabs. This indicates that as far as punching strength is concerned, no precaution needs to be taken for slabs suffering axial cracking.

Ammash et al. (2012) [31] offered simple exact equation to estimate the punching shear strength for reinforcement concrete flat slabs for normal and high compressive strength. The influence of slab thickness, flexural reinforcement ratio, concrete strength, column dimension and location of critical section were considerable. The results from suggested equation were compared with experimental data from 58 cases. They suggested the following equation:-

$$Vc = \alpha f'c\gamma\beta_{\circ}d \qquad \text{.....(2.4)}$$

Where;

vc: punching shear resistance of concrete in N.

$\gamma = 0.5$ For $f_{c}` < 80$ MPa

$\gamma = 0.71 - 0.0028f_c$ For $f_{c}` \geq 80$ MPa but $\gamma \geq 0.45$

$\alpha = 0.8(\frac{(15+350\rho)\rho a}{\beta_0 d} + 0.425)$

a = diameter of column (if circular column) or the bigger dimension of column (if rectangular column).

β_0= perimeter of critical section.

d = effective depth.

ρ = reinforcement ratio

It was concluded that increasing of compression strength, tension reinforcement ratio, and slab thickness will increase the punching shear strength but to limit stages. It was also shown that the slabs supported by square column have bigger punching shear resistance than those supported by circular column.

2.3 Strengthening of Existing Flat Slabs For Punching Shear Resistance with CFRP

Harajli and Soudki (2003) [32] investigated by experimental work the capacity of punching shear of slab column internal connection strengthened by carbon fiber reinforced polymer (CFRP) strips. They tested sixteen square specimens having dimensions (670*670) mm, with two reinforcement ratios (1 and 1.5) % and various slab depth (55 and 75) mm. Four slabs were left as controls.

On tension face of specimens the CFRP strips were installed in orthogonal way. As shown in Figure. (2.1). All specimens were designed to fail in punching shear. Results showed considerable improvements of slab column connection in shear capacity, flexural durability, and stiffness when using of CFRP. Increase in flexural strength of almost (26 to 73) % and in shear capacity of (17 to 45) % was obtained. Also they suggested analytical formula to prediction capacity of punching shear for slab column connection strengthened with CFRP.

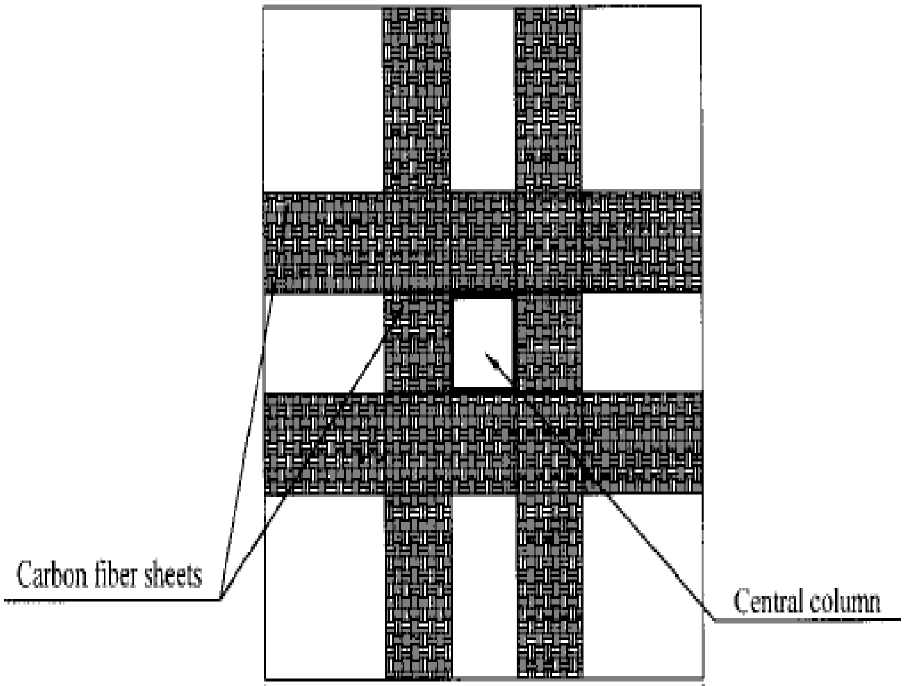


Figure (2.1): Configuration of CFRP Sheets on the Tension Face of the Slab [32]

Baris (2003) [33] presented an upgrading scheme for slab column connections using externally installed CFRP strips. The behavior of slab specimens subjected to shear and combined shear and moment transfer was studied experimentally. Various configurations of strengthening, amounts and details of CFRP installation were investigated. Figure (2.2) illustrates the CFRP patterns and amounts used in strengthening specimens. The effectiveness of proposed details of external CFRP reinforcement was evaluated. Simple models were used to predict punching shear strength, post punching resistance and anchorage strength of CFRPs bonded to concrete.

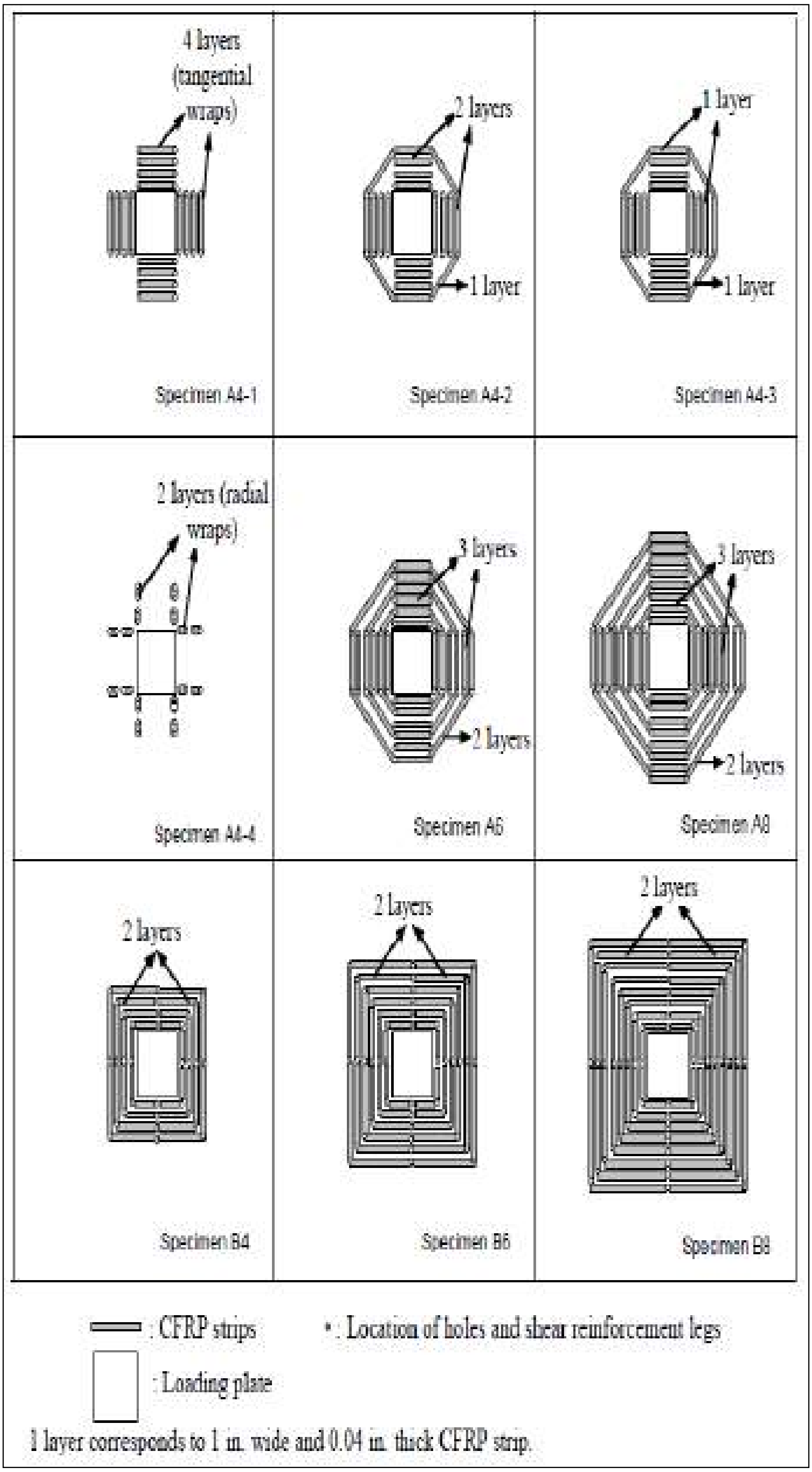


Figure (2.2): Strengthened Specimens (plan view) [33]

El-Salakawy et.al. (2004) [34] investigated the punching shear resistance of edge slab column connections strengthened with FRP. Seven slabs with dimensions (1540*1020*120) mm and square columns (250*250) mm were tested. FRP strips were externally bonded on tension face. Experimental results showed that FRP reinforcement enhances punching shear capacity, flexural stiffness and retards flexural cracks. The increment in capacity of punching shear varied between (2 -23) %.

Rochdi et al.(2006)[35] studied experimental and analytical for estimating the punching shear capacity of eight concrete two way slabs strengthened with external CFRP lamina. All slabs were designed to fail in punching. The theoretical model was suggested to estimate the ultimate punching strength of slabs with different levels of reinforcement with CFRP. The results showed good agreement between experimental and predict values.

Esfahani et al. (2009) [36] studied punching shear of flat slabs stiffened by CFRP sheets. Thirteen slabs were reinforced by CFRP sheets and two control specimens were left. CFRP sheets were used with different width. CFRP sheets were installed in two orthogonal orientations on tension face of the slabs. Enhancement was observed in punching shear strength for slabs that have low ratio of steel reinforcement and made with high strength concrete. The comparison between experimental results and equations of design codes showed that the ACI code was more conservative evaluating the punching shear strength because the effect of flexural reinforcement is not taken into consideration.

Maro (2014) [37] studied the punching capacity of concrete slabs stiffened by CFRP strips by experimental work and compared the results with a finite element model. Experimental work contains testing thirty two slabs of dimensions (800 x 800 x 70) mm and (800 x 800 x 90) mm. The variables were concrete strength, amount of flexural reinforcement, thickness of slabs and shape of the CFRP distribution. The experimental results showed that, the CFRP leads to increase the ultimate punching load of the slabs by (5- 26) %. Also the first cracking load increased by (12-200) %. The strengthened slabs showed less deflection during loading stage by 36% compared to the non strengthened slabs. The results showed that the increase in ultimate punching load of high strength concrtet (50) MPa was between (20-50) % more than the normal strength concrete.

2.4 Strengthening of Existing Flat Slabs with Steel Plates and Steel Bolts

Farhey et al. (1995) [38**].** Studied the repair of flat slabs failed by punching. Four slabs with full scale were subjected to cyclic loading and ratio of moment to shear was left constant through testing operation. Full destruction specimens were repaired the damage concrete zone around the connection of slab column with epoxy mortar and steel plates. The variables were dimensions of column and steel plate.They observed increasing in stiffness, ductility, resistance and moment capacity of repaired specimens.

Ramos et al. **(2000)** [39] carried out an experimental work on rehabilitation of flat slabs by drilling holes through the slab, near the column, and inserting steel bolts which are prestressed against the slab surfaces. Seventy percent of the failure load was applied before repair method doing. Study was conducted to assess the influence of different direction and location of shear bolts. They found that 51% of improvement was reached in punching load compared to failure load of specimen without repair.

Ebead and Marzouk (2002) [40] studied the influence of strengthening and rehabilitation of two-way slabs by shear bolts and steel plates. On both faces of the slab they installed steel plates and fixed by shear bolts. Fifty percent of ultimate load for control slab was applied to specimens prior application of strengthening. Various arrangements of steel plates and shear bolts were studied in order to assess their influences on the punching shear capacity. They concluded that using steel plates and shear bolts increased the stiffness and absorption energy of specimen. They recommended at least (6 mm) thickness of steel plat and eight shear bolts should be used.

Locations of openings with respect to central column in flat reinforced concrete plats were studied by **Al-Shammari (2011)** [41]. Some of these opening were strengthened with steel plates and the remaining left unstrengthened. Nine reinforced normal concrete flat plates were casted with dimensions (850 mm x470 mm x50 mm). Each slab contained a square opening (75 mmx75 mm) and propped by (75mmx75mm) square column at center. The variables were the opening type (strengthened or unstrengthened) and the net distance between column and opening which is taken as relative to effective depth (d, 2d, 4.5d and 7d). It was demonstrated that the maximum value of ultimate load takes place for slab without opening and increase in the ultimate load was (19.44, 19.51, 35.13 and 13.46) % for the specimens having distance (d, 2d, 4.5d and 7d) respectively, between column and opening.

Inacio et al. (2012) [42] conducted a strengthening method by using prestressed vertical bolts for flat slabs subjected to punching through experimental work. Eight from nine slabs were strengthened with prestressed vertical bolts by using several anchorage methods as shown in Fig.(2.3), and one slab left as control. Punching loads, shear reinforcement and failure mode were compared with design codes. They concluded that using small embed anchorage plates gives applicable and an effective method to improve punching resistance and have aesthetic appearance.

Rasheed and Al-Azawi (2013) [43] casted and tested five concrete slabs strengthened with epoxy bonded steel plates. The variables considered were the thickness, dimensions, and location of steel plates. The test results revealed that the steel plate dimensions are the high effective parameter for improvement of the overall behavior of RC slabs. The maximum increase in ultimate strength was found as 135%.

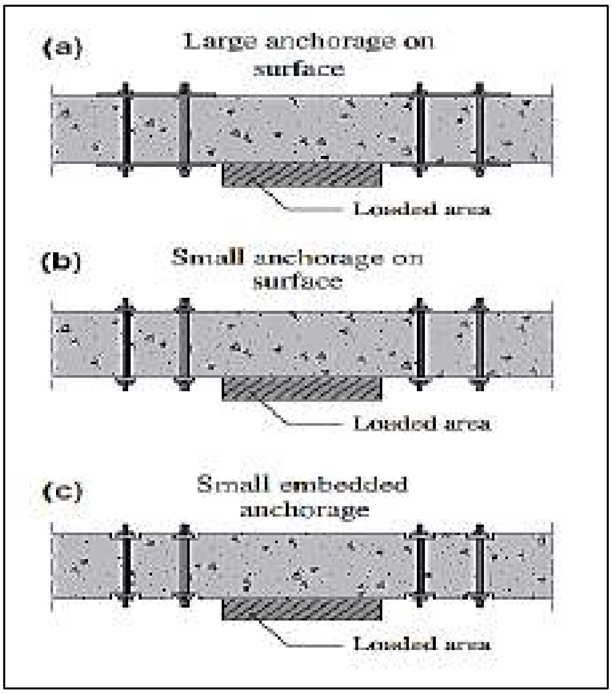


Figure (2.3) Different anchorage technique approaches[42]

Askar (2015) [44] conducted an experimental study on slabs damaged due to punching shear and repaired using prestress vertical bolts. Slab thickness, central column size and number of vertical pressteressed bolts were the major parameters considered in study. The results showed that the proposed system of repair was effective and could be used in practice. Also the experimental results and those obtained by formulas adopted by different codes were compared.

2.5 Building Code Approaches for Punching Shear Design

2.5.1 ACI 318M-11 Code [45]

The nominal shear strength shall be taken not greater than any of the following three equations:

$$V_c=0.17\left(1+\frac{2}{\beta}\right)\sqrt{f_c'}\ b_o\ d \quad \text{….. (2.5)}$$

$$V_c = 0.083\left(\frac{\alpha_s\, d}{b_o} + 2\right)\sqrt{f_c'}\ b_o\, d \qquad \text{….. (2.6)}$$

$$V_c = 0.33\sqrt{f_c'}\ b_o\, d \qquad \text{….. (2.7)}$$

where;

Vc = the nominal shear strength provided by concrete (N).

f_c' = cylinder concrete compressive strength (MPa).

d = effective depth (mm).

b_o = perimeter of the critical section ,{4(c + d)}.where c is side length of column.

β = the ratio of the long side to the short side of the concentrated load or reaction area,

α_s= a factor for slab column connections based on the location of the column (40 for interior, 30 for exterior, 20 for corner columns).

2.5.2 BS8110-97 [46]

The equation presented in this code is as follows:

$$V_n = 0.79(100\,\rho)^{\frac{1}{3}}\left(\frac{400}{d}\right)^{\frac{1}{4}} b_0 d \qquad \text{….. (2.8)}$$

where;

b_0 = control perimeter located 1.5d from the face of the column,{ 4(c + 3 d)}for square column, where c is side length of column.

$\left(\frac{400}{d}\right)$ should not be taken as less than 1.

ρ = the ratio of steel within 1.5d of column face. (Not greater than 3%)

For characteristic concrete strengths of cube greater than 25 (N/mm^2). vaue of V_n in this equation should be multiplied by $(f_{cu}/25)^{0.33}$.

2.5.3 The Eurocode 2-2004 [47]

Euro code recommends the following expression to estimate punching shear strength of slabs:

$$V_n = 0.18\, k\, (100\, \rho\, f_c')^{\frac{1}{3}}\, b_o\, d \qquad \text{..... (2.9)}$$

where:

b_0 = control perimeter located 2d from the face of the column, $\{4(c + \pi\ d)\}$ for square column, where (c) is side length of column.

