Structures 65 (2024) 106673

Contents lists available at ScienceDirect

Structures

journal homepage: www.elsevier.com/locate/structures

# An experimental and numerical study on two-way RC slabs with openings strengthened by ferrocement technique

Mahmoud Elsayed Elnagar, Mohamed H. Makhlouf*, Khaled M. El-Sayed, Gamal I. Khaleel

*Civil Department, Benha Faculty of Engineering, Benha University, Egypt*

ARTICLE INFO

*Keywords:*
Ferrocement
Openings
Strengthening
Welded and expanded steel mesh
ABAQUS

ABSTRACT

This study investigates the impact of creating a central square opening on reinforced concrete slabs and assesses the strengthening process using ferrocement layers. The investigated key parameters were the opening sizes, type, number, and extension length (outside the opening sides) of steel mesh layers used to strengthen the tested slabs. The experimental program included the preparation and testing of twelve two-way reinforced concrete slabs with identical dimensions, thickness, and reinforcement, but were different with respect to opening sizes and strengthening schemes. Four slabs acted as control specimens without strengthening; one was solid; the other three had different opening sizes; and the other eight slabs were strengthened using a ferrocement layer of 2 cm thickness applied on the bottom of the slab around the openings with various reinforcement schemes which included the number, type, and extension length (outside the opening) of steel mesh. All slabs were supported along the four sides with a clear span of 1 m in both directions and tested under four-point loading. The test results demonstrate that creating an opening in the slab decreases the ultimate load by 21.5 %, 31.9 %, and 40.7 % for opening dimensions (15, 25, and 35 cm), respectively. Using the ferrocement strengthening method helps to increase slabs' flexural load-carrying capacities and reduce crack propagation from opening corners. The study found that strengthening specimens with opening sizes of 15, 25, and 35 cm increased their flexural load-carrying capacities by 26 %, 33 %, and 34 %, respectively. The expanded steel mesh type also resulted in a higher ultimate load by 6–7 % than the welded mesh type. When the length of the strengthening ferrocement layers was doubled, the ultimate load went up by 6–7 %. Increasing steel mesh layer numbers from 1 to 4 increased the ultimate load by 25 % to 40 % compared to the corresponding un-strengthened slab with an opening. The maximum load of a slab with an opening was achieved by applying a 2 cm thickness of ferrocement layer reinforced with expanded metal mesh, with extension lengths equal to the opening's length. The study utilizes commercial software ABAQUS for finite element analysis (FEA) to validate the experimental results, resulting in a great agreement between the analysis and the experimental findings.

## 1. Introduction

Openings in reinforced concrete components are often needed for various reasons, including accommodating design changes or installing new facilities like lifts, staircases, windows, and electrical or HVAC systems. The creation of openings in concrete and reinforcing steel can result in a substantial reduction in the load-carrying capacity of structural elements. Therefore, it is imperative to employ an appropriate strengthening technique [1,2]. Numerous methodologies have been developed to tackle this particular concern. Banu et al. [3] concluded that reinforced concrete slabs are strengthened using various techniques to address issues like inadequate maintenance, overloading, and corrosion. The method chosen is based on aspects like the need for strength, position, design needs, ease of use, speed of application, and overall cost. Techniques like steel plate bonding, section enlargement, and external plate bonding increase slab moment capacity but can interfere with flooring systems. However, these methods can increase concrete member size and weight, require new formwork, and may cause corrosion damage. Fiber-reinforced polymers (FRPs) are corrosion-resistant materials that can extend service lives and reduce maintenance costs in reinforced concrete structures, offering a sustainable alternative to steel reinforcement and thereby reducing repair and maintenance costs [4,5]. M. Seliem et al. [6] assessed the effect of creating an opening in existing RC slabs and evaluated the strengthening

---

* Corresponding author.
*E-mail address:* mohamedmakhlouf83@yahoo.com (M.H. Makhlouf).

https://doi.org/10.1016/j.istruc.2024.106673
Received 1 February 2024; Received in revised form 6 May 2024; Accepted 28 May 2024

process using three different techniques. Cutting an aperture into a slab decreased its load-bearing capability by a percentage equal to the opening's size to the slab's main span. Strengthening with NSM CFRP strips restored 10 % of the slab's capacity, but stiffness remained unchanged, whereas EB CFRP plates recovered only 6 %. On the other hand, the slab's entire flexural capacity and stiffness were restored since the CFRP anchors were used to physically anchor the EB plates and prevent total separation.

R. Khajehdehi and N. Panahshahi [7] highlighted the importance of taking into account apertures, particularly corners, when retrofitting reinforced concrete slabs. The in-plane behavior of slabs is substantially altered by yielding bars and concrete cracking around these corners; therefore, further investigation is needed in this area.

H. Chand Dewangan et al. [8] investigated a composite curved/flat panel structure with square, circular, and elliptical cutout profiles for its deflection and stress responses. It shows that bigger cutout sizes decrease structural rigidity and increase deformation. Geometry can affect structural stiffness differently for different cutout forms. Rectangular cutouts deflect the most, whereas elliptical ones deflect the least.

Even though evaluating the structural cracks is crucial for assessing the quality of concrete construction, automated inspection systems have reduced the need for individual inspections but need improvement in cost efficiency and accuracy. This study compares various deep learning approaches for crack detection and classification in concrete structures, finding that pre-trained networks are suitable due to their faster convergence rate and accuracy [9].