ρ = bending reinforcement ratio (not greater than 0.02). $\rho = \sqrt{\rho_x \rho_y}$

d= effective depth (mm).

f_c' = the compressive strength of the concrete MPa,(not greater than 50 MPa)

k= factor accounting for size effect defined by the following expression:

$$k = 1 + \sqrt{200/d} \quad \leq 2.0 \qquad \text{..... (2.10)}$$

2.6 Concluding Remarks

This chapter has reviewed many experimental and theoretical studies concerning the behavior of punching shear strength of flat slabs with and without strengthening.

It is clear that there is little applications of steel plate in strengthening concrete flat slabs to improve punching shear resistance in comparison with the CFRP strips. Also, there is no application concerning the use of aluminum sheets to strengthening concrete flat slabs for punching shear resistance.

This research is an attempt to examine the punching shear strength of flat plates strengthened by aluminum sheets through experimental work.

CHAPTER THREE

EXPERIMENTAL WORK

3.1 Introduction

The main purpose of the test program is to study the behavior of reinforced concrete slabs strengthened with aluminum sheets and designed to fail in punching shear. The experimental program includes preparation and testing of sixteen slabs. The slabs are divided into two groups according to the compressive strength of used concrete. Details of the test specimens, their construction, material properties, test set-up, instrumentation, and test procedure are presented in this chapter.

The parameters studied include area of aluminum sheets (plan area), width of aluminum sheets, location of aluminum sheets and concrete compressive strength.

3.2 The Objectives of Experimental Work

The main objectives of experimental work are to study the influence of the following on the ultimate punching shear resistance:

1. The variation of the area of aluminum sheets (plan area).
2. The distribution of aluminum sheets (width and location of sheets) for the same area of aluminum (same plan area)
3. The concrete compressive strength (normal and high strength).

3.3 Materials Used to Fabricate the Specimens

The materials used in this investigation are commercially available materials, which include aluminum, cement, natural gravel, natural sand, water, superplasticizer, steel reinforcement and epoxy.

3.3.1 Aluminum

Structural aluminum alloy box section (200x50) mm with 4 mm thickness produced by Jordanian aluminum industry are used in this investigation. Aluminum sections are cut to segments to get sheets which are used for strengthening purposes. Two widths of aluminum sheets are used in this investigation (100 and 50) mm. The Aluminum sections and segmentation processes are shown in Figs. (3.1) and (3.2). Also, Fig. (3.3) shows the geometrical details of segmented sheets used in this study.

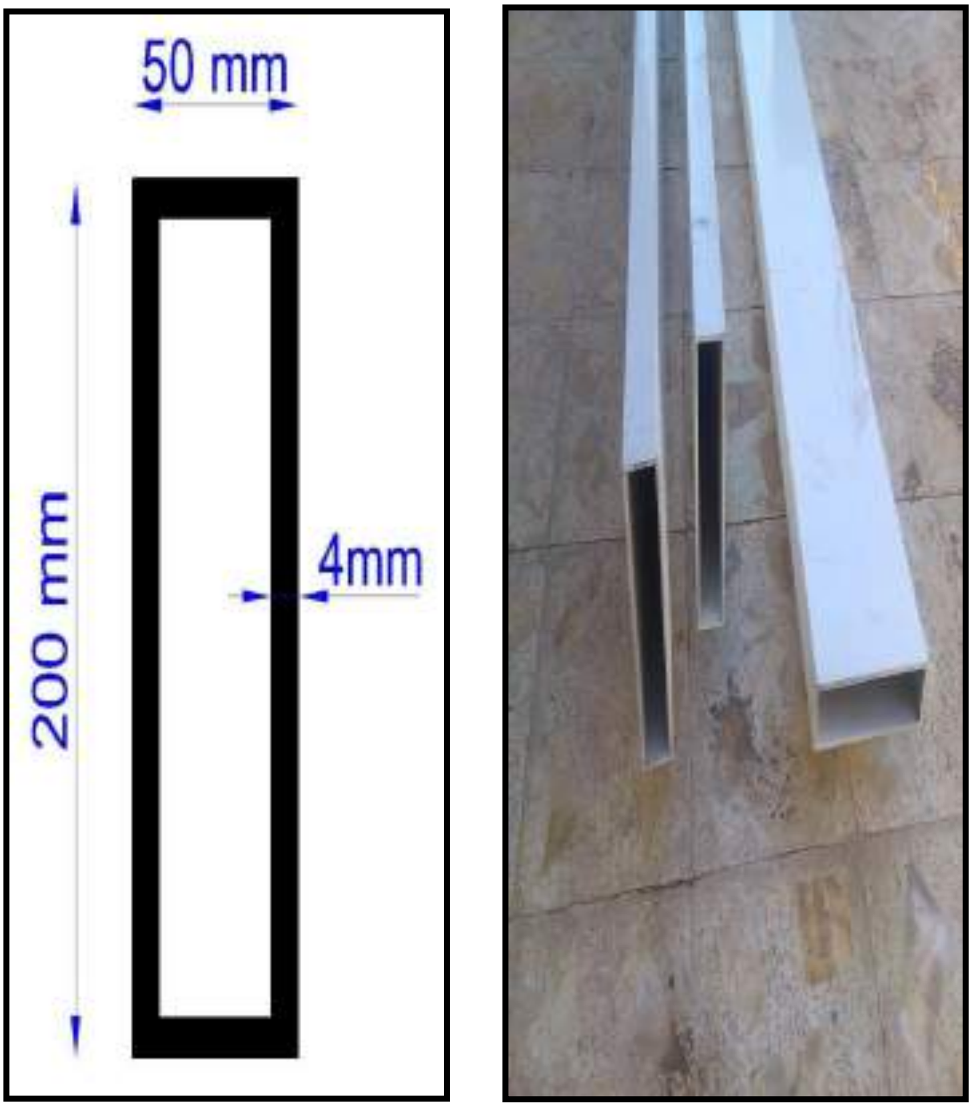


Figure (3.1) Aluminum sections

Figure (3.2) segmentation processes

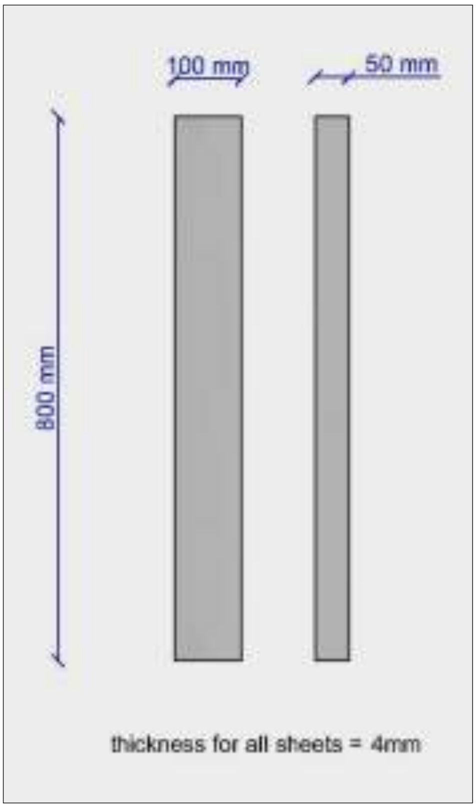


Figure (3.3) geometrical details of segmented sheets

3.3.1.1 Mechanical Properties of Aluminum

Aluminum material standards quote two levels of stress, both of which must be attained for a batch of material to be accepted:

$f_{0.2}$: minimum value of the 0.2% proof stress (or '0.2% offset') and

f_t : tensile strength (or 'ultimate stress').

The mechanical properties of the aluminum are determined by using tensile coupon. The tensile coupons are taken from the center of plate in the longitudinal direction of the aluminum boxes. The tensile coupons are prepared and tested according to the American Society for Testing of Materials standard (**ASTM-B557M 2003-Standard: Test Methods of Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products**) [48]. In the tensile test 12.5 mm wide coupons of 50 mm gauge length are used as shown in Fig. (3.4). The coupons are tested under direct tension by universal testing machine. The material properties obtained from the tensile tests are summarized in Table (3.1), which includes the measured Young's modulus (*E*), the static 0.2% tensile proof stress $f_{0.2}$, the static tensile strength (f_t) and the elongation after fracture. Figures (3.5), (3.6) and (3.7) show the tested coupons before, during and after the test, respectively**.** Figure (3.8) shows the typical stress-strain for aluminum alloy indicating the different stress levels, Figure (3.9) and (3.10) show the stress-strain curves for the tested samples.

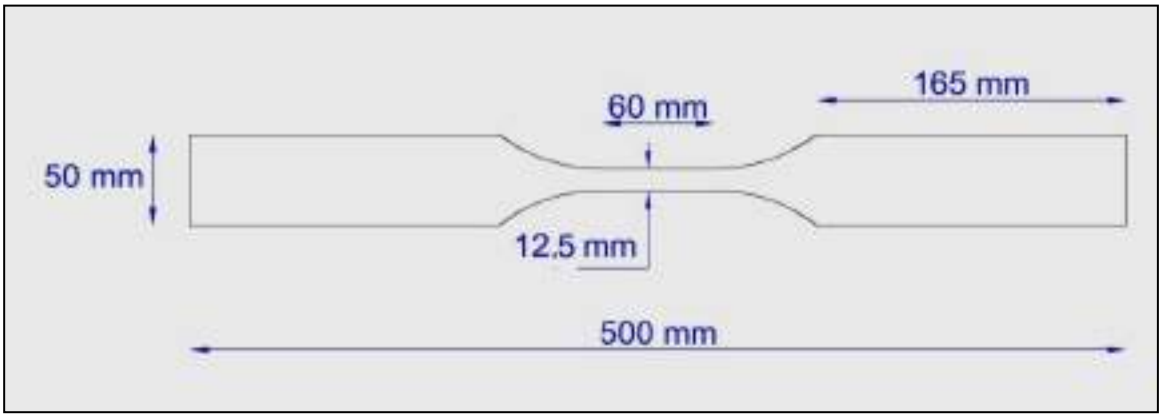


Figure (3.4) Geometrical details of aluminum tensile coupons

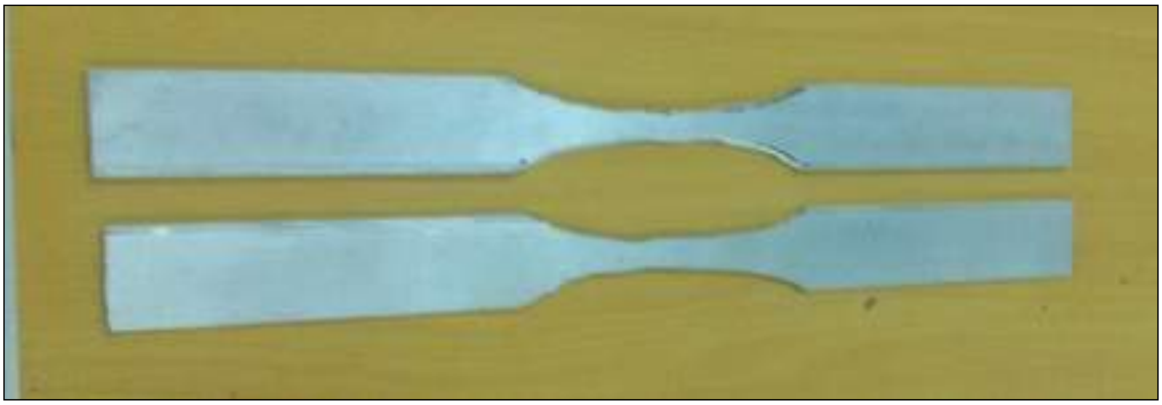


Figure (3.5) Aluminum alloy tensile coupons before test

Figure (3.6) Test arrangement for aluminum alloy tensile coupons

Figure (3.7) Aluminum alloy tensile coupons after test

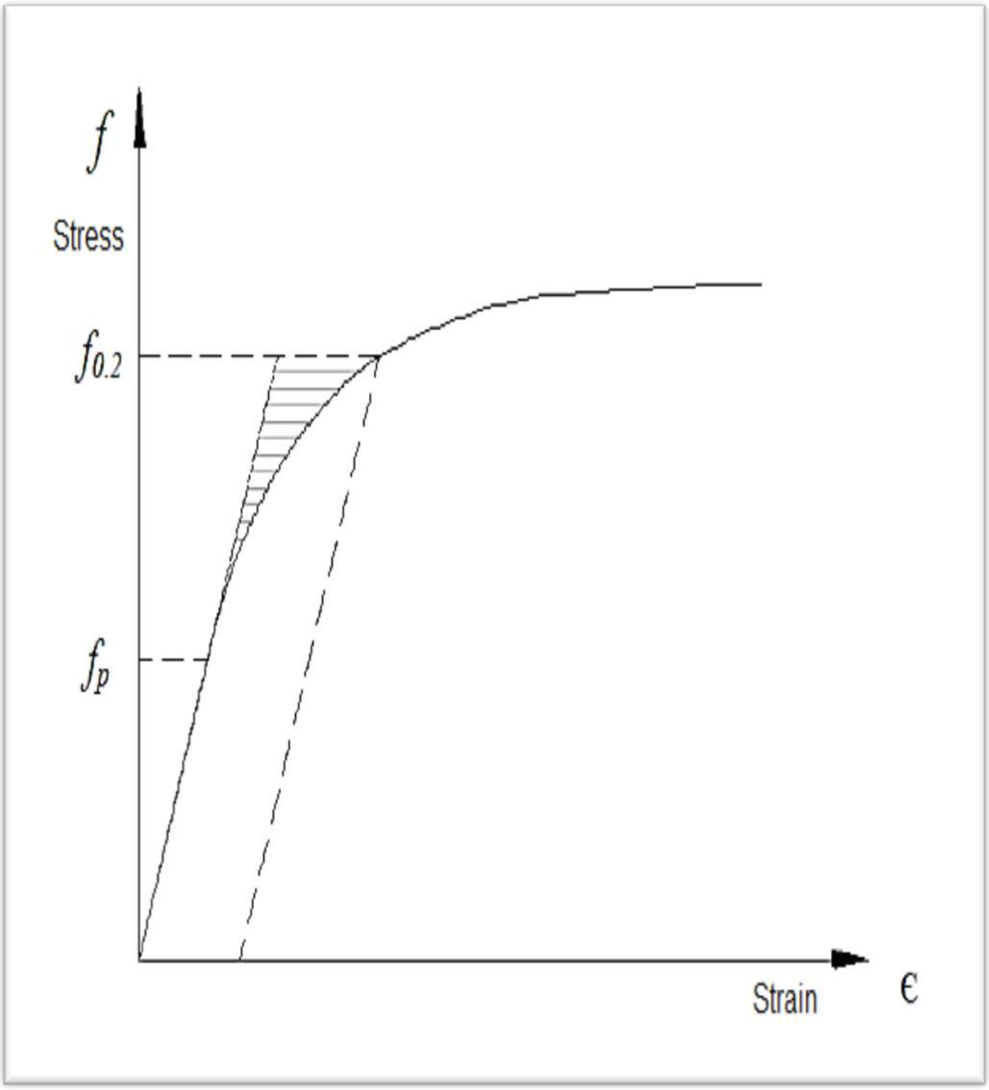


Figure (3.8) Typical stress - strain relationship for aluminum alloy

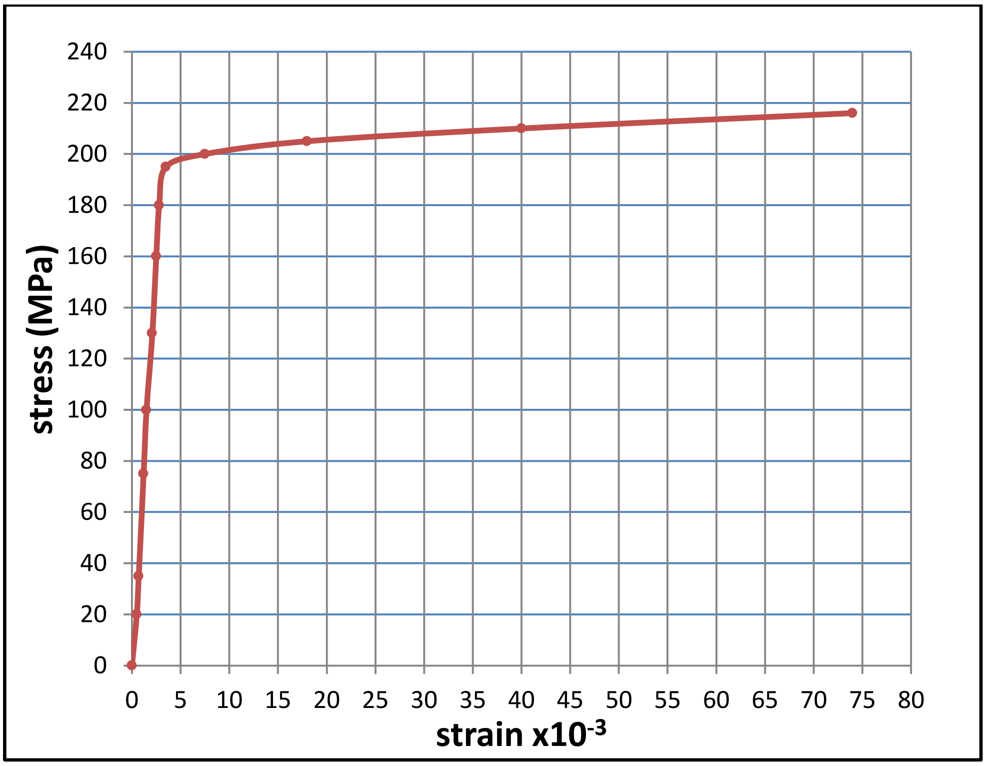


Figure (3.9) Stress-strain relationship for aluminum alloy (sample 1)