Failure capacity and laminate failure strength were assessed using a numerical analysis, and it was found that the kind of loading affects both the maximum stress and the location at which it occurs. Comparisons are made based on ANSYS's output. The maximum stress areas in square holes are at the corners because the aspect ratio is close to 1, but in rectangular holes, they are positioned along the longer sides [10].

Different methodologies for enhancing the strength of flat slabs with centrally located apertures were investigated. A total of six specimens were utilized for experimental and numerical analysis. The techniques employed in the study encompassed close-surface-mounted steel bars, carbon fiber laminates, steel strips with anchor bolts, and an external layer of cementitious composite material (ECC) reinforced with welded wire mesh. The findings of the study indicate that creating an aperture reduced the slab's flexural strength by about 10 %, that the implementation of the different strengthening strategies resulted in an enhancement of load-carrying capacity up to 17 % compared to the reference specimen, and that the highest gain percentage is achieved by the ECC strengthening technique [11].

Experimental investigation of different strengthening schemes on R. C. slabs with openings reveals that using anchors to fix EB-CFRP sheets prevents de-bonding and restores slabs' flexural capacity. Preparing the substrate surface before casting the ECC overlay significantly impacts composite activity, resulting in better structural performance and complete bonding. The study found that the maximum flexural capacity was achieved when applying both NSM-steel bars and ECC overlay techniques together, exceeding the reference slab by 23 % [12].

H. K. Shehab et al. [13] examined opening size and locations, CFRP layer number, widths, and configurations in an experimental study comprising five R.C. slabs with cantilever. Openings were cut after the load reached 45 % of the reference slabs' ultimate load, and then loading was applied until failure. CFRP-strengthened slabs had 10.7 % and 9.7 % higher ultimate loads and 23 % and 17 % lower deflection than un-strengthened slabs with openings. Slabs reinforced with CFRP sheets along cutout edges outperformed those with 45° inclined sheets. Three layers of CFRP sheets reduced crack propagation; hence, 90° and 45° strengthening had the maximum load-bearing capability. Due to confinement stress from CFRP sheets, ultimate loads increased with strip number and width. Un-strengthened and reference slabs failed in a flexural mode, but CFRP sheet-rupture controlled failure in strengthened slabs.

CFRP sheets are used to enhance flat slab-to-column corner connections. The test series was further varied by adding apertures at slab-column junctions. Punching shear capacity was reduced by the opening. All reinforced slab systems had low CFRP stresses at ultimate load and little load enhancement, which shows that raising the amount of CFRP is not going to enhance the load or save money [14].

Although using FRP is common in most of the research as a non-traditional strengthening technique for R.C. members, its main disadvantages include highly skilled labor requirements, expensive materials, fire susceptibility, special surface preparation to prevent delamination from the substrate-reinforced concrete layer, and brittle failure. Also, C. S. Madan et al. [15] shows that GFRP-reinforced slabs have a higher ultimate load-carrying capacity and flexural strength, while steel-reinforced slabs have a higher average ductility.

X. Zheng et al. [16] suggest using a hybrid strengthening method that combines thin steel plates and carbon fiber laminates to make structures more flexible and long-lasting and to get around the problems that come with using each material separately. Steel plates' heavy weight, poor corrosion resistance, and the clear height of the floor limit their thickness for strengthening RC structures. The EB-FRP technique's limitations lie in its weak bond interface, which results in insufficient utilization of FRP's full strength in retrofitted or reinforced concrete components, leading to rapid debonding failure and ineffective use of FRP's strength. The proposed technique combines the two materials to enhance load-carrying capacity and addresses the disadvantages of using each material individually. Even though hybrid strengthening provides considerable advantages throughout the building and strengthening process, the over-cost of using both expensive materials and skilled labor as well as steel plate corrosion, which might compromise the strengthened buildings' durability, are potential issues.

N. I. Shbeeb et al. [17] examined the impact of various strengthening methods on R.C. slabs, testing them up to failure. Five techniques were applied, all enhancing ultimate and cracking strength. Although carbon fiber laminates and rods increased cracking strength, load capacities, and deflection responsiveness, they also caused punching shear failure.

Currently, ferrocement is widely recognized as a highly utilized technique. Nevertheless, there is a limited number of studies available regarding the structural performance of slabs comprising openings, whether they are strengthened with ferrocement or not. Further investigation into the matter is required. Ferrocement is a thin-walled reinforced concrete construction that uses small-diameter wire meshes uniformly throughout the cross-section. It is used in various construction sectors, including housing, marine, agricultural, rural energy, and anticorrosive membrane treatment. Ferrocement is known for its cost-effectiveness, strength, and versatility, making it suitable for structural strengthening and repair of damaged members. It can be applied around defective circular, square, or rectangular RC columns to enhance their strength, ductility, and energy absorption capacity. It can also be used to reinforce roof and floor slabs, especially in older buildings that have weakened over time, and to wrap existing beams, increasing their load-bearing capacity and resistance to structural failure. Ferrocement is also commonly used in bridge rehabilitation and strengthening, enhancing their strength and extending their service life. It is also a popular choice for seismic retrofitting in earthquake-prone areas, adding strength and flexibility to existing structures. Ferrocement is also used in the construction of water tanks and silos due to its high tensile strength and resistance to water and corrosion [18,19].

The studies' objectives were to investigate the different ways to strengthen structural elements, see how well ferrocement technology improves the behavior of reinforced concrete elements, compare and evaluate the use of ferrocement techniques with other techniques used in the strengthening process in terms of load-carrying capacity, crack propagation, and intensity, durability, and ductility, and do an analytical study to ensure the quality and consistency of the lab results.

Previous researchers have conducted numerous experimental tests to evaluate the effectiveness of ferrocement and concluded that using ferrocement in retrofitting and strengthening different R.C. elements helped to achieve greater load capacity, control crack propagation, and width, and improve failure patterns [20–36]. Some of the experimental tests conducted were shear strength investigations on rectangular ferrocement specimens [34], extensive laboratory investigations on the flexural and impact response of ferrocement panels formulated with varying amounts of steel fiber and expanded wire mesh layers [35], torsional behavior of reinforced concrete beams using U-shaped ferrocement [24], flexural behavior of ferrocement channel slabs [36], as well as the effect of confinement using ferrocement as wrapping material on the circular RC columns under concentric loading conditions [25,26]. All these tests provided valuable insights into the effectiveness of the ferrocement technique, assessing load-carrying capacity, shear strength, bending, and impact responses. There are also tests recommended to predict the structural properties of ferrocement, like the compressive strength of mortar and the tensile strength of mesh reinforcement [21].

The key findings structural performance of the RC slabs with ferrocement strengthening are that using ferrocement in retrofitting and strengthening different R.C. elements can improve their structural performance by increasing their flexural capacity and enhancing the first cracking load, improving ductility and crack resistance, controlling crack propagation and width, and improving failure patterns.

The specific findings regarding the structural performance of RC slabs with ferrocement strengthening contribute to the existing knowledge in the field of structural engineering and construction by expanding the understanding of the structural performance of RC slabs with ferrocement strengthening, contributing to the ongoing advancements in structural engineering practices, design methodologies, and construction techniques. The study enhances understanding of ferrocement's effectiveness as a strengthening material for RC slabs, aiding structural engineers in making informed decisions regarding suitable strengthening methods. Research findings enhance retrofitting strategies for RC slabs, focusing on flexural strengthening, resulting in more efficient and cost-effective methods for improving load-carrying capacity and performance of existing slabs, and encourage the coming research to extend and investigate advanced points like the durability of ferrocement-reinforced slabs, highlighting their resistance to corrosion and long-term performance, aiding engineers in assessing the sustainability and maintenance requirements of ferrocement-strengthened structures.

In real-world applications, reinforced concrete openings are frequently required in RC slabs for design changes or the installation of new facilities, reducing the load-carrying capacity of structural elements. Therefore, ferrocement is a cost-effective solution for strengthening RC slabs with openings, improving their structural performance and load-carrying capacity. It is simple and easy to install, making it a practical choice for retrofitting existing structures without complex construction techniques or specialized labor. Ferrocement-reinforced slabs are durable, low-maintenance, and resistant to corrosion, ensuring the longevity and sustainability of strengthened structures. This cost-effective solution offers a balance between performance and affordability. Previous research has investigated the environmental impact and sustainability aspects of using ferrocement for slab strengthening, demonstrating its positive effects on the environment. According to previous search results, ferrocement is considered a sustainable construction material with several environmental benefits. It uses less cement and steel compared to traditional reinforced concrete, resulting in lower carbon emissions and reduced energy consumption during manufacturing and transportation [37].

Furthermore, ferrocement is known for its potential to contribute to affordable and sustainable housing solutions, particularly for rural and poor urban populations. It offers advantages such as lower material usage, overall structural weight reduction, and cost-effectiveness. The flexibility of ferrocement allows for the elimination of formwork and ease of repairs in cases of local damage [38].

The application of ferrocement methodology for enhancing the structural integrity of concrete slabs under flexural loading is a highly effective strategy owing to its exceptional strength and streamlined installation procedure, which outperforms other available methods for reinforcement. Furthermore, the utilization of ferrocement reinforcement methods presents a cost-effective and proficient approach to structural design. Ferrocement demonstrates superior characteristics in terms of toughness, durability, strength, and resistance to cracking. Furthermore, the use of specialized craftsmanship is not required in the process of reinforcing structures with ferrocement laminates. Kaish et al. [39] demonstrated that RC columns' load-carrying capability and axial deflection are improved by ferrocement jacketing.

Badawy et al. [40] suggested that ferrocement can be a cost-effective and effective external strengthening material, showing that ferrocement laminates could significantly improve the flexural behavior of reinforced concrete slabs with openings and concluding that employing nuts, steel washers, and anchors as a fastening technique enhanced strain energy and ultimate strength. While adding more layers of wire mesh did raise the ultimate load, it had no discernible effect on overall deflection. Strengthening with Ls = ts and Ls = 2ts decreased the ultimate load by 25 % and 24 %, respectively, compared to strengthening the whole slab, where "Ls" and "ts" refer to the length of the strengthening layer surrounding the aperture of the slab and the thickness of the slab, respectively.