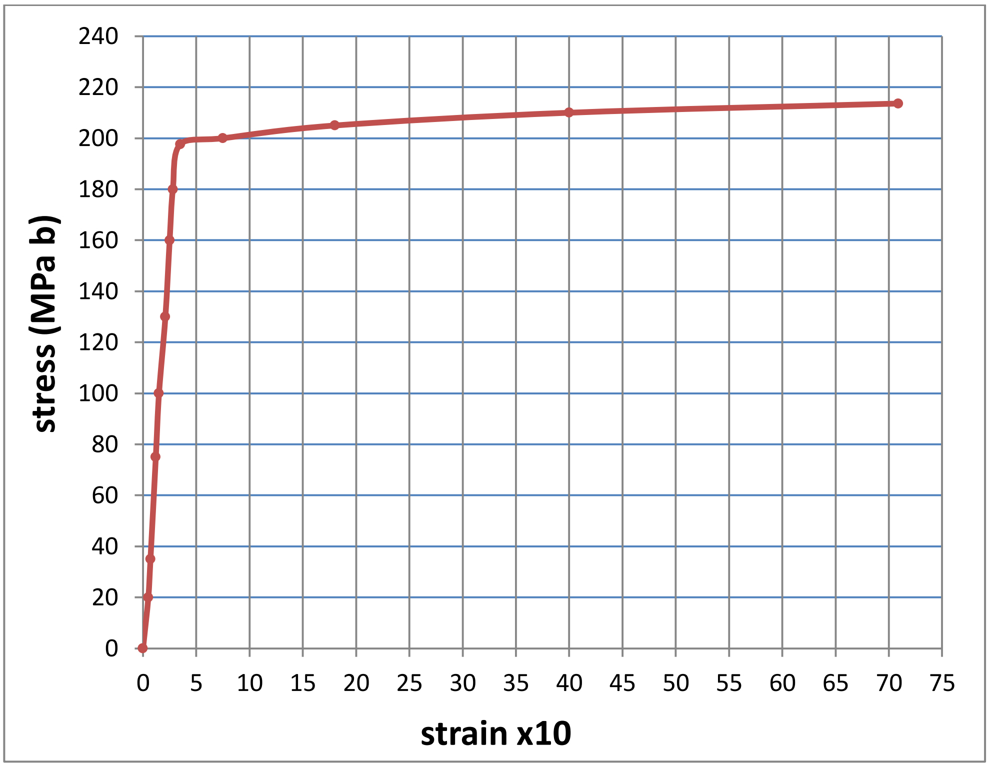


Figure (3.10) Stress-strain relationship for aluminum alloy (sample 2)

Table (3.1) Mechanical properties of aluminum alloy

Sample	$f_{0.2}$ yield stress (MPa)	Ultimate stress (MPa)	E (GPa)	Fracture elongation (%)
Sample 1	195.66	216.4	67.92	7.46
Sample 2	197.66	213.6	68.02	7.09
Average	196.66	215	68.42	7.275

3.3.1.2Aluminum Alloy Chemical Analysis

Structural aluminum alloys (6xxx series alloys) contain magnesium and silicon in proportions that form magnesium silicide (Mg_2Si) as the main ingredient of alloy base. It contains other elements such as Iron, Copper, Manganese, Chromium, Zinc, Titanium, and other elements [49]. Table (3.2) shows the weight percentage of main ingredients of the used structural aluminum alloys

Table (3.2) Main ingredients of structural aluminum alloy

Chemical elements	Composition, wt%
Al	95.02
Mg	0.32
Si	0.35

3.3.2 Cement

Ordinary Portland cement is used throughout this investigation. The whole quantity required is brought to the laboratory and stored in a dry place. The physical properties of the cement used throughout this work are presented in Table (3.3). The setting time test is conducted according to ASTM C191[50].The compressive strength test is accomplished according to ASTM C109 [51]. The chemical composition of the cement is presented in Table (3.4). Results indicate that the cement conforms to the Iraqi standard No. 5/1984 [52].

Table (3.3) Physical properties of ordinary Portland cement

Physical and Mechanical Properties	Test Result	Limits of Iraqi specification No.5/1984
Compressive strength, N/mm²		
3 – day	18	≥ 15.00
7 – day	25	≥ 23.00
Setting time, h:minutes		
Initial setting	02:31	≥ 00: 45
Final setting	03:19	≤ 10: 00
Fineness Specific surface area (by Blaine method), cm²/gm	3011	≥ 2300

Table (3.4) Chemical composition of cement

No.	Compound composition	Chemical composition	Weight (%)	Iraqi specification No. 5/1984
1	Silicon Dioxide	SiO_2	21.14	-
2	Aluminum Trioxide	AL_2O_3	4.00%	-
3	Ferric Oxide 3.05%	Fe_2O_3	3.05%	-
4	Calcium Oxide	CaO	62.69%	-
5	Magnesium oxide	MgO	2.11%	5% max
6	Sulphate	SO_3	2.32%	3%
7	potassum oxide	K_2O	0.66%	
8	Sodium Oxide	Na_2O	0.18%	
9	Insoluble Residue	Ins.Res.	1.14%	1.50%
10	Loss on Ignition	LOI	LOI	-
11	Freelime	FL	0.84%	-
12	Lime Saturation Factor	LSF	91.2	Min 66 Max 102
13	Silicon Ratio	SM	2.66%	-
14	Alumina Ratio	AM	1.61%	
15	Tricalcium Silicate	C_3S	50.59%	
16	Dicalcium Silicatr	C_2S	22.44%	
17	Tricalcium Aluminates	C_3A	7.82%	
18	Tetracalcium Aluminoferrate	C_4AF	9.27%	

3.3.3 Aggregate

1. ***Fine aggregate (Sand)****:* Natural sand brought from Al-Zubair area is used as a fine aggregate in this study. The grading test result of the fine aggregate is shown in Table (3.5).The obtained results indicated that the fine aggregate grading and the sulfate content are within the limits of Iraqi specification number (45/1984) [53]. Sulfate content, specific gravity, moisture content and absorption of the fine aggregate are shown in Table (3.6)

Table (3.5) Grading of fine aggregate

No.	**Sieve size** (mm)	**Passing (%) fine aggregate**	**Passing (%) Iraqi specification 45/1984 for zone No.(1)**
1	4.75	97.76	90-100
2	2.36	81.41	60-95
3	1.18	63.91	30-70
4	0.6	32.43	15-34
5	0.3	9.73	5-20
6	0.15	0.45	0-10

Table (3.6) Properties of fine aggregate

Physical properties	**Test results**	**Iraqi specification. 45/1984 for zone No.(1)**
Specific gravity	2.65	---
Sulfate content	0.3 %	Not more than 0.5%
Absorption	1 %	---

2. Coarse Aggregate (Gravel)**:** Crushed gravel from Chlat area (Ali Al-Garby) in Missan province with max.size of (20) mm is used. The grading of the coarse aggregate is shown in Table (3.7). Results indicate that, the grading is within the requirements of Iraqi specification No. 45/1984 [53]. Table (3.8) shows the specific gravity, sulphate content and absorption of the used coarse aggregate.

Table (3.7) Grading of coarse aggregate

No.	**Sieve size (mm)**	**Passing (%) coarse aggregate**	**Passing (%) Iraqi specification No. 45/1984**
1	20	100	100-95
2	14	80	--
3	10	37	30-60
4	5	2	0-10

Table (3.8) Physical properties of coarse aggregate

Physical properties	**Test results**	**Iraqi specification. 45/1984**
Specific gravity	2.67	-
Sulfate content	0.06 %	Not more than 0.1%
Absorption	0.6 %	-

3.3.4 Mixing Water

Ordinary potable water is used in making and curing the concrete.

3.3.5 Superplasticizer

The superplasticizer known commercially as Hyperplast PC260 is used in this work. It is based on polycarboxylic ether polymers with long chains specially designed to enable the water content of the concrete to perform more effectively. This effect can be used in high strength concrete and flowable concrete maixes, to achieve highest concrete durability and performance.

Hyperplast PC260 is free from chlorides and complies with ASTM C 494 types A and G. Hyperplast PC260 is compatible with all Portland cements that meet recognized international standards [54]. Table (3.9) shows the typical properties of Hyperplast PC260 used in this study.

Table (3.9) Typical properties of Hyperplast PC260

Main action	**Concrete super – plasticizer**
Form	Viscous fluid
Appearance	Light yellow
Density	1.1 +/- 0.02 g/cm^3 @ 20C°
ph value	6.6
Viscosity	128+/-30 cps @ 20 C°

3.3.6 Steel Reinforcement.

One steel reinforcement ratio is used in this study (ρ=0.00859) with (20) mm concrete cover and bar size of (Ø10 mm) in diameter, with the same distribution of steel reinforcement in all specimens as given in Table (3.10).

Tensile tests are conducted on three specimens are prepared from the steel reinforcement bars. Static yield stress and ultimate strength of the tested bars are summarized in Table (3.11). The tensile tests are performed by the universal testing machine, shown in Figure (3.11). Also, Fig (3.12) shows the steel reinforcement distribution for all specimens.

Table (3.10) Reinforcement details used in the tested specimens

Symbol	Steel ratio	No. of bars in each direction	Spacing in between bars c/c (mm)
All specimens	**0.00859**	**7Ø10mm**	**100×100**

Table (3.11) Properties of steel bars (average for three specimens)

Dia. (mm)	Area (mm^2)	Weight (kg/m)	Yield strength (MPa)	Ultimate strength (MPa)	Elongation%
10	***78.53***	***0.682***	***569.94***	***704.8***	***13.8***

Figure (3.11) Universal testing machine

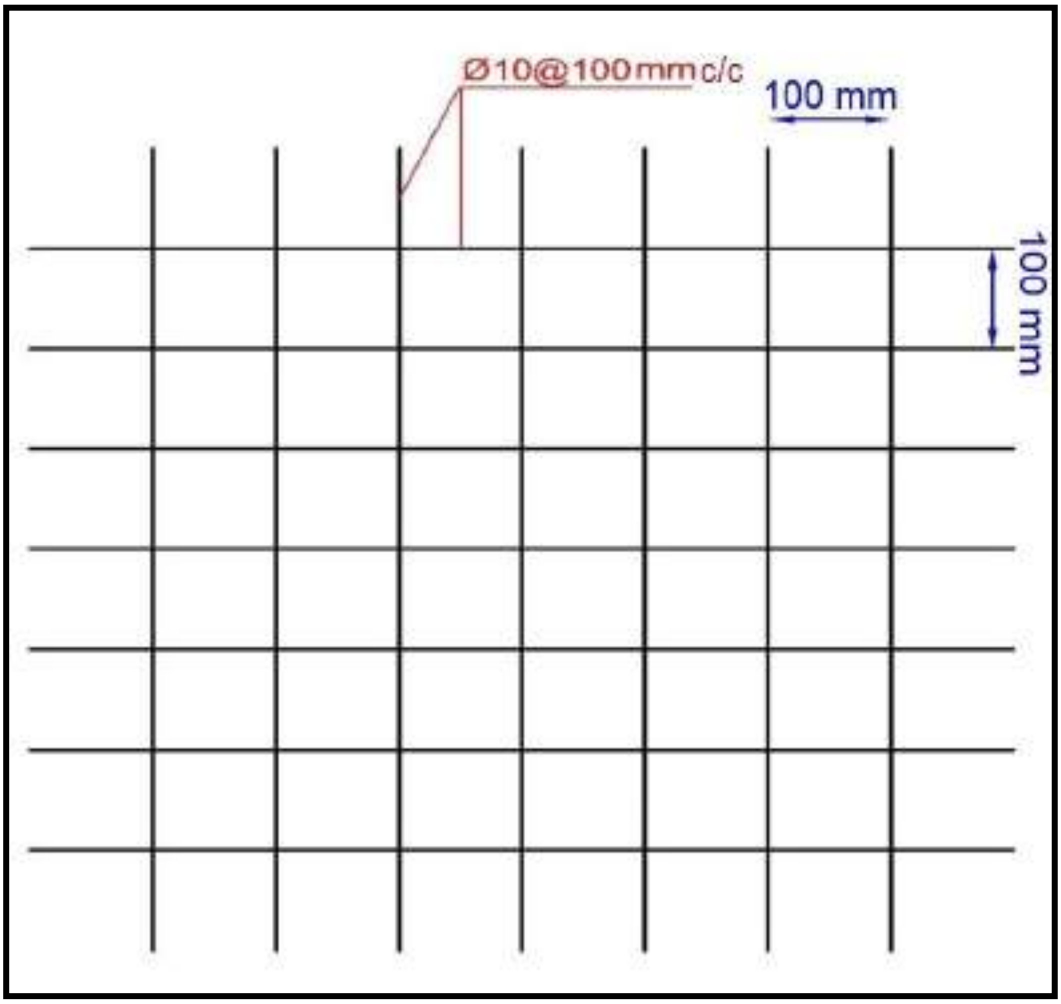


Figure (3.12) Distribution of reinforcement bars

3.3.7 Epoxy

Sikadur-31 thixotropic epoxy resin adhesive is used in this study which is a solvent-free, thixotropic, two component adhesive and repair mortar, based on a combination of epoxy resins and specially selected high strength fillers. It complies with ASTM C-881 [55]. Mechanical strengths are determined by casting cubes and prism and testing them for compressive and flexural strengths while the modulus of elasticity is provided by the manufacturer [56]. Mechanical properties of Sikadur 31 epoxy resin adhesive are listed in Table (3.12). Fig. (3.13) shows the two components of the epoxy resin.

Table (3.12) Properties of the epoxy resin

Appearance	**Mixing ratio**	**Open time min.**	**Tensile strength MPa**	**Compressive strength MPa**	**Tensile E-modulus MPa**
Part A: white Part B: gray	A:B 4:1	30 (at +35°C)	19-25	60-70	4600

Figure (3.13) Two component of epoxy resin

3.4 Specimens Description

A total of sixteen RC square two-way slabs are casted and cured under laboratory conditions. the specimens are designed to study the punching response of strengthened by aluminum sheets RC two-way slabs. All the tested slabs are identical in the dimensions (800×800×100) mm and flexural reinforcement ratio (ρ=0.00859). The slabs are simply spanned over (700×700) mm four Φ 25 bars and subjected to a central concentrated load over an area of (80×80) mm. All the support lines are placed at 50 mm distance from the slab edges, so the effective span of the slab in both directions is 700 mm. Fig. (3.14) shows specimen dimensions, reinforcement details, support locations, and location of loaded area.

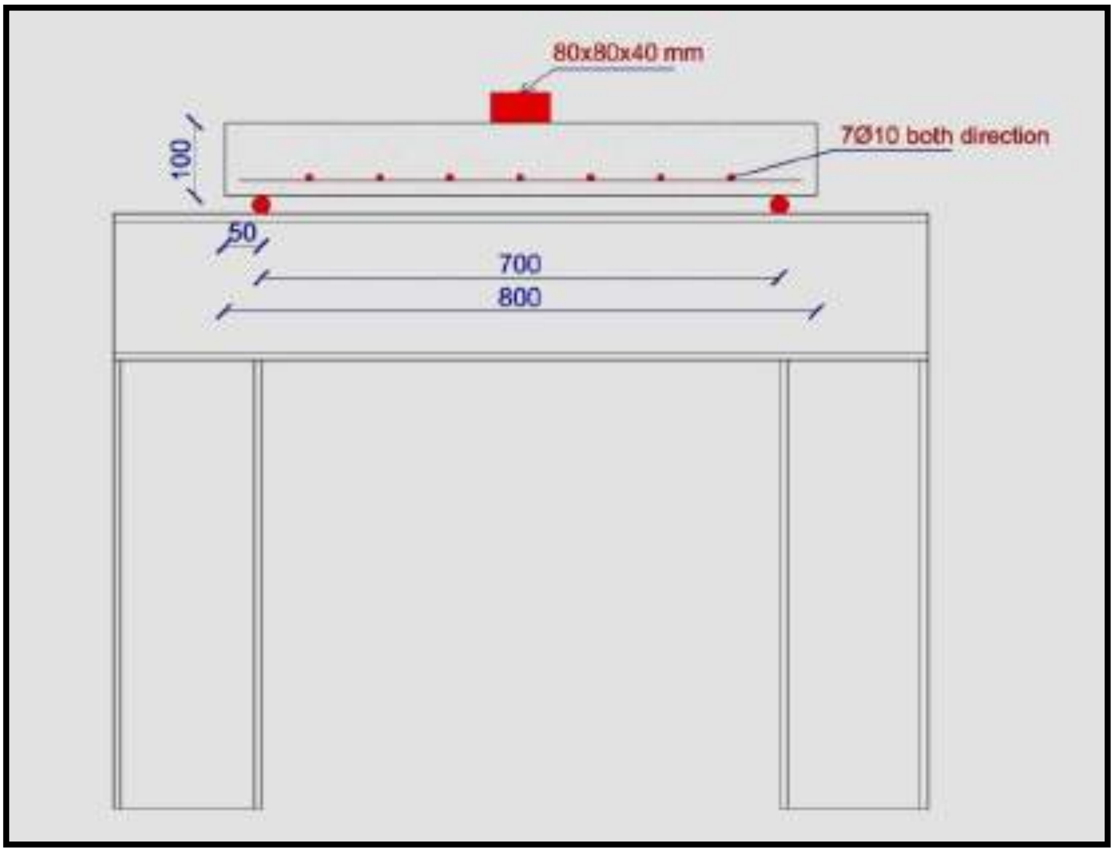


Figure (3.14) Specimen dimensions, reinforcement details, support, and location of loaded area

Figure (3.14) continued

3.5 Test Parameters and strengthening procedure

All test specimen details are presented in Table (3.13) including the test variables. To summarize, parameters studied during the experimental work are area of aluminum sheets, width of aluminum sheets, location of aluminum sheets and concrete strength. All parameters and strengthening configuration are presented in Figs (3.15) and (3.16).

The following designation system is used:

- ***Area of aluminum sheets (plan area)*:** the specimens are divided into two groups according to concrete compressive strength, each group strengthened with three different plan areas (areas of aluminum sheets)

(0.16, 0.24, and 0.32) m^2 that are provided to the tension sides of the slabs.

- ***Width of aluminum sheets:*** In this study, each area is divided into two types according to width of aluminum sheets (100 and 50) mm. All aluminum sheets used are in one layer per line and thier thickness is (4 mm).

- ***Location of aluminum sheets reinforcement*** **:**

  The **ACI Code**[45] assumes that the control perimeters are located at a distance of 0.5 times the effective depth (d) from the edge of the load area, and **BS8110**[46] considers a control perimeter at (1.5 d), while **Eurocode 2-2004**[47] at a larger control perimeter (2d) with circular corners, as shown in Fig. (3.17).

In this study, each plan area (areas of aluminum sheets) is used as following:

1. ***0.16 m^2***: applied as (2 x 100 mm) located at distance (2d, 1.5d, 0.5d) from column face or as (4 x 50mm) located at distance (2d).as shown in Figs (3.16 a), (3.16 b), (3.16 c) and (3.16 d).
2. ***0.24 m^2***: applied as (3 x 100 mm) or (6 x 50mm) located at distance (2d) from column face and at center of column (two sheets at 2d and one sheet at center for 100 mm width), as shown in Figs (3.16 e) and (3.16 f).
3. ***0.32 m^2***: applied as (4 x 100mm) and (8 x 50mm) located at distance (2d) from column face and at column face (two sheets at 2d and two sheets at column face for 100mm width). As shown in Figs (3.16 g) and (3.16 h).

- ***Concrete strength***:

  In this study two types of concrete compressive strength (f_{cu}) are used (30, 65) MPa.

Table (3.13) Classifications of slabs

Groups	No.	Symbol	No. of aluminum sheets	Location of sheets from column face	Width of alumi-num strips (mm)	Plan area of aluminum (m^2)
G1	1	N.C.0.0	----			
	2	0.5d-N.C.10.2	2	0.5d	100	0.16
	3	1.5d-N.C.10.2	2	1.5d	100	0.16
	4	2d-N.C.10.2	2	2d	100	0.16
	5	N.C.10.3	3	2d&center	100	0.24
	6	N.C.10.4	4	2d & colu.face	100	0.32
	7	2d-N.C.5.4	4	2d	50	0.16
	8	N.C.5.6	6	2d&center	50	0.24
	9	N.C.5.8	8	2d & colu.face	50	0.32
G2	10	H.C.0.0	----			
	11	0.5d-H.C.10.2	2	0.5d	100	0.16
	12	1.5d-H.C.10.2	2	1.5d	100	0.16
	13	2d-H.C.10.2	2	2d	100	0.16
	14	H.C.10.3	3	2d&center	100	0.24
	15	H.C.10.4	4	2d & colu.face	100	0.32
	16	2d-H.C.5.4	4	2d	50	0.16

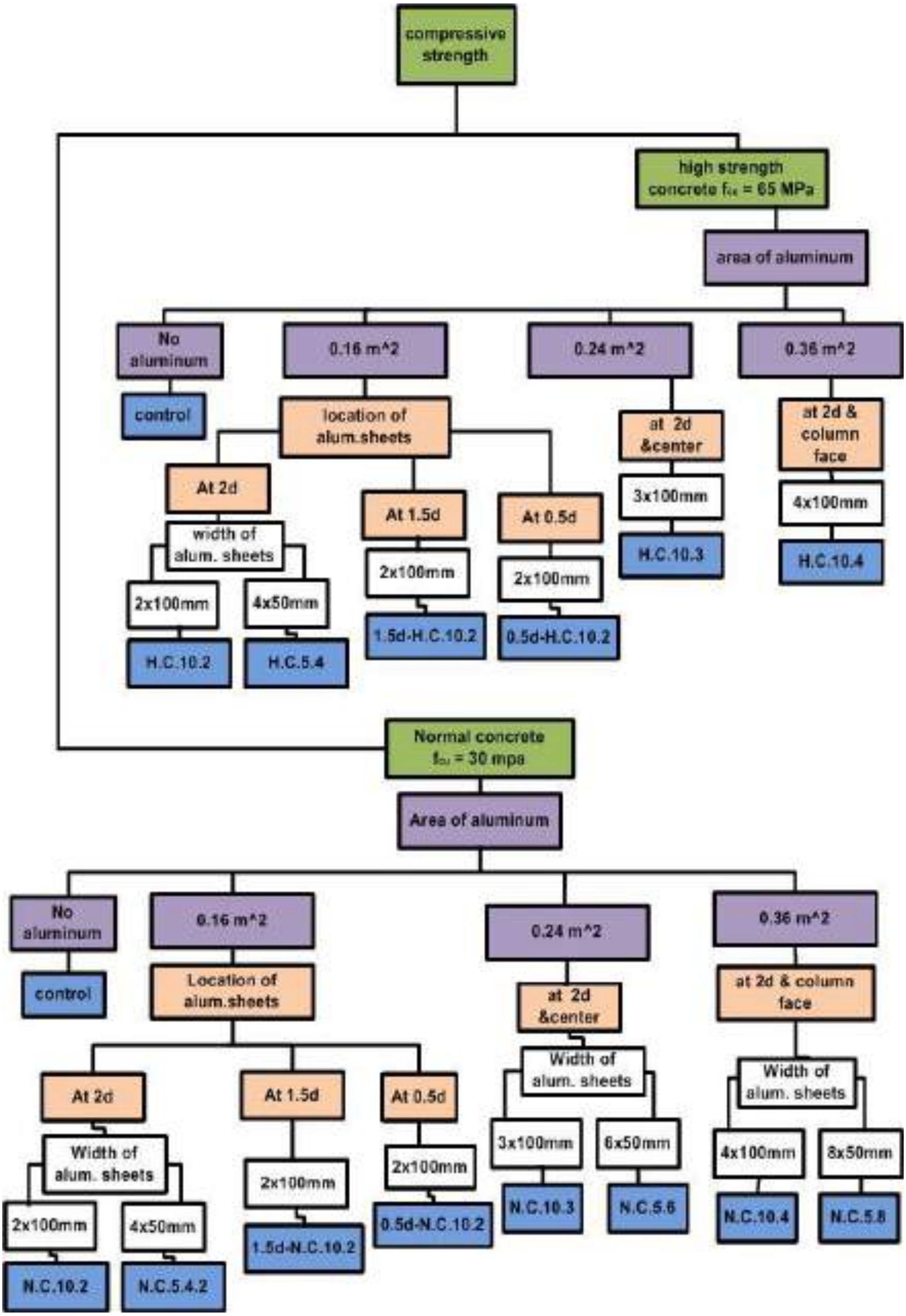


Figure (3.15) Parameters of the study

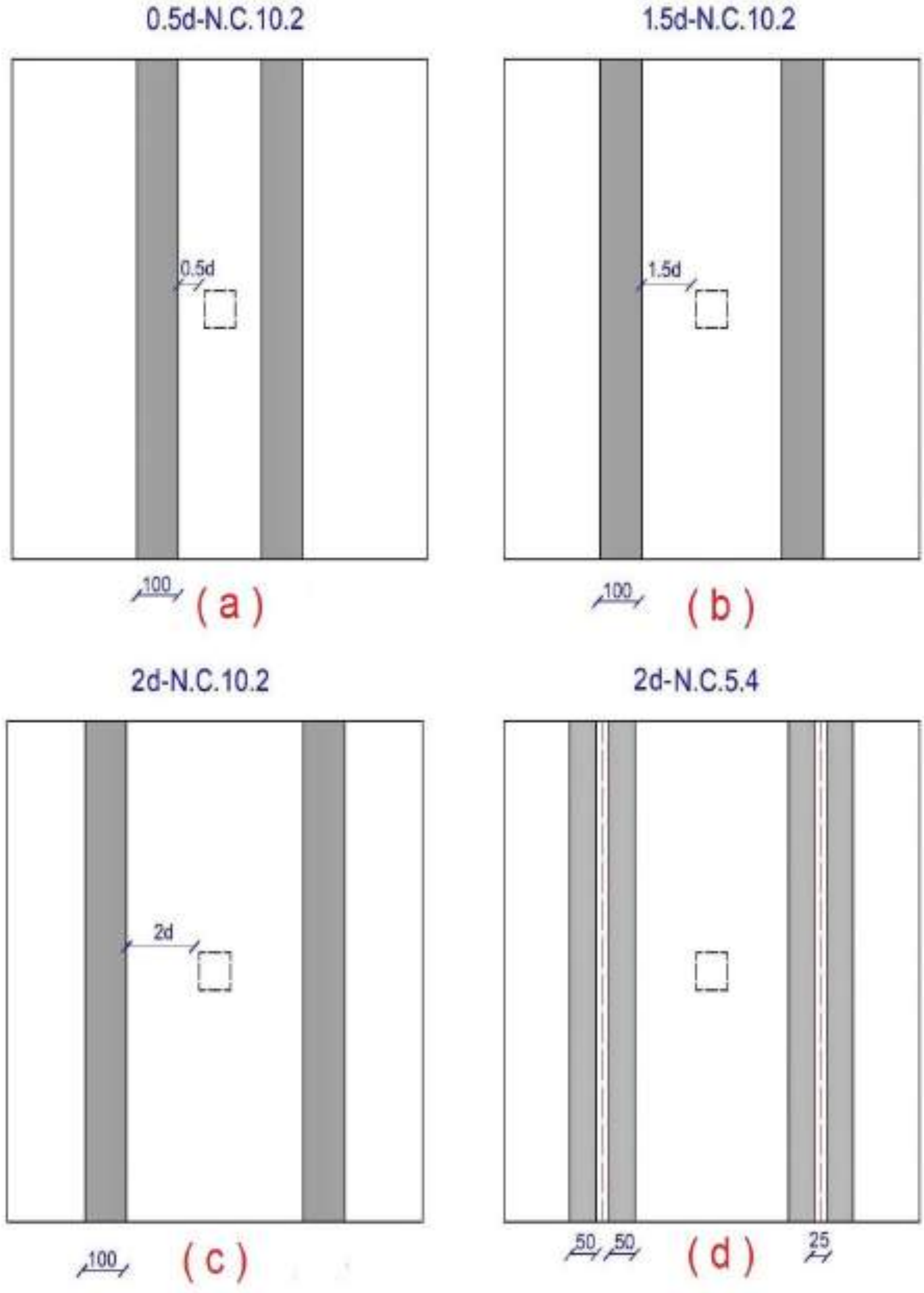


Figure (3.16) Shapes and strengthening configuration of the tested slabs

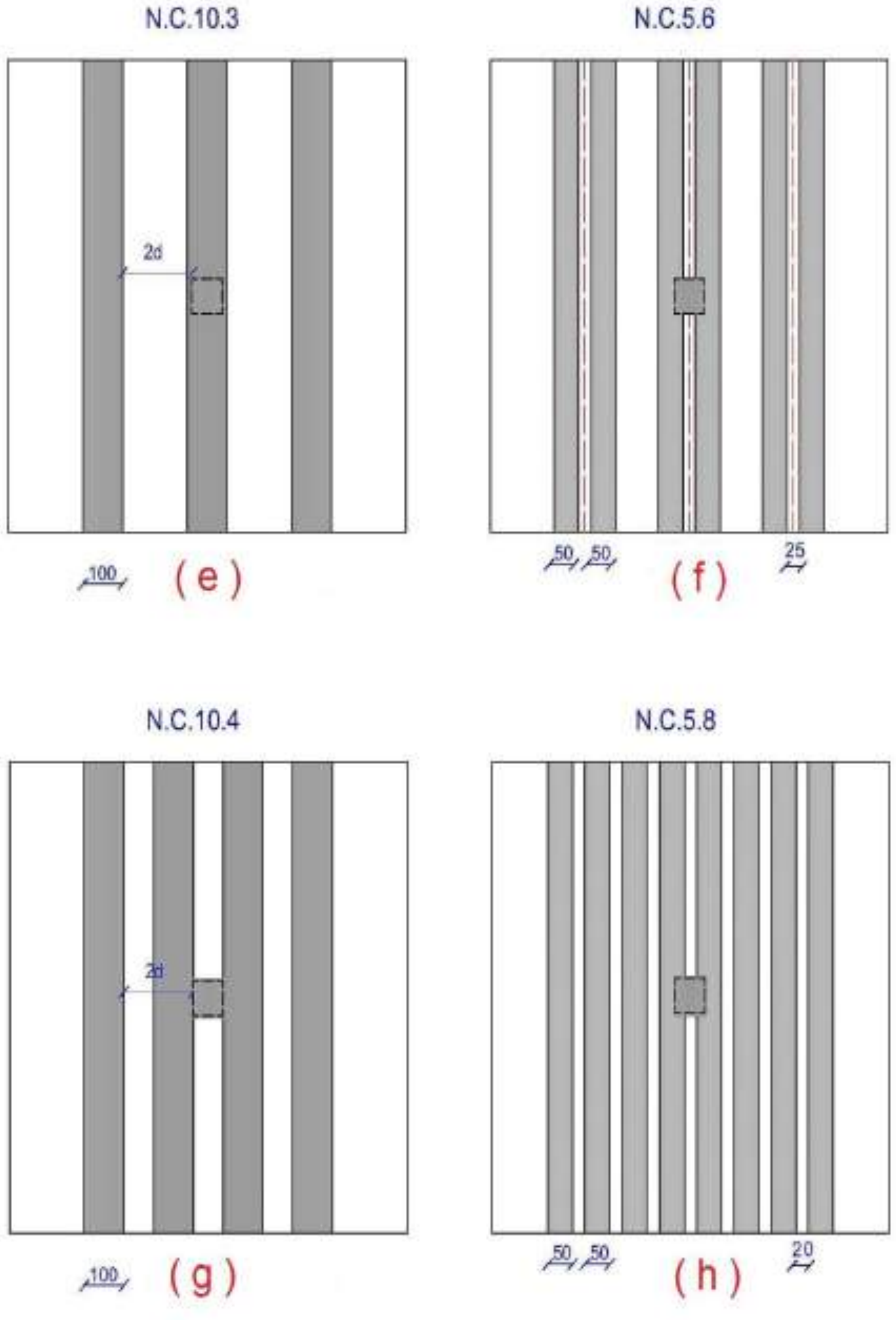


Figure (3.16) continued

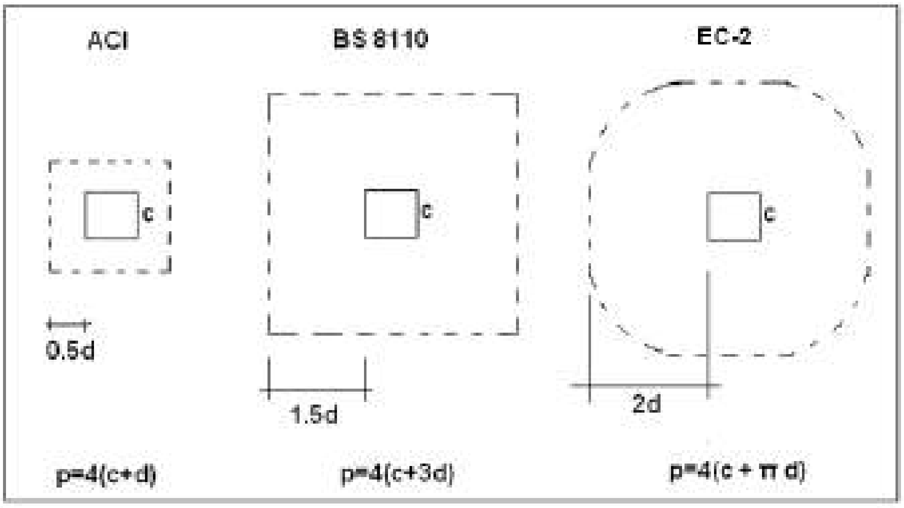


Figure (3.17): Critical section and perimeter of punching failure in different codes for square column.

3.6 Preparation of Test Specimen:

3.6.1 Mix Design

In order to select the mix proportions of the normal and high strength concrete used for casting the slab specimens, many trial mixes are carried out in order to obtain a cube strength of 30 MPa at 28 days for normal concrete and 65 MPa for high strength concrete by using the method of design proposed by **Nevile** 1995 [57]. The final mixes used are as shown Table (3.14).

Table (3.14) Properties of the mix used

Type of concrete	*Cement content kg /m³*	*Sand kg/ m³*	*Gravel kg/ m³*	*Water kg/ m³*	*W/C ratio*	*Sp.% by weight of cement*
Normal concrete	333	666	1109	166.5	0.5	——
High strength concrete	528	597	965	158	0.300	2.16

3.6.2 Mold

Six steel molds are used in this work. The dimensions of these molds are (800*800*100 mm) as shown in Fig. (3.18). They are cleaned with a scraper and a steel hair brush and were lubricated by oil to ensure an easy demolding.