M. Elsayed [41] numerically investigated the structural performance of R.C. slabs with openings strengthened by ferrocement layers. Results show that ferrocement laminates increase ultimate carrying capacity by up to two times compared to un-strengthened specimens. The ultimate capacity and stiffness were both enhanced by raising the mortar matrix's compressive strength and the ferrocement layer's thickness. Additionally, raising the volume fraction for strengthened groups increases ultimate capacity by 8 %. Y. B. I. Shaheen and A. M. Mahmoud [42] examines the performance of different types of reinforcement in ferrocement-reinforced RC channel slabs. It found that welded steel mesh is the most effective, providing higher load capacities and strength compared to expanded and fiber glass meshes. Adding additional steel mesh layers improves performance in terms of load capacities and energy absorption but reduces ductility. Overall, ferrocement specimens outperform conventionally reinforced concrete in terms of load capacities and energy absorption. Chkheiwer et al. [43] investigate the use of wire mesh strengthening and steel fiber to recover flexural strength in slabs with different opening shapes. The slabs were divided into two groups: those with square openings and those with rectangular openings. Slabs with square and rectangular holes have 28.9 % and 39.7 % less carrying capacity than solid slab. Two techniques, wire mesh strips and steel fibers, were utilized to enhance the load-carrying capacities of slabs with openings and could restore much of the slabs' load capability, with wire mesh being more effective than steel fibers dispersed throughout the slab body. The wire mesh also reduced cracks at the inside faces of openings and prevented them at the inside corners. The behavior of double-layered 5 cm-wide wire mesh slabs and single-layered 10 cm-wide wire mesh slabs was found to be similar.

P. Sivanantham et al. [44,45] revealed that concrete reinforced with 1.5 % steel fiber has superior compressive and split tensile strength compared to regular concrete. The fibers improve bonding and ductility, leading to a 1.5 times higher split tensile strength. The modulus of elasticity is 1.14 times better than conventional concrete, and flexural strength is 1.39 times improved. Steel fiber reinforcement is more economical and less expensive.

The enhancement of RC slabs with apertures through the application of ferrocement laminates is an aspect that necessitates further investigation since a few numbers of studies have addressed this issue. This study aims to enhance understanding of the failure mechanism, current design techniques, and effective methods for enhancing the structural performance of R.C. slabs with openings using ferrocement.

The experimental program aimed to investigate the impact of an unstrengthened or strengthened central opening on the structural performance of slabs in order to assess the strengthening process using

**Table 1**
Specimens details.

| Slab Number | Slab Code | Opening Dimension (cm) | Strengthening Layers | | |
|---|---|---|---|---|---|
| | | | Number | Type | Extension length |
| S1 | C 0 | — | — | | |
| S2 | C 15 | 15 × 15 | — | | |
| S3 | C 25 | 25 × 25 | — | | |
| S4 | C 35 | 35 × 35 | — | | |
| S5 | W2/15 | 15 × 15 | 2 | welded | L1 |
| S6 | W2/25 | 25 × 25 | 2 | welded | L1 |
| S7 | W2/35 | 35 × 35 | 2 | welded | L1 |
| S8 | E2/25 | 25 × 25 | 2 | Expanded | L1 |
| S9 | W1/25 | 25 × 25 | 1 | welded | L1 |
| S10 | W4/25 | 25 × 25 | 4 | welded | L1 |
| S11 | E2/25/EXT. | 25 × 25 | 2 | Expanded | L2 |
| S12 | W2/25/EXT. | 25 × 25 | 2 | welded | L2 |

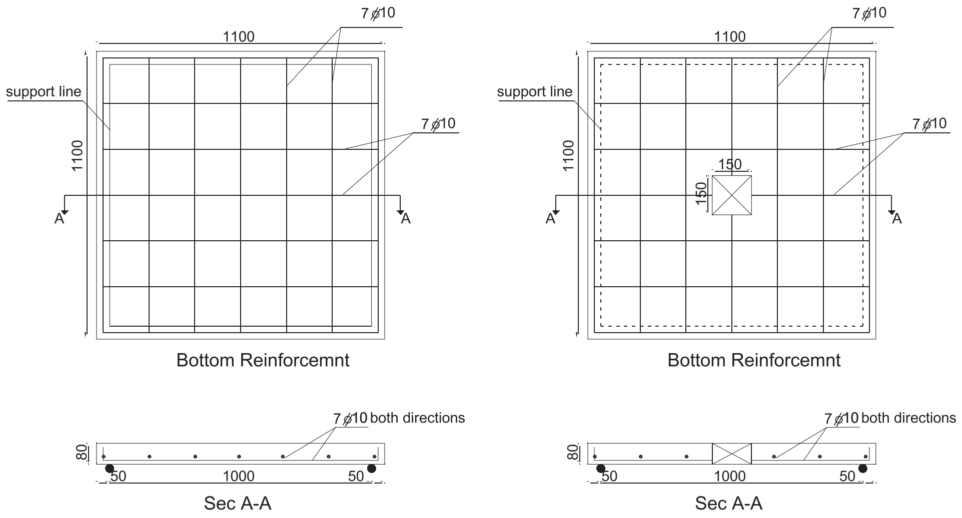
L1, L2: Extension lengths of steel mesh layers outside the slab opening from each side, where L1 equals the half-length of the opening and L2 equals the total length of the opening.

ferrocement layers. The impact of the subsequent factors was investigated: (i) the opening sizes (15, 25, and 35 cm); (ii) the employed steel mesh type (welded or expanded); (iii) the number of welded steel mesh layers utilized (one, two, and four); and (iv) the extension length of ferrocement layers outside the opening sides (half or equal to the opening length). Additionally, software (ABAQUS) [46] was utilized to validate the behavior of tested specimens through the implementation of nonlinear finite element models.