3.6.3 Mixing, Casting and Curing of the Specimens

Sixteen slab specimens are caste and cured under laboratory conditions. The concrete casting and curing procedure is described below:

- The molds of specimens are treated with oil before putting the reinforcement grid or casting the concrete.
- Steel grid for each specimen is placed in their correct position with cover 20 mm.
- Before mixing, all the quantities are weighed and packed in clean containers.
- Prior to starting rotation of the mixer the coarse aggregate is added with part of the mixing water. After starting the mixer, the fine aggregate is added with the cement and the remaining part of water.
- After the mixing process is completed, concrete is poured in the molds in two layers, and each layer is compacted by rod vibrator. The upper surface of concrete is smoothly finished after casting is completed using hand trowel.
- After casting, the molds are left 24 hours, and then the specimens are removed from their molds. The burlap sacks are placed over the slabs and wetted down. The burlap sacks are watched and kept wet for successive seven days.
- Once the slabs are cured, they are placed off to the side until they are tested. The same procedures are performed on the concrete test cubes. Table (3.16) shows the mechanical properties of the two types of

concrete. The steps of casting process and curing of specimens are shown in Fig. (3.19).

Table (3.15) Properties of specimens

Batch	***Compressive strength, f_{cu} (MPa)***	***Compressive strength, f_c' (MPa)****	***Modulus of Elasticity, (Ec) (MPa)*****
Normal concrete	**30.77**	**24.61**	**23315.97**
High strength concrete	**65.55**	**52.44**	**37892.61**

* fc' = 0.8 f_{cu} , ** $Ec = 4700\sqrt{f_c'}$ In MPa

Figure (3.18) the molds used in the casting process

a - Mixing process

b - Casting procces

c - Compacting process

d - Curing process

Figure (3.19) The steps of mixing, casting, compacting and curing process of specimens.

3.6.4 Preparation of Concrete Surface and Installation of Aluminum Sheets

Before the aluminum sheets are applied to the soffit of the slabs, the surfaces of the concrete are grinded using an electrical hand grinder to expose the aggregate and to obtain a clean sound surface, free of all contaminants such as cement laitance, and dirt see Fig. (3.20). External strengthening of specimens by aluminum sheet is described below:

- First of all, the aluminum sheets are cut into the required lengths and widths. Then, the surfaces of the aluminum sheets are cleaned to remove any dust or other contaminants prior to installation.
- The component A (white) and component B (gray) of adhesive (Sikadur-31) are mixed respectively with an electric mixer (here electric low speed drill is used according to the recommendation of the manufacturer) and mixed in 4: l proportion, until the color is a uniform gray, the adhesive paste is then applied with a special tool to the concrete surface and the adhesive is also applied to the aluminum sheets.
- The aluminum strips are then placed on the concrete, epoxy to epoxy, and after the installation of strips, a rubber hammer is used to press sheets. Excess adhesive is squeezed out the sides and is removed; this ensures that any trapped air is removed then steel weights are put on sheets to ensure the fixing of the sheets.
- The specimens are then left for no less than 24 hours to allow for the setting of adhesive before starting the test. Then, the concrete surfaces painted white for easy detection of cracks.

The steps described above are shown in Fig. (3.20).

3.7 Test Setup Procedure:

3.7.1 Support and Loading Conditions

All slab specimens are tested in the testing machine shown in Fig. (3.21), with a

a - Grinding process

b -Epoxy mixing process

c – Epoxy sawing process

d – Installation process

Figure (3.20) Steps of installation of aluminum sheets

Figure (3.20) Continued

maximum capacity of 60 tons. The slabs are simply supported on four sides each 700mm long (knife edge) resting on rigid steel frame and subjected to a central concentrated load over a steel area of (80 × 80) mm placed on the top face of the slabs. All four support lines are 50 mm from the slab edges, so the effective span of the slab in both directions is 700mm. 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.

Figure (3.21) Test setup

3.7.2 Instrumentation

Dial gauges 50 mm maximum reading and 0.025 mm accuracy are used to detect the deflection of the slabs at every loading stage. During each load increment, the corresponding central vertical displacement (deflection) is recorded. The load and deflection at first crack and failure are also recorded.

Figure (3.22) shows dial gauges used for recording the central deflection of the tested slab.

Figure (3.22) Deflection dial gauge

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter describes the results of the experimental work conducted on reinforced concrete flat slabs strengthened with aluminum strips under punching shear forces. The slabs behavior and failure modes are discussed. The behavior of strengthened slabs is compared with that of the control slabs (unstrengthened slabs). Load deflection relations are analyzed at different load increments acting at slab centers. Failure loads, areas, perimeters and angles of failure zone are investigated. Photographs for the tested slabs are presented to show the crack patterns. Also, a comparison of the tested results with those calculated from different available codes (**ACI 318-11Code** [50], **the BS8110-1997** [51] **and Eurocode 2-2004** [52]) are made.

A study is carried out to explore the effect of the various parameters which are expected to affect the behavior of the slabs. The parameters include:

1. Area of aluminum sheets (plan area).
2. Width of aluminum sheets.
3. Location of aluminum sheets
4. Compressive strength of concrete

For the first variable (area of aluminum), three areas are used in this study which are (0.16, 0.24 and 0.32) m^2.

The second variable is the aluminum sheet widths and two sheet widths (100 and 50) mm are selected.

For the third variable (location of aluminum sheets), five locations are used as shown in Figure (3.16), the plan area (0.16) m^2 is placed in three different locations at distance (0.5d, 1.5d and 2d) from column face according to the critical section provided in design codes (ACI, BS and Europcode2). Plan area of (0.24) m^2 is placed at the center of slab and 2d from column face. While the plan area of (0.32) m^2 is placed at distance 2d and at column face.

For the last variable (strength of concrete), two types of concrete are used in this work, the normal strength concrete of (30) MPa at 28 days and high strength concrete of (65) MPa at 28 days.

4.2 Observed Behavior of Slabs During Tests

The general behavior (crack pattern and failure mechanism) of all tested slabs is approximately identical. When a two-way flat slab is loaded with a concentrated column load, the diagonal tension cracks (first visible cracks) form enclosing the loaded area of the slab at load level around (22 – 29) % of ultimate load as shown in Table (4.1). other cracks appear at the central zone of the slab. These cracks widen and increase in number and extend towards the slab edges when increasing the load. A complete sudden punching shear failure occurrs by increasing the load. Figure (4.1) explains failure modes and crack patterns of some tested specimens. From this figure, it is evident that the hair cracks appear in the tensile face of the slabs. It revealed that the negative moment cracks developed around columns. No cracks were observed in the compression side of the slabs, except those which are seen around the loaded area at failure which are almost the same as that of the loading plate dimensions.

It is noticed that the first crack loads are increased in value by (11.58-53.57) % compared to the value of the crack load in control slabs which means an increase in elastic range, as given in Table (4.2). While the increase in ultimate load is between (4.71- 41.66) % compared to ultimate load in control slabs, as given in Table (4.2).

A- Bottom face

B- Bottom face

C- Bottom face

D- Bottom face

Figure (4.1) Punching shear failure and crack patterns of R.C. slabs

E- Bottom face

F- Top face

G- Bottom face

H- Bottom face

Figure (4.1) continued

4.3 Observation of Failure Modes

The general behavior of all slabs is all nearly identical as shown in Fig. (4.1). When the load is applied to the slab specimen, the first visible crack (bending cracks) was observed at the tension face of the tested slab and the relationship between load and displacement is linear till flexural cracks occur. In all slabs, cracking on the tensile face began near the center and radiated towards the edges (semi-random phenomena). As the load is increased the cracking propagated to the opposite face. At higher loads, the already formed cracks got widened while new cracks started to form. The new formed cracks are roughly semi-circular or elliptical in shape and occurred in the tension surface of the slab. Failure of the slab occurred when the cone of failure radial outward from the point of load application pushed up through the slab body (brittle failure with limited warning). At failure, the slab was no longer capable of taking additional load.

Figure (4.1) presents general patterns cracking and failure on the top and bottom faces of the specimens after failure. No cracks are observed in the compression face of any slab, except those which are observed around the loaded area at failure, which are almost the same as that of the loading plate dimensions. The cracks on the bottom face of specimens are radial, propagating from the center of slab. These patterns are occurred at the center of slabs and propagated across the slab to the sides in the redial direction. Different cracking patterns may be noticed in Fig. (4.1) such as spacing, extent of cracks and perimeter of failure cone. These variations in crack patterns that appeared in bottom face of slabs depending on the plane area (reinforced area), the location of aluminum strips and concrete compressive strength.

4.4 Effect of the Tested Variables on the Ultimate Punching Strength.

Table (4.1) First crack, ultimate loads and ultimate deflection of all slabs

Groups	No.	Symbol	Area of alum-inum (m^2)	First cracking load, Pcr. (kN)	Ultimate load, Pu. (kN)	Deflection at Pu (mm)	Pcr/Pu %
G1	1	N.C.0.0	------	28	120	10.11	23.33
	2	0.5d-N.C.10.2	0.16	38	155	7.50	24.52
	3	1.5d-N.C.10.2		37.40	152	7.70	24.61
	4	2d-N.C.10.2		33	150	8.00	22.00
	5	N.C.10.3	0.24	38.3	157	7.00	24.24
	6	N.C.10.4	0.32	43	170	6.40	25.29
	7	2-N.C.5.4	0.16	33	150	6.9	22.00
	8	N.C.5.6	0.24	37.5	153	6.00	24.51
	9	N.C.5.8	0.32	40	169	6.37	23.67
G2	10	H.C.0.0	------	44.2	170	8.04	26.00
	11	0.5d-H.C.10.2	0.16	53.9	192	7.20	28.07
	12	1.5d-H.C.10.2		53.2	186	7.52	28.6
	13	2d-H.C.10.2		51.2	180	7.88	28.44
	14	H.C.10.3	0.24	54.5	195	6.83	27.94
	15	H.C.10.4	0.32	56.95	220	6.26	25.89
	16	2-H.C.5.4	0.16	49.32	178	7.20	27.71

Table (4.2) Increase in first cracking and ultimate load of concrete slabs compared with reference slab

Groups	Slab	Increase in Pcr compared with (control slab) %	Increase in Pu compared with (control slab) %
G1	N.C.0.0	0	0
	0.5d-N.C.10.2	35.71	29.17
	1.5d-N.C.10.2	33.57	26.67
	2d-N.C.10.2	17.86	25
	N.C.10.3	36.78	30.83
	N.C.10.4	53.57	41.67
	2d-N.C.5.4	17.86	25
	N.C.5.6	33.93	27.5
	N.C.5.8	42.86	40.83
G2	H.C.0.0	0	0
	0.5d-H.C.10.2	21.95	12.94
	1.5d-H.C.10.2	20.36	9.41
	2d-H.C.10.2	15.84	5.88
	H.C.10.3	23.3	14.70
	H.C.10.4	28.85	29.41
	2d-H.C.5.4	11.58	4.71

4.4.1 Effect of Aluminum Area (Plan Area)

Strengthening of RC slabs with aluminum sheets attained a noticed increase in both strength and stiffness. Figure (4.2) and Table (4.2) show the effect of aluminum amount (plan area) on the ultimate punching resistance of slabs strengthened with aluminum strips. It can be seen from this figure and the table, when all other parameters are the same, the increase in amount of aluminum leads to significant increase in ultimate resistance and decrease the corresponding deflection of the strengthened slabs with aluminum strips.

Also, the test resulst show that the effect of aluminum area on the normal strength concrete is higher than that on high strength concrete for both ultimate load and stiffness. The increase in ultimate load is ranged (25-41.6) %, for normal strength, while these increases become (4.71-29.41) % for high strength concrete. the greater contribution of aluminum in normal concrete than in high strength concrete is because normal concrete cracks early making aluminum contributes effectively and the bond layer (epoxy) between aluminum and concrete in small load level is more effective than in high load level.

4.4.2 Effect of Aluminum Sheets Width

Two widths of aluminum sheets are used as a variable in this study. These are (50 and 100) mm. The total area of aluminum sheets remains constant (0.16, 0.24 and 0.32) mm^2 with changing width of sheets as shown in Figure (3.15). The influence of aluminum sheet width on ultimate punching capacity of strengthened slabs are presented in Figs. (4.3) and (4.4). From these figures, it can be noticed that the ultimate punching capacity of test specimens does not vary when using aluminum sheets widths (50 or 100) mm in strengthening process for both normal and high strength slabs. It is due to the both widths used having the same area of aluminum providing the same strengthening on tested specimens.

The small difference in ultimate load between the two cases may be - to the expected scattering of concrete strength and experimental results.

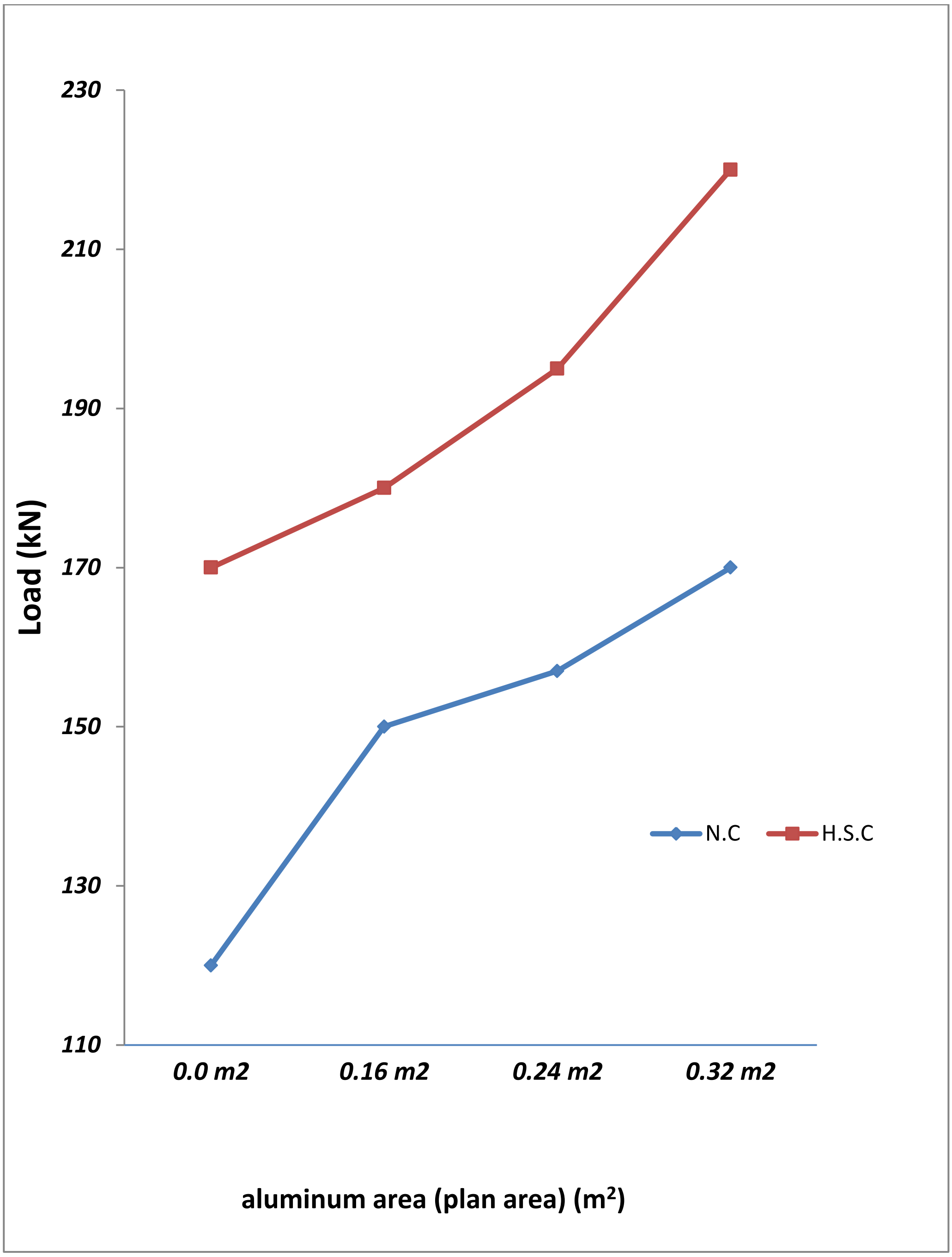


Figure (4.2) Comparison of the ultimate punching resistance of slabs with different aluminum area

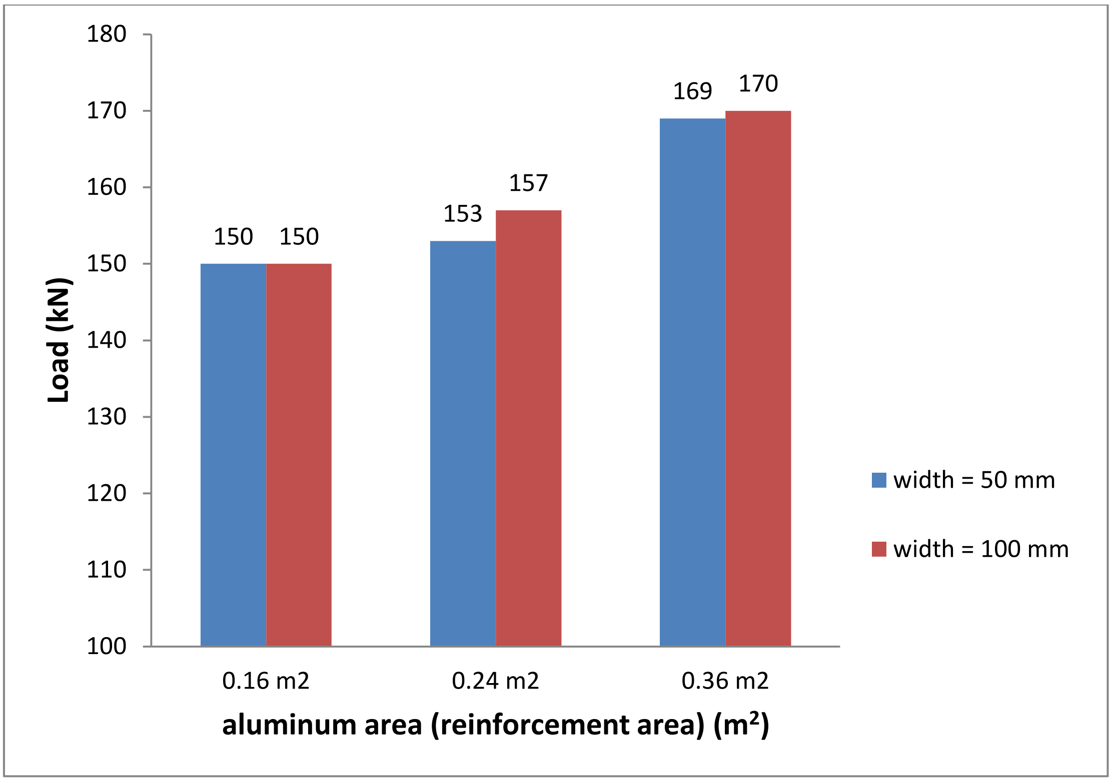


Figure (4.3) Comparison of the ultimate punching resistance of slabs with different aluminum sheets width(for normal concrete)

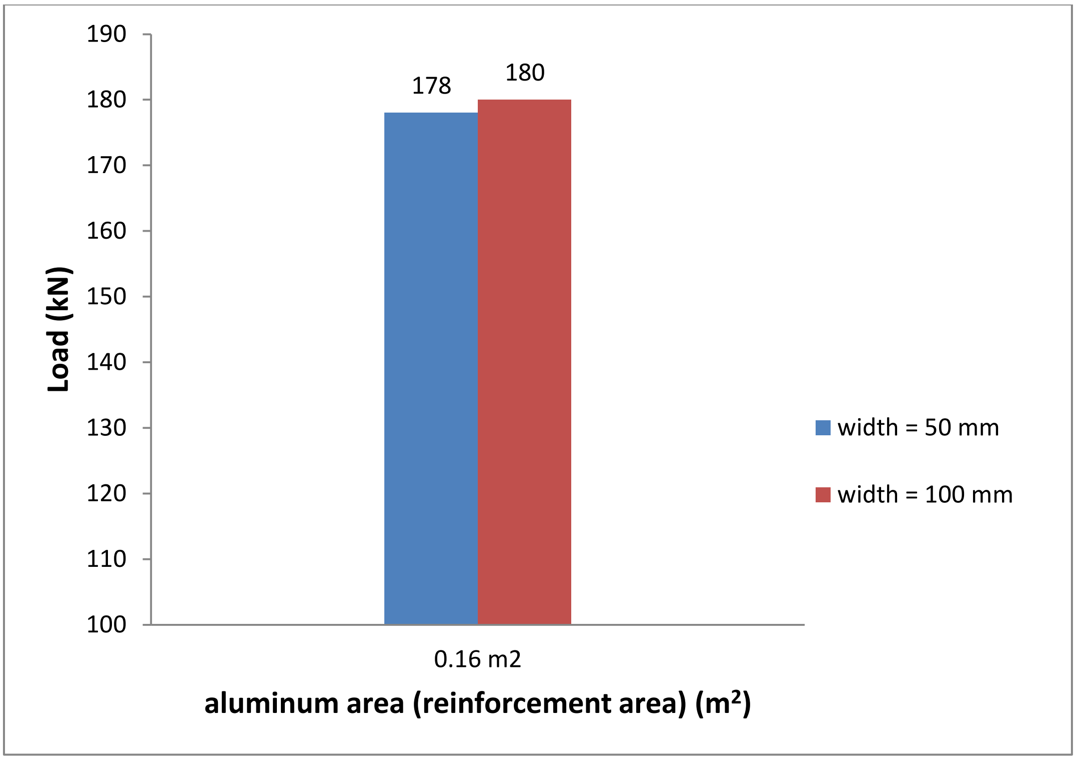


Figure (4.4) Comparison of the ultimate punching resistance of slabs with different aluminum sheets width(for high strength concrete)

4.4.3 Effect of Location of Aluminum Sheets

The area of aluminum (0.16) m^2 of two strips with width (100) mm is located in three different positions. The offset are (**0.5d**, **1.5d** and **2d**) from the column face for the specimens (**0.5d-N.C.10.2**, **1.5d-N.C.10.2** and **2d-N.C.10.2**) and (**0.5d-H.C.10.2**, **1.5d-H.C.10.2** and **2d-H.C.10.2**). The positions are selected according to critical perimeter provided in design models of the **ACI 318-11Code** [50], **BS8110-1997** [51] and the **Eurocode 2-2004** [52] in predicting the punching shear strength of slabs. These are shown in Fig. (4.5).

Comparing the different locations of aluminum strips, it can be noted that the location of aluminum sheet at a distance (0.5d) from column face gives higher increase in punching load compared with other locations (1.5d) and (2d) for both normal and high strength concrete. This is due to the higher number of tension cracks that appeared and spread in radial pattern near this region (0.5d) from column face. This makes the aluminum sheets at this distance more efficient in resisting the growth of these cracks. Figures (4.5) to (4.6) illustrate the effect of aluminum sheets location on the ultimate punching resistance of the strengthened slabs by aluminum strips.

4.4.4 Effect of Concrete Compressive Strength

Table (4.3) shows the ultimate load and corresponding deflection of the strengthened slabs with aluminum strips for two different used concrete strength. From this table, it can be seen that the ultimate load of the strengthened slabs increases as the compressive strength increases, while the maximum deflection of strengthened slab decreases as the concrete strength increases.

The effect of aluminum sheets on RC slabs with different concrete compressive strengths are shown in Figure (4.6). As shown in this figure, the effect of aluminum area on the normal strength concrete is higher than that of high strength concrete for ultimate load.

Table (4.3) Ultimate load of specimens with different compressive strength

Aluminum area (m^2)	Ultimate load (kN)		Maximum deflection (mm)	
	Normal concrete	High strength concrete	Normal concrete	High strength concrete
0	120	170	10.11	8.04
0.16	150	180	8.00	7.88
0.24	157	195	7.00	6.83
0.32	170	220	6.40	6.26

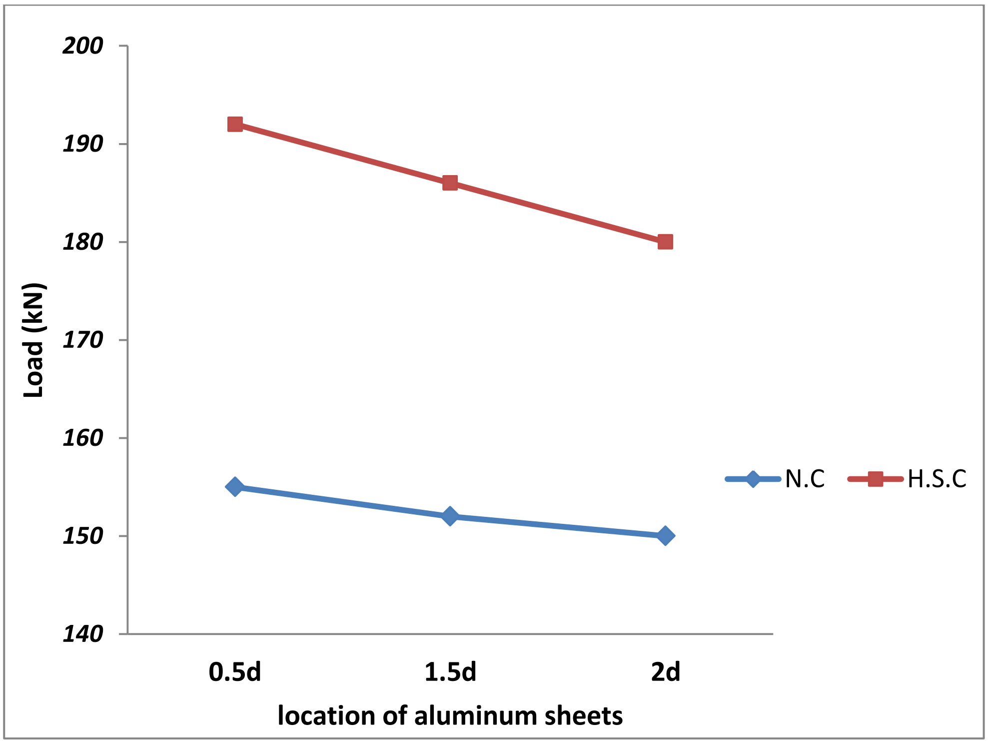


Figure (4.5) Comparison of the ultimate punching resistance of slabs with different location of aluminum sheets

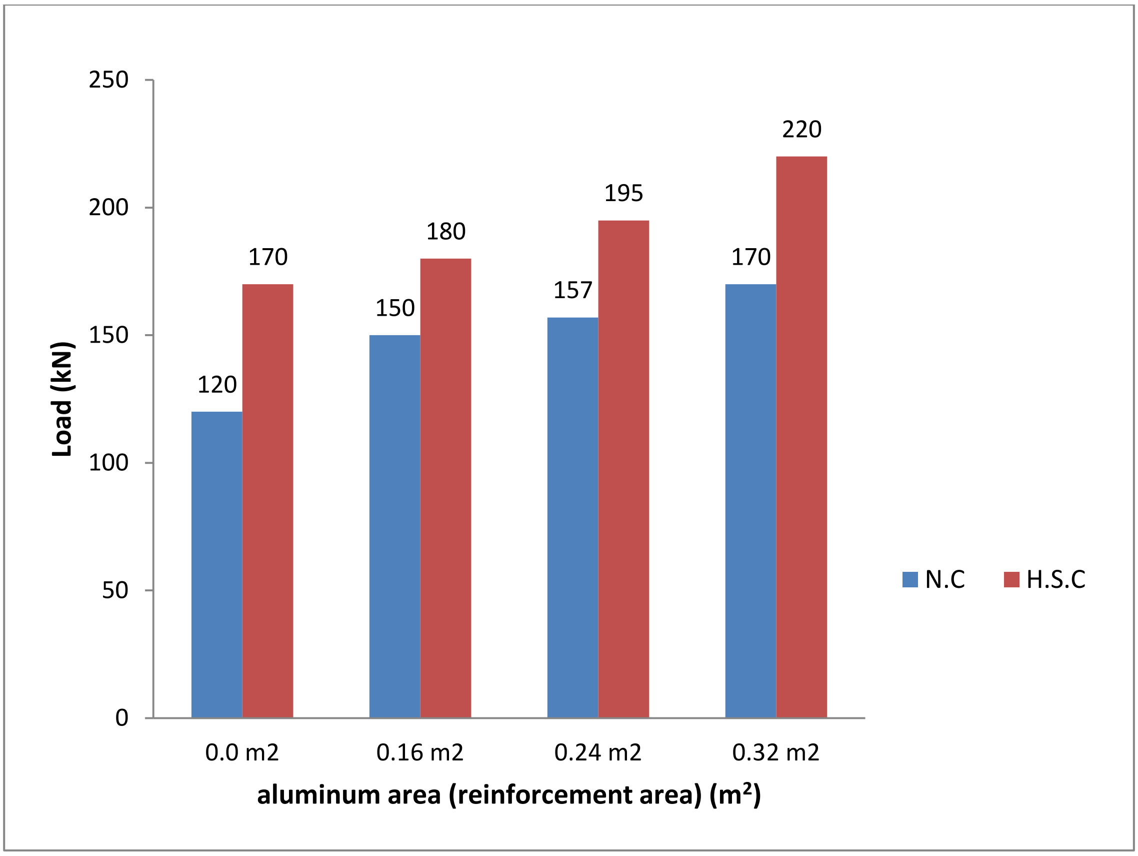


Figure (4.6) Comparison of the ultimate punching resistance of slabs with different compressive strength

4.5 Effect of the Tested Variables on Load-Deflection Behavior of Slabs.

4.5.1 General

From the experimental results of the tested slab, it is observed that the some properties of R.C. slabs are enhanced when strengthened with aluminum sheets, which include increase their first crack loads, ultimate loads, and stiffness after cracking due to the presence of aluminum sheets.

The load–deflection curve of the tested slabs can be divided into uncracked and cracked stages. In uncracked stage the load–deflection response is linear and for cracked stage response is parabola up to the ultimate load.

4.5.2 Effect Of Aluminum Area (Plan Area)

Figures (4.7) to (4.9) show the load deflection relation of all tested slabs. The deflection is measured at the center of slabs. In all these figures, each single curve in any figure consists of two parts; the first part is for the uncracked stage and up to the initiation of the first crack, then the second part which represents the cracked slab and up to failure.

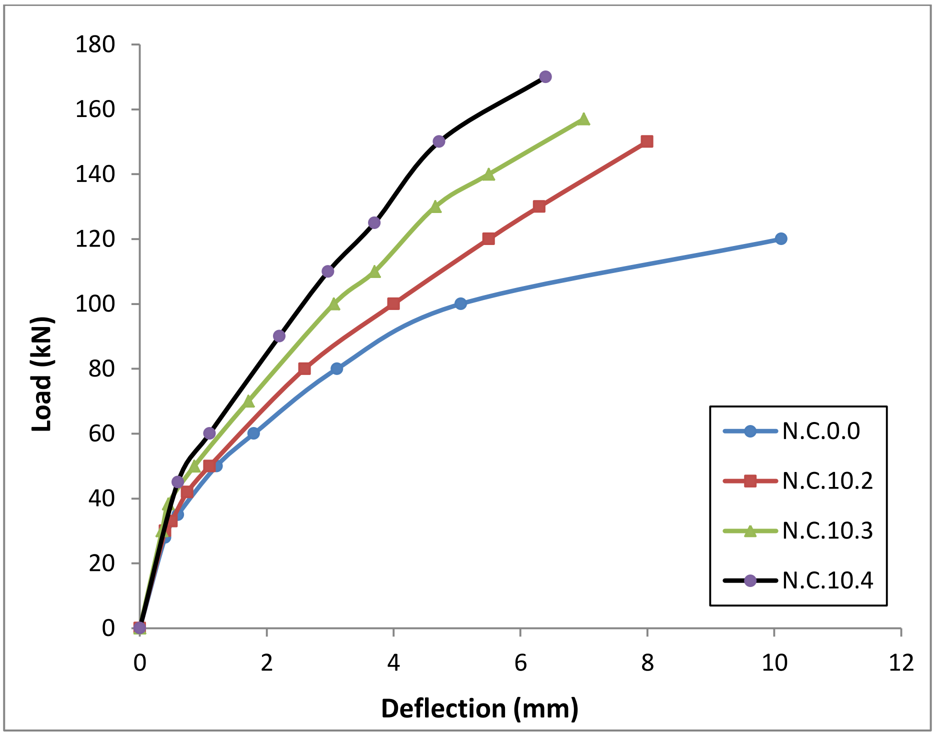
The first part of the curves is approximately a straight line with a high slope angle. The second part of the curves is a curved line. In uncracked stage the relationships of all models coincide and the difference between them is starting at point of crack first. It is very clear from these curves that increasing the amount of aluminum area (plan area) increases ultimate punching resistance and first cracking load.

4.5.3 Effect Of Aluminum Sheet Width on Load-Deflection Behavior of Slabs

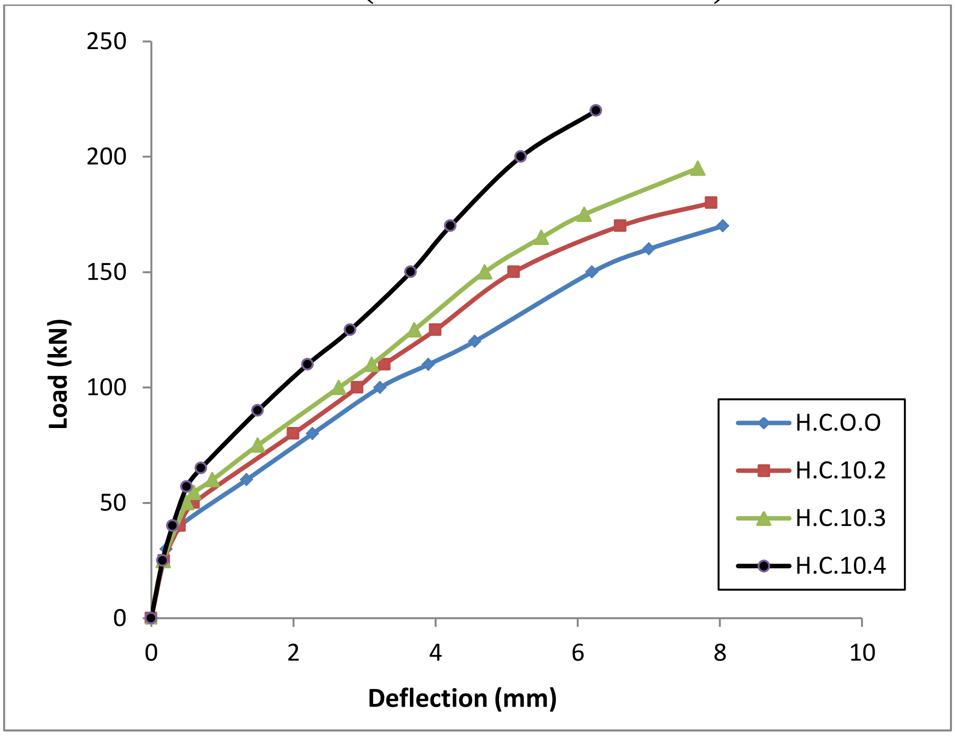
From test results it is observed that strengthening slabs with aluminum sheets of width (50) mm leads to a slightly decrease in deflection values at the cracked stage. This may be attributed to that when using aluminum sheets with width (50) mm for any area of aluminum, increasing number of sheets provide better resistance to crack propagation than aluminum sheets with width (100) mm. Figs. (4.12) to (4.15) show the comparison between slabs with different aluminum sheets width.