## 2. Experimental study

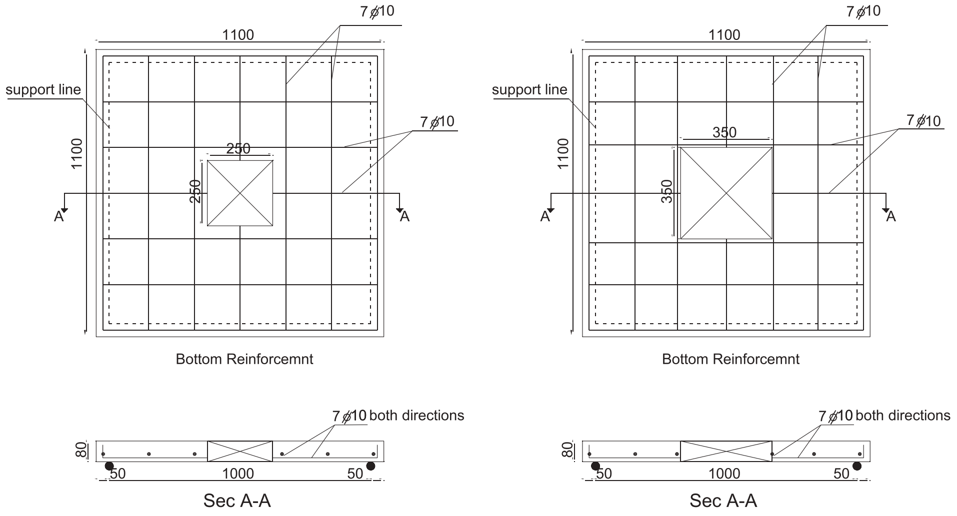
### 2.1. Slabs details and Test scheme

In the experimental program, twelve two-way RC slabs were prepared and tested under four concentrated point loadings. The slabs were 1100 × 1100 mm and 80 mm thick, supported along their four boundaries with 1000 mm clear spans in both directions, with a bottom mesh of 7Ø10 high-tensile steel bars for reinforcement and a concrete cover of 15 mm. Four slabs were used as control samples that weren't strengthened. One was solid, and the other three had openings of different sizes. The other eight slabs were strengthened using ferrocement layers with different schemes that differ with respect to the amount of mesh layers,



a) Slab without opening

b) slab with opening 150*150 mm



c) slab with opening 250*250 mm

d) slab with opening 350*350 mm

**Fig. 1.** Details and dimensions of tested specimens (all dimensions in mm).

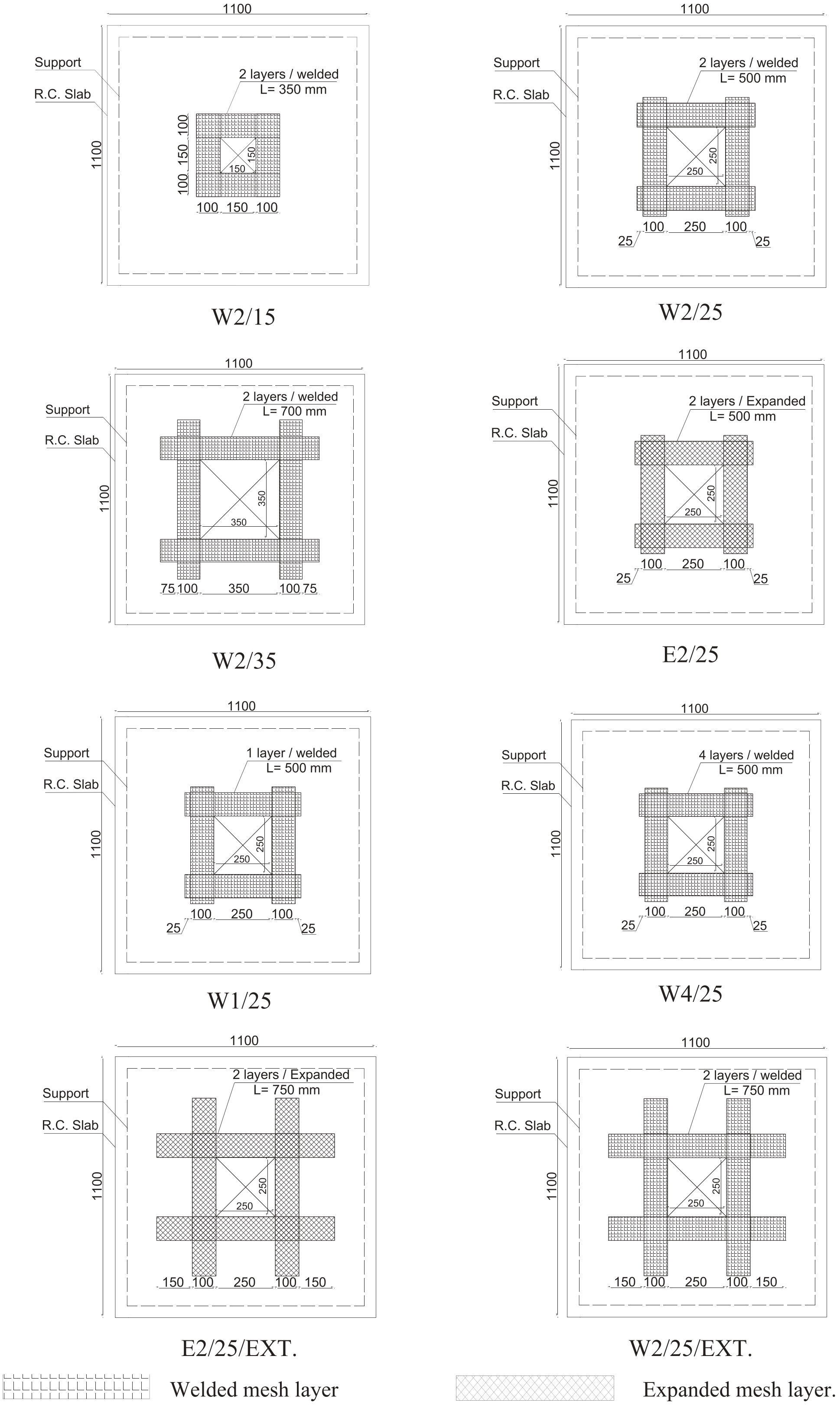


**Fig. 2.** Different meshing patterns for strengthened specimens. (measurements in mm).

the type of mesh, and the extended length of the strengthening layers outside the opening side. Table 1 and Fig. 1 display the specimen's details. Also, Fig. 2 shows the different meshing patterns for strengthened specimens employed in this study.

### 2.2. *Materials used*

#### 2.2.1. *Concrete*

Using ordinary Portland cement (42.5 N), natural local siliceous sand (2.67 specific gravity), and crushed dolomite aggregates (maximum size

**Table 2**
Steel mesh's physical, geometric, and mechanical properties.

| Mesh type | Mesh opening (mm) | | Diameter or Thickness | Weight (kg/m2) | Proof Strength (MPa) |
|---|---|---|---|---|---|
| | Long way | short way | (mm) | | |
| WWM | 12.5 | 12.5 | 0.60 | 0.430 | 400-600 ult |
| EMM | 31 | 16 | 1.25 | 0.730 | 199-320 ult |

**Table 3**
Ferrocement mortar mix proportions by weight.

| Material | Cement | Sand | Silica fume | water |
|---|---|---|---|---|
| Weight (kg/m3) | 700 | 1040 | 70 | 347 |

19 mm), the compressive strength of concrete was evaluated at 28 days using 150×150×150 mm cubes with an average of 25 MPa.

#### *2.2.2. Reinforcement steel*

The steel bars used as internal longitudinal reinforcement in both directions for the tested slabs were high-tensile deformed bars having a modulus of elasticity (E) of 210 GPa and a nominal yield stress of 400 MPa.

#### *2.2.3. Welded and Expanded steel mesh*

Locally available expanded metal mesh (EMM) and welded wire mesh (WWM) are used to reinforce the ferrocement strengthening layers. The meshes' properties are detailed in Table 2.

#### *2.2.4. Ferrocement mortar*

Table 3 displays the ferrocement mortar mix proportions by weight per cubic meter. Based on cubes (70.7 mm), the average compressive strength of the mortar mix at 28 days was 51.3 MPa.

### *2.3. Specimens preparation and strengthening schemes installation*

After the wooden formworks were assembled according to the specifications of the specimens and apertures, the steel reinforcement was installed, and the concrete was placed and surface-finished. After curing for one week, the specimens were kept in the lab environment for fifty days until the strengthening day.

Eight specimens were turned over to conduct the strengthening process. Strengthened areas that were located on the bottom faces of slabs around the slabs' openings with 100 mm width and variable lengths depending on the opening dimensions were roughened using an angle grinder. The welded and expanded steel mesh layers were cut according to the lengths, widths, and numbers that were previously determined in the experimental program, then fixed in their positions using anchors of 5 mm diameter and washers. These anchors were fixed in the concrete layer after drilling 6 mm-diameter holes, using plastic plugs to prevent separation from the concrete. Before applying a 20-mm-thick coating of ferrocement mortar, the specimens were air-blown to remove dust and debris, and a chemical compound called addibond-65 was sprinkled to enhance the bond between the original specimen and the strengthening layer. Fig. 3 shows the strengthening procedures.

### *2.4. Test setup*

A rigid reaction frame supporting a 1000 kN hydraulic jack that is powered by an electric pump with the same maximum load capacity made up the loading system, with a load cell positioned under the hydraulic jack to record the force applied. All of the test findings were collected and stored on a computer using a data collection system. The tested specimens were simply supported on all four sides over a 1000-mm clear span and subjected to four-point loadings. The loading schemes for the various tested slabs, with and without apertures, are depicted in Figs. (4-a to 4-d), where the loading areas were strategically positioned in the quarter spans along both sides of the tested slabs. A main rigid steel I-beam transferred the vertical load to two parallel steel I-beams and then through four 15-cm-side concrete cubes to the loaded areas of the tested slabs. This system was used to transfer a central vertical load to four concentrated loading points on the top of the tested slabs, as illustrated in Fig. (5-a). A load cell with a maximum capacity of 1000 kN was positioned under the hydraulic jack to measure and record the force applied. In order to measure the vertical deflection, four LVDTs were placed on the bottom face of the tested specimens, right below the center of the spots where the concentrated four-point loads were applied, as illustrated in Fig. (5-b). After every increase in load, the progression of cracks was monitored until failure occurred.

## 3. Experimental results and discussion

The structural properties that were examined encompassed the first cracking and ultimate loads, deflection at the first and ultimate loads, ductility, cracking behavior, and failure mechanism. Furthermore, the investigated specimens' load-deflection curves were plotted. The values mentioned above are recorded in Table 4.