4.5.4 Effect of Location of Aluminum Sheets on Load-Deflection Behavior of Slabs.

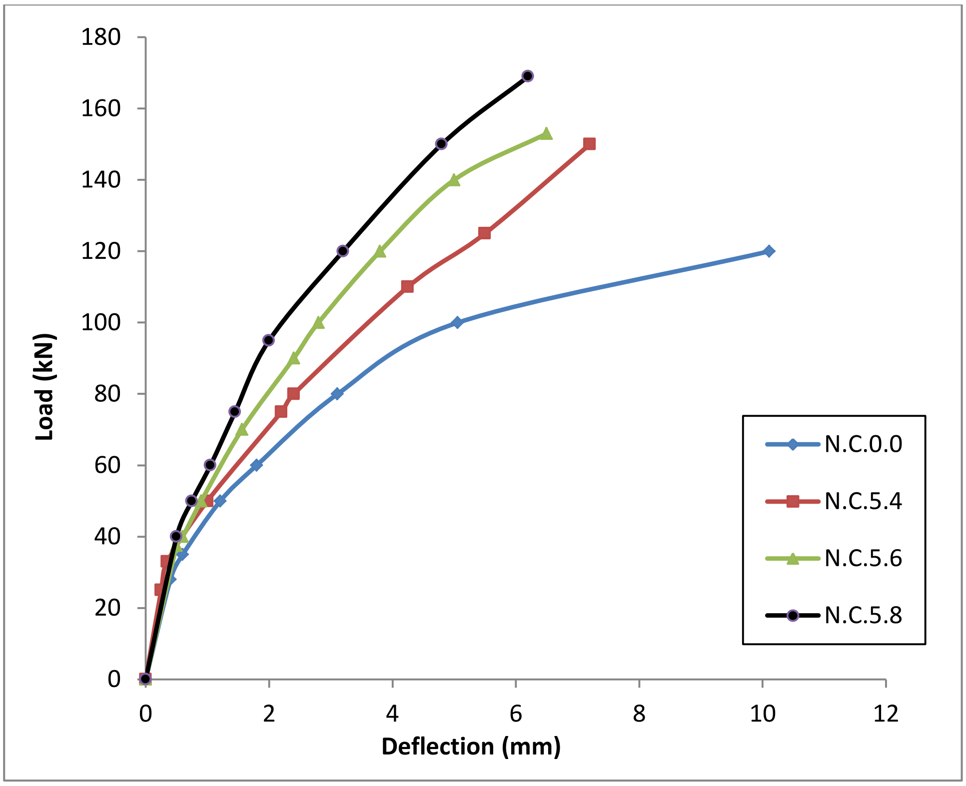
Considering the location of the aluminum sheets from the column face, it can be noted that the sheets location have considerable affection punching capacity. For slabs strengthened with area of aluminum sheets (0.16) m^2 the location (0.5d) from column face leads slightly to higher stiffness than other slabs which offset by (1.5d and 2d). Figures (4.14) and (4.15) show the comparison between slabs with different locations of aluminum sheets.



Figure(4.7) effect of aluminum area on load – deflection for normal concrete(sheets width =100 mm)



Figure(4.8) effect of aluminum area on load – deflection for high strength concrete(sheets width =100)



Figure(4.9) effect of aluminum area on load – deflection for normal concrete(sheets width =50 mm)

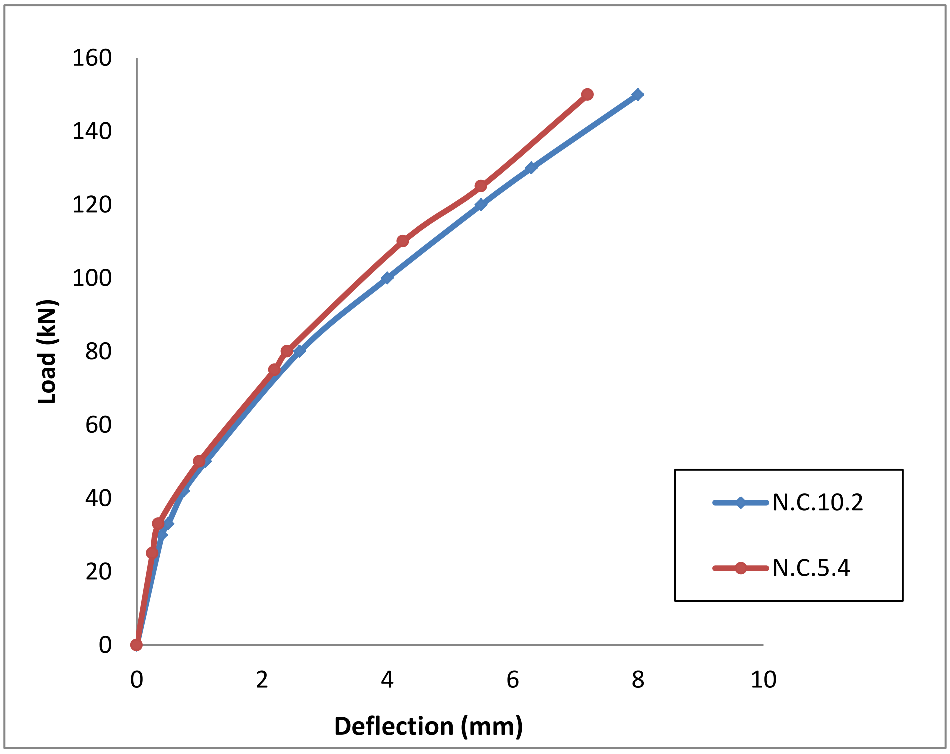


Figure (4.10) effect of aluminum sheets width on load – deflection curve between for normal concrete slabs with (0.16)m^2 aluminum area

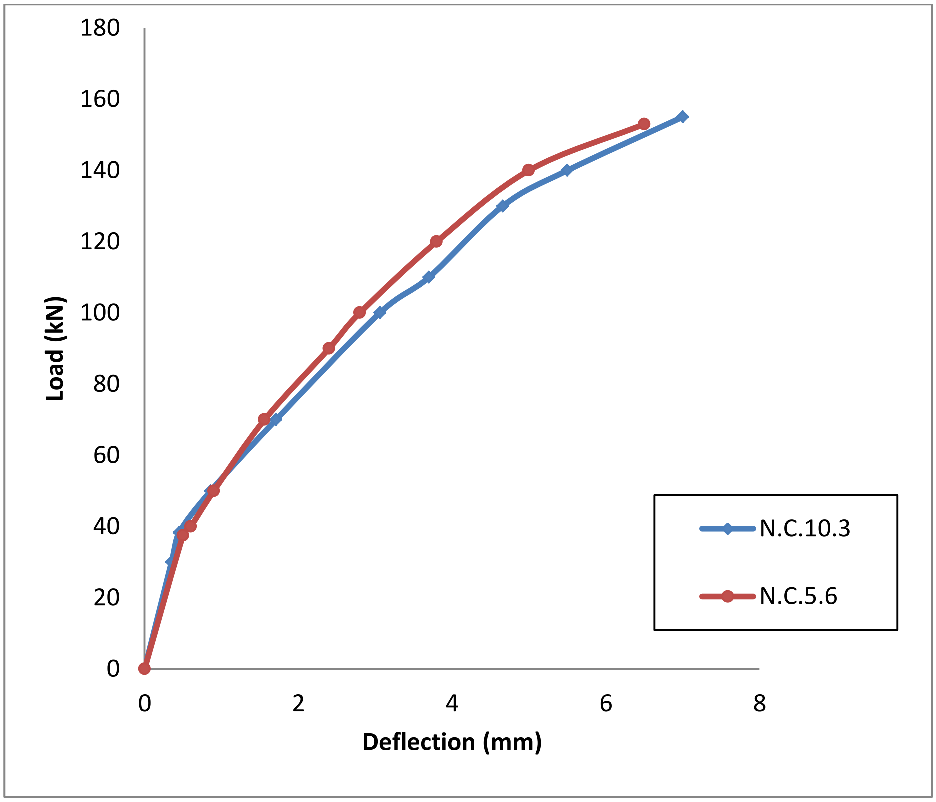


Figure (4.11) effect of aluminum sheets width on load – deflection curve between for normal concrete slabs with $(0.24)m^2$ aluminum area

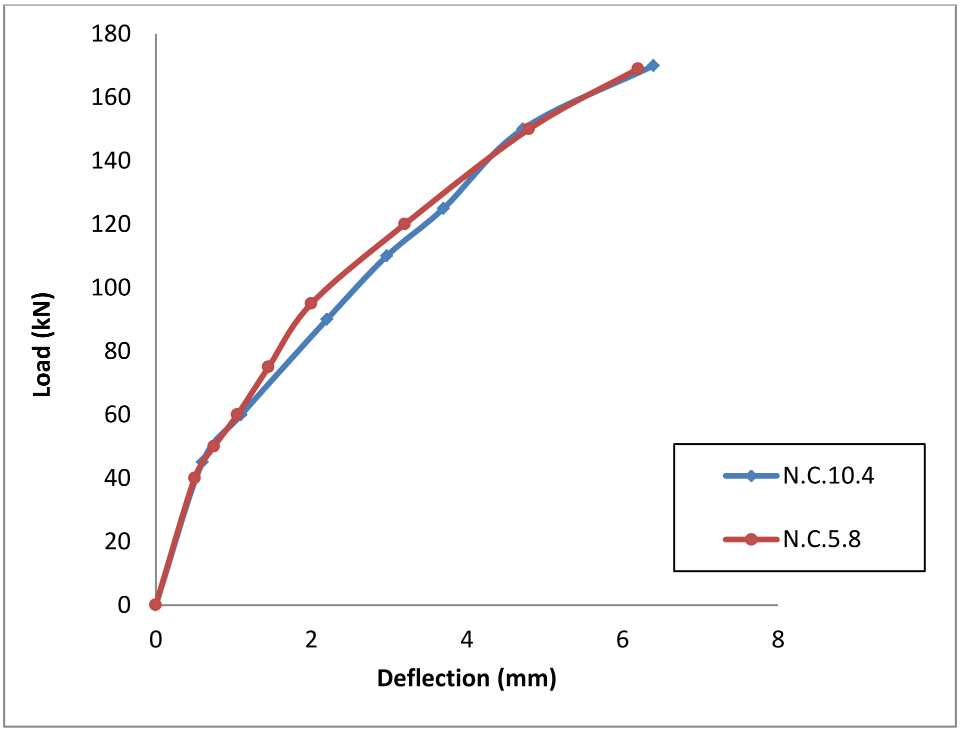


Figure (4.12) effect of aluminum sheets width on load – deflection curve between for normal concrete slabs with (0.32)m2 aluminum area

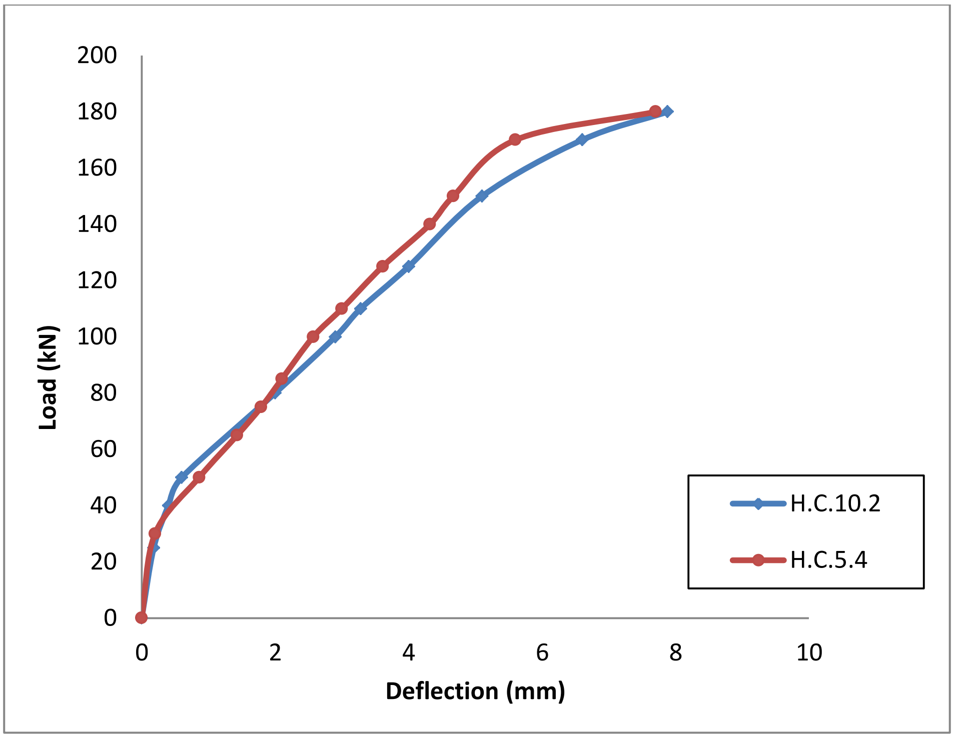


Figure (4.13) effect of aluminum sheets width on load – deflection curve between for high strength concrete slabs with (0.32)m^2 aluminum area.

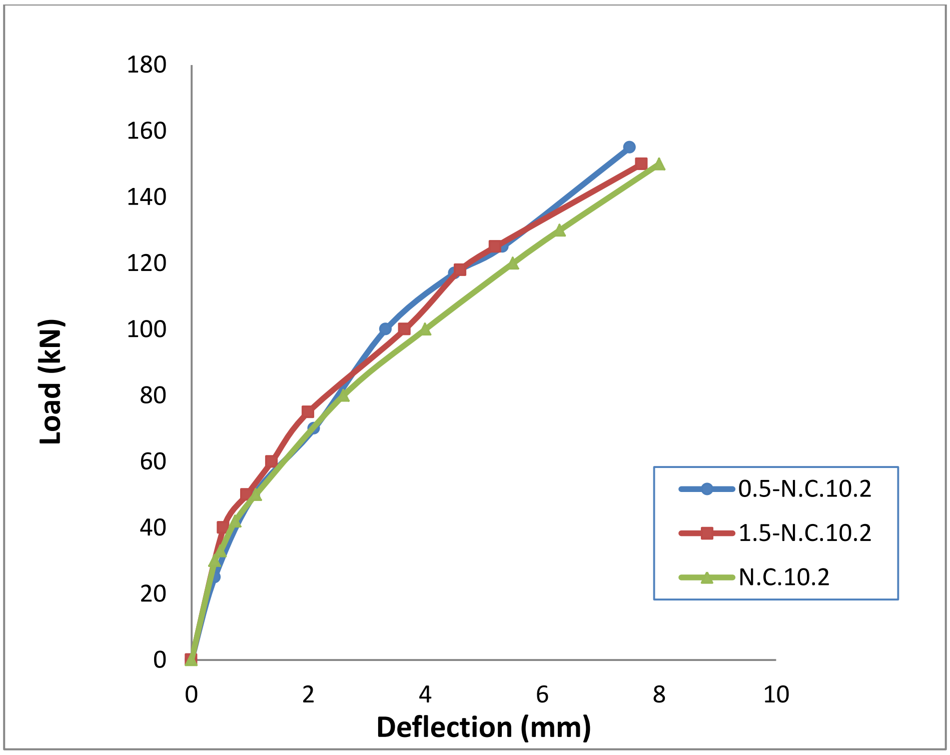


Figure (4.14) location effect of aluminum sheets on load – deflection curve for normal concrete slabs with (0.16) m^2 aluminum area

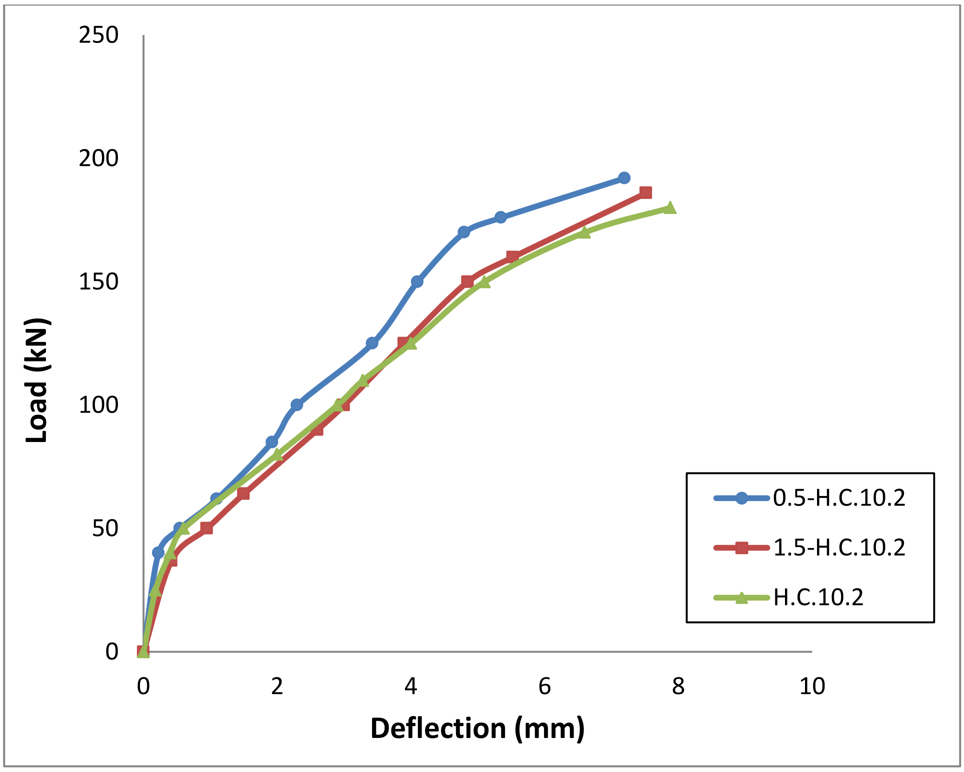


Figure (4.15) location effect of aluminum sheets on load – deflection curve for normal concrete slabs with (0.16) m^2 aluminum area

4.6 Size of Failure Zone and Failure Angles

The failure angles of the punching pyramid are measured by indicating the dimensions of the crushed zone as shown in Figure (4.16).