### *3.1. Load-deflection relationships*

As the size of the slab opening increases, the load-deflection curves demonstrate a reduction in the maximum load and an increase in the deflection at that load in comparison to the reference specimen that does not have an opening. The utilization of diverse techniques to strengthen slabs with different opening sizes resulted in a substantial enhancement in both strength and stiffness. All strengthened specimens show an improvement in ultimate load and lower deflection at the same load in comparison to the corresponding control specimens with openings. The tested slabs' load-deflection relationships are displayed in Fig. 6(a–f).

#### *3.1.1. Impact of opening size*

This parameter examined the impact of three different opening sizes on the ultimate load of specimens. The results showed that specimens with opening sizes of 15, 25, and 35 cm had a decrease in the ultimate load by 21.5 %, 31.9 %, and 40.7 % compared to the reference specimen without an opening, as illustrated in Fig. (6-a). Openings in slabs decrease their stiffness as they reduce their resistance to deformation under loads. Larger opening sizes result in higher deflections at any load compared to reference specimens without openings, indicating that the size of openings directly impacts the specimen's strength and stiffness.

#### *3.1.2. Effect of strengthening on different opening sizes*

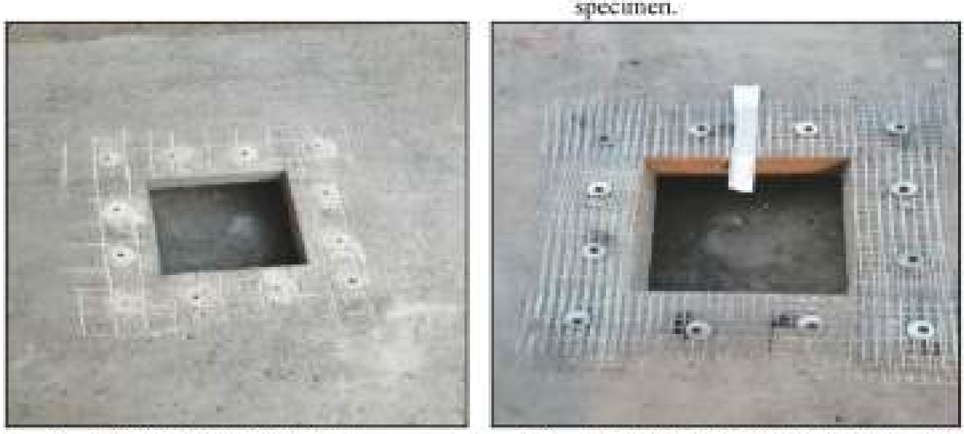
This parameter investigates the influence of strengthening slabs of different opening sizes using two layers of welded steel mesh. The results show that the maximum load increased by 26 %, 33 %, and 34 % for strengthened specimens with opening sizes of 15, 25, and 35 cm, respectively, compared to the un-strengthened control specimens with the same openings, due to providing additional reinforcement, which acts as a secondary reinforcement system. Additionally, the addition of two layers of welded steel mesh increases the flexural rigidity of the slabs with openings, making them stiffer and more resistant to deflection under applied loads, as the ultimate deflection increased by 22.3 %, 12.4 %, and 12 % for opening sizes of 15, 25, and 35 cm, respectively, as illustrated in Fig. (6-b, c, d).

#### *3.1.3. Impact of strengthening layer number*

To assess the effect of strengthening mesh layer number, a slab with an opening size of 25×25cm was chosen. The results showed that increasing layer numbers led to greater load-carrying capacities and ultimate deflection. When comparing the results of specimens

a) Concrete placing.

b) Notching the lower surface of the specimen.



c) Drilling holes for anchors.

d) Installation of steel mesh layers and anchors.

e) Sprinkling of Addibond-65 to the surface of the specimen.

f) Placing mortar and finishing the surface.

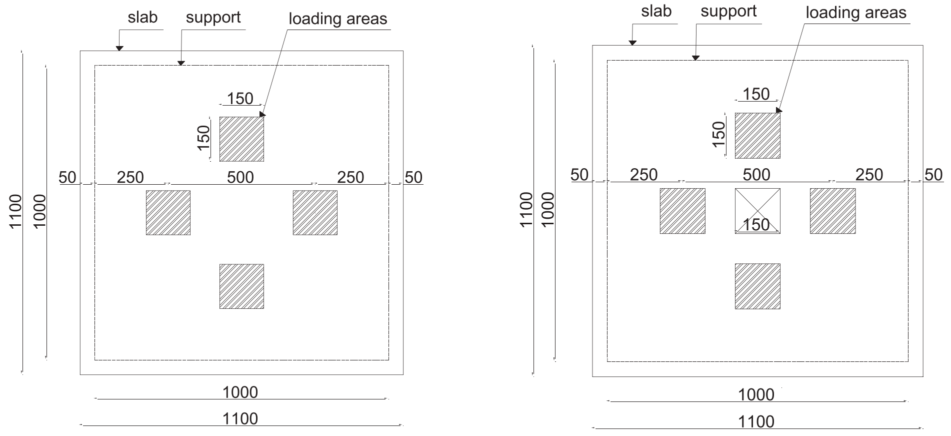
**Fig. 3.** Strengthening Procedures.

strengthened with 1, 2, and 4 layers of welded steel mesh with the control un-strengthened specimen, it was found that the maximum load was 25 %, 33 %, and 40 % higher than the control un-strengthened specimen. Additionally, the ultimate deflection increased by 12 %, 12.4 %, and 13.2 %, as indicated in Fig. (6-e). As the number of layers increases, more reinforcement is provided to resist loads, resulting in a higher load-carrying capacity. Strengthening layers also help redistributing stresses, mitigating stress concentrations around opening edges, and improving overall slab structural performance.