All the test specimens failed in punching shear. Table (4.4) summarizes the size and inclination angle of punching shear failure of the tested slabs. Sudden failure is noticed in all test specimens, all the slabs failed in a similar manner and the failure shape is nearly of elliptical shape.

4.6.1 Size of the Failure Zone

The punching shear surface on the tension face occurred at a distance from the column face, 1.57 to 2.89 times the effective depth (d) for NCS slabs, and 1.46 to 3.14 for HCS slabs.

It can be noticed that, the size of the failure zone decreases by about (8.6-27.2) %, (28.4-43.2) % and (34.5-53.4) % by strengthening slabs with area of aluminum sheets (reinforcing area) of (0.16, 0.24 and 0.32) m^2 respectively. It can also be noticed that the failure zone is very large in conventionally reinforced concrete slabs without strengthening by aluminum sheets, as compared to slabs strengthened by aluminum sheets.

4.6.2 Failure Angles

From Table (4.4) it can be observed that the angle of failure surface increases with the increase in area of aluminum sheets. The angle increases by about (10.4-33.7) %, (35.2-64.4) % and (46.2-94.3) % by strengthening slabs with area of aluminum sheets (reinforcing area) of (0.16, 0.24 and 0.32) m^2 respectively. It is noticed that the failure pyramid that is pushed out in slabs without aluminum sheets has a much wider base than that in slabs with aluminum sheets. This indicates that aluminum sheets help to prevent the disintegration of concrete cover under the flexural steel reinforcement and tend to integrate the whole section.

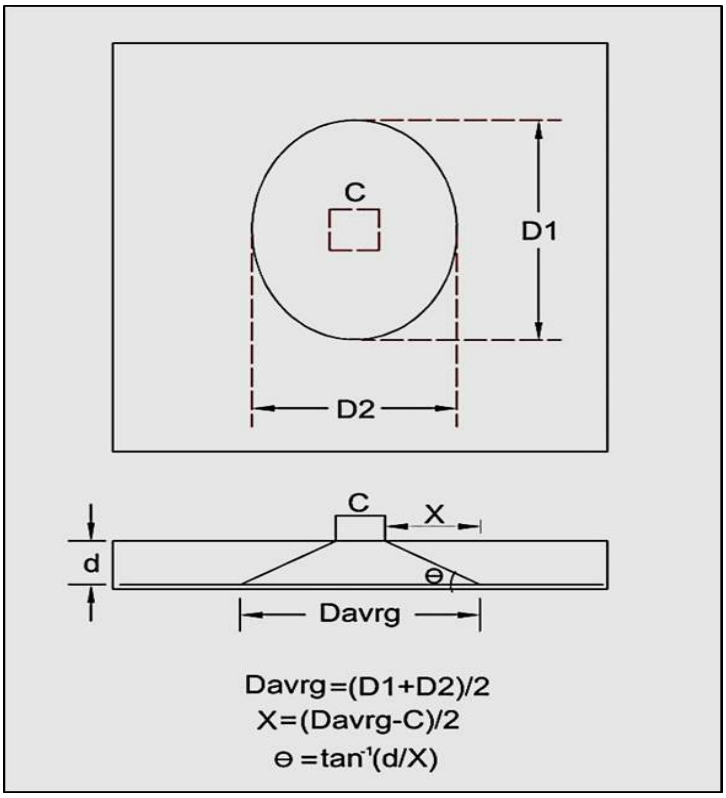


Figure (4.16): Size of the failure zone and failure angle

Table (4.4): Size of the failure zone and failure angle for tested slabs.

Slab	Effective depth, d (mm)	Punching size, D (mm)		Average distance from the column face, x (mm)	x/d	Angle of punching shear failure, ϴ (degree)
		D_1	D_2			
N.C.0.0	70	470	500	202.5	2.89	19.03
0.5d-N.C.10.2	70	400	480	180	2.57	21.20
1.5d-N.C.10.2	70	390	480	177.5	2.54	21.50
2d-N.C.10.2	70	360	400	150	2.14	24.98
N.C.10.3	70	300	320	115	1.64	31.29
N.C.10.4	70	300	300	110	1.57	32.45
2d-N.C.5.4	70	450	450	185	2.64	20.70
N.C.5.6	70	360	380	145	2.07	25.73
N.C.5.8	70	330	360	132.5	1.89	27.83
H.C.0.0	70	520	520	220	3.14	17.64
0.5d-H.C.10.2	70	440	510	197.5	2.82	19.49
1.5d-H.C.10.2	70	400	500	185	2.64	20.70
2d-H.C.10.2	70	400	400	160	2.29	23.60
H.C.10.3	70	350	350	135	1.93	27.38
H.C.10.4	70	270	300	102.5	1.46	34.29
2d-H.C.5.4	70	400	400	160	2.29	23.60

4.7 Prediction of Punching Shear Strength

Many codes and researchers have presented different formulas for predicting the punching shear strength of slabs based on their understanding of punching shear behavior. Most codes present formulas, where the design punching load is a product of design nominal shear strength and the area of a chosen control surface.

Generally, punching strength is predicted by considering a nominal shear stress, a control perimeter and an effective depth. The main differences of approaches depend on the assumed location of the different control perimeter, concrete strength contribution, the size effect and the reinforcement ratio. Depending on the method used, the critical section to check punching shear in slabs is usually situated between 0.5 to 2 times the effective depth from the face of the load. The provisions of three building codes, **ACI 318-11Code** [50], and **BS8110-1997**[51], **Eurocode 2 -2004**[52], are considered. In this study also, the influence of various parameters such as configuration, amount and spacing of aluminum sheets on the predicted punching shear capacity of strengthened of slabs by these models are included.

In the ACI Code, shear stress is expressed in term of a square-root relationship with the concrete compressive strength, while the BS8110 and Eurocode 2 consider a cubic-root proportion.

The Eurocode 2 and BS8110 consider reinforcement ratio and size effect into consideration by different modification factor, while the ACI Code neglects these effects.

The main difference in the results between the various design methods appears to be due to different calculation approaches of punching pyramid perimeter. The punching area calculation according to BS8110 assumes that punching crack is inclined towards an angle of about 33.7° to slab plane, and 26° in the Eurocode 2, while the ACI Code assume this angle to be equal to 45°.

Table (4.5) presents detailed calculations of the predicted punching shear capacity of the slab specimens tested in the current study according to Equations of (ACI, BS8110 and Eurocode 2). While these predicted values are compared with the experimental result as given in Table (4.5).

Table (4.5): Comparison between experimental and predicted punching shear strength

Slab	Failure load(kN)				Ratio (1/2)	Ratio (1/3)	Ratio (1/4)
	Exp. (1)	ACI (2)	B.S81-10 (3)	EC-2 (4)			
N.C. 0.0	120	68	99	111	1.76	1.21	1.08
0.5d-N.C.10.2	155	68	99	111	2.28	1.57	1.4
1.5d-N.C.10.2	152	68	99	111	2.24	1.54	1.37
2d-N.C.10.2	150	68	99	111	2.21	1.52	1.35
N.C.10.3	157	68	99	111	2.3	1.58	1.41
N.C.10.4	170	68	99	111	2.5	1.72	1.53
2-N.C.5.4	150	68	99	111	2.21	1.52	1.35
N.C.5.6	153	68	99	111	2.25	1.55	1.38
N.C.5.8	169	68	99	111	2.49	1.71	1.52
Average					**2.25**	**1.55**	**1.38**
standard deviation (SD)					**0.21**	**0.15**	**0.13**
H.C. 0.0	170	100	135	144	1.7	1.26	1.18
0.5d-H.C.10.2	192	100	135	144	1.92	1.42	1.33
1.5d-H.C.10.2	186	100	135	144	1.86	1.38	1.29
2-H.C.10.2	180	100	135	144	1.8	1.33	1.25
H.C.10.3	195	100	135	144	1.95	1.44	1.35
H.C.10.4	220	100	135	144	2.2	1.63	1.53
2-H.C.5.4	178	100	135	144	1.78	1.32	1.24
Average					**1.89**	**1.4**	**1.31**
Standard deviation (SD)					**0.16**	**0.12**	**0.11**

4.8 Results and Discussion of Predicted Punching Shear Strength

The experimental results are compared with design models of the **ACI 318-11Code** [50], the **BS8110-1997** [51] and **Eurocode 2-2004** [52] in predicting the punching shear strength of slabs strengthened with aluminum sheets. These equations have been applied to calculate the punching shear strength for slabs failing in punching shear. The relative shear strength values (V_{TEST}/V_{PRED}) are found using these equations, as shown in Table (4.5). The values of the average and standard deviation are calculated for each equation and listed in Tables (4.5). From this Table, it can be observed that (V_{TEST}/V_{PRED}) of normal concrete slabs are greater than those of high strength concrete slabs for all equations.

The design codes of ACI Code, B.S8110 and Eurocode 2provide conservative predictions for the punching shear strength. It should be noted that the code equations do not account the effect of aluminum sheets reinforcement.

The average ratio (V_{TEST}/V_{PRED}) for normal concrete are (2.25, 1.55and1.38) when using (ACI, B.S8110 and Eurocode 2) equations, and for high strength concrete are (1.89, 1.40 and 1.31) when using (ACI, B.S8110 and Eurocode 2) equations.

It can be noticed from Tables (4.5). The (SD) values for the high strength concrete are smaller than those for the normal concert group, that means, the variation in (V_{TEST}/V_{PRED}) for the slabs made with high strength concert are less than those of slabs made with normal concrete, this may be attributed to that the high strength concert more homogenous than normal concert. The lowest (SD) values mean less dispersion in (V_{TEST}/V_{PRED}).

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

In this chapter, the conclusions drawn from the test results are described and some recommendations for future work are presented.

5.2 Conclusions

The main conclusions drawn from the experimental work can be summarized as given below:

1- Using aluminum sheets to strengthen RC slabs is simple and easy to install, and it effectively improves the overall properties of these members.

2- The strengthened slabs exhibited higher punching capacity compared with the control slab. The increase in punching capacity is up to 41%.

3- The use of aluminum sheets as external strengthening has a significant effect on initiation of crack of the reinforced concrete two-way slabs by delaying the crack appearance and reducing the crack width. The increase in cracking loads is about (6.25 -53.57)% compared with the unstrengthened (control) slab.

4- The external aluminum sheets attached to the tension faces of reinforced concrete slabs lead to decrease of ultimate deflection of slabs. The decrease in final deflection is about (2-40.65) % for strengthening specimens compared with that of unstrengthened (control) slab.

5- Increasing the amount of aluminum sheets (plan area) significantly increase the ultimate punching load of the slabs. The ultimate punching loads are increased (25%, 29.1% and 41.6%) when using aluminum area of (0.16, 0.24 and 0.32) m^2 respectively for normal concrete slabs and (5.88%, 11.76% and 29.4%) respectively for slabs with high strength concrete.

6- For the same area of aluminum sheets (plan area), the ultimate punching capacity of strengthened slabs is similar for both different widths of sheets (100 or 50 mm).

7- Strengthening specimens by aluminum sheets placed at (0.5d) from columns faces produces higher stiffness values and higher punching capacity.

8- Increasing the concrete strength leads to increase the punching resistance of all the tested slabs.

9- Strengthening by aluminum sheets for slabs made with normal concrete is more effective than for slabs made with high strength concrete.

5.3 Recommendations for Future Work

A further investigation is required for better understanding the punching behavior of reinforced concrete two-way slabs strengthened with aluminum sheets. The areas, which are to be of a particular importance, are listed here:

1- Further studies should focus on expanding the experimental database of reinforced concrete two-way slabs strengthened with aluminum sheets through full scale experimental tests and on wide range of slab geometry.

2- Investigating the structural behavior of reinforced concrete slabs strengthened or repaired with aluminum strips under cyclic and dynamic loading conditions.

3- Studying the structural behavior of lightweight concrete slabs strengthened or repaired with aluminum sheets.

4- Studying the structural behavior of concrete slabs with openings strengthened or repaired with aluminum sheets.

5- Studying the structural behavior of edge slab-column connections strengthened or repaired with aluminum sheets.

6- Studying other parameters including slab thickness, column dimensions, column shapes and aluminum sheets thickness.

7- Studying long-term structural behavior of reinforced concrete slabs strengthened or repaired with aluminum sheets.

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الخلاصه

ان الغرض من هذا البحث العلمي هو دراسة التأثير شرائح الألمنيوم المستخدمة خارجيا في تقوية السقوف الخرسانية تحت تاثير قوى القص الثاقب عمليا ومقارنة النتائج مع مجموعه من كودات التصميم.

تضمن البرنامج العملي صب و فحص (16) بلاطة بأبعاد (800×800×100)ملم، حيث تم تقسيم هذه النماذج إلى مجموعتين استنادا الى مقاومة انضغاط الخرسانة؛ المجموعه الاولى ضمت تسعة بلاطات من الخرسانة العادية اما المجموعة الثانيه ضمت سبعة بلاطات من الخرسانه عالية الانضغاط. في كل مجموعه تم ترك بلاطه واحده بدون تقويه كبلاطة مرجعيه، في حين تم تقوية البلاطات الباقية بأنماط مختلفة من شرائح الالمنيوم.

تم دراسة تأثير كل من كمية شرائح الالمنيوم (مساحة التعزيز) (0.16,0.24,0.32) م^2، عرض شرائح الالمنيوم (100 و 50) ملم، موقع شرائح الالمنيوم و مقاومة انضغاط الخرسانة على مقاومة القص الثاقب للبلاطات المقواة بالألمنيوم. صممت جميع البلاطات الخرسانية المستخدمة في هذا البحث بشكل يضمن فشلها بالقص الثاقب. أسندت البلاطات إسنادا بسيطاً على طول حوافها الأربع و حملت مركزياً عن طريق لوحة تحميل ذات مقطع مربع بأبعاد (80×80) ملم.

من خلال الفحوصات المختبرية تم تسجيل وتحري ومناقشة كل من مقاومة القص الثاقب ، منحنيات الحمل – الهطول ، وأنماط التشقق ، تأثير اختلاف المتغيرات على البلاطات.

أظهرت النتائج العملية التي تم الحصول عليها أن عملية تقوية البلاطات الخرسانية باستخدام شرائح الالمنيوم أدت إلى زيادة في قيمة تحمل القص الثاقب الأقصى للبلاطات (Ultimate Loads)

بمقدار يتراوح بين (5 – 41)% مقارنة بالبلاطات الخرسانية غير المقواة وكذلك كانت الزيادة في حمل التشقق الأول (First Cracking Loads) تتراوح بين (11 – 53)%، بالإضافة إلى أن البلاطات الخرسانية المقواة بشرائح الالمنيوم كانت أكثر مقاومة للهطول (Deflection) مقارنة مع مثيلتها من البلاطات الخرسانية غير المقواة حيث كان الفرق في مقدار الهطول يصل الى (40)%.

اظهرت النتائج بان الزيادة في تحمل القص الثاقب الاقصى للالواح كان متغير بين (25 – 41) % باستخدام الخرسانة الاعتياديه ذو مقاومة انضغاط MPa (30) بينما كانت النسبه (5–29) % باستخدام الخرسانة عالية المقاومة MPa (65) .

بينما اظهرت زيادة مساحة التعزيز بالالمنيوم تؤدي الى زيادة في الحمل الاقصى، وان استخدام شرائح المنيوم بعرض 100 ملم او 50 ملم لا تؤثر على الحمل الاقصى بثبوت مساحة التعزيز.

تم تمثيل نسبة التعزيز ($0.16\ m^2$) ملم في ثلاثة اماكن على بعد (0.5d,1.5d and 2d) من وجه العمود، حيث ان المسافه (0.5d) اعطت اعلى تحمل للقص الثاقب.

تم مقارنة النتائج العمليه مع النتائج المحسوبه من خلال الكود الامريكي والبريطاني والاوربي حيث اظهرت كودات التصميم تحفظا كبير في تقدير تحمل القص الثاقب.

تحسين مقاومة القص للبلاطات الخرسانية باستخدام شرائح الالمنيوم

رسالة مقدمه إلى

كلية الهندسة - جامعة البصرة

وهي جزء من متطلبات نيل درجة الماجستير في

الهندسة المدنية (انشاءات)

من قبل

حيدر حسن حيدر

(بكلوريوس علوم في الهندسه المدنيه /2006)

2016