#### *3.1.4. Effect of strengthening mesh layer type and extension length outside the opening*

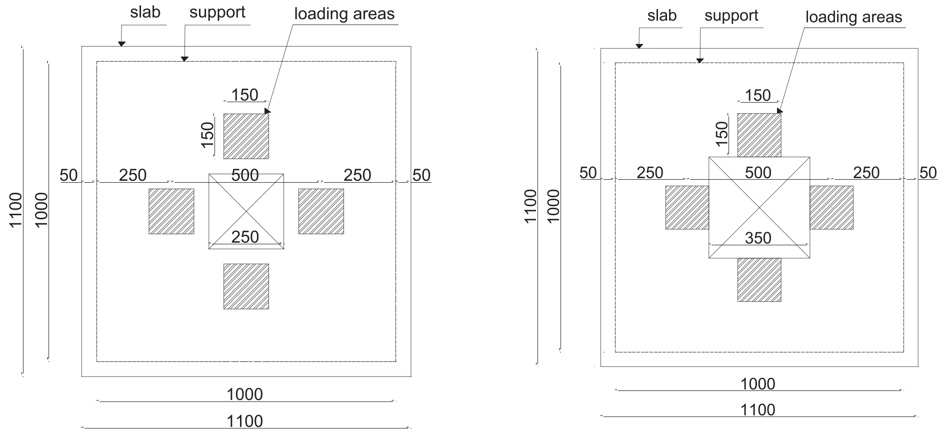
The behavior of specimens W2/25 and E2/25, as well as specimens W2/25/EXT and E2/25/EXT, which stand for welded and expanded metal mesh reinforcing layers, respectively, as indicated in Fig. (6-f), demonstrates the impact of these parameters. By raising the ultimate load, both mesh types used in the strengthening process improved flexural performance.

The expanded and welded steel mesh strengthening layers increased the ultimate load by 41 % and 33 % for specimens with opening 25 cm strengthened with extension equals to half the opening size, and enhanced the ultimate load by 50 % and 41 %, respectively, for



**a)** Loading scheme for slab without openings.

**b)** Loading scheme for slabs with an opening 150*150 mm.



**c)** Loading scheme for slabs with an opening 250*250 mm.

**d)** Loading scheme for slabs with an opening 350*350 mm.

**Fig. 4.** Loading schemes for the various tested slabs (measurements in mm).

specimens with opining 25 cm strengthened with extension equals to the opening size, when compared to the un-strengthened control specimen (C25). Increasing the extension length of strengthening layers for specimens E2/25/EXT. and W2/25/EXT. resulted in a higher ultimate load by 6–7 % compared to specimens E2/25 and W2/25. Also, using the expanded steel mesh type in specimens E2/25/EXT. and E2/25 resulted in a higher ultimate load by 6–7 % compared to specimens of welded steel mesh W2/25/EXT. and W2/25.

### *3.2. Cracking and ultimate loads*

The first crack and ultimate loads and deflections, ductility, and ratio between the ultimate load of each specimen compared to both the reference specimen without opening and the corresponding control un-strengthened specimens with openings are displayed in Table 4.

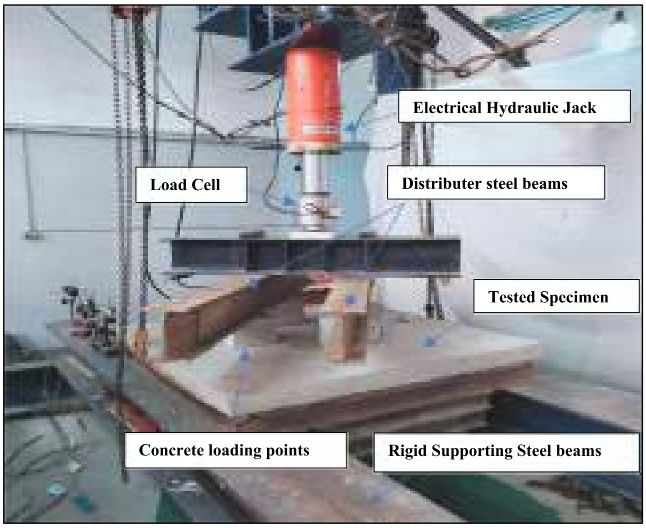
The specimen labeled as C35 exhibited the lowest ultimate load, which was 40.7 % lower than that of the reference specimen. Such a result was predictable as the former specimen had the biggest opening size among all tested specimens, which led to a major lack of the slab's capacity to resist flexural loads. The ultimate load value was highest for specimen (E2/25/EXT). In comparison to all other specimens, the specified specimen had a 2.2 % higher ultimate load than the reference specimen without an opening, which means that the effect of the opening had been demolished. The higher weight per unit area for the expanded steel mesh type, which leads to a higher reinforcement ratio, and the more extended length of the strengthening layers outside the opening provide an explanation for the specimen's (E2/25/EXT) effective strengthening system.

### *3.3. Ductility*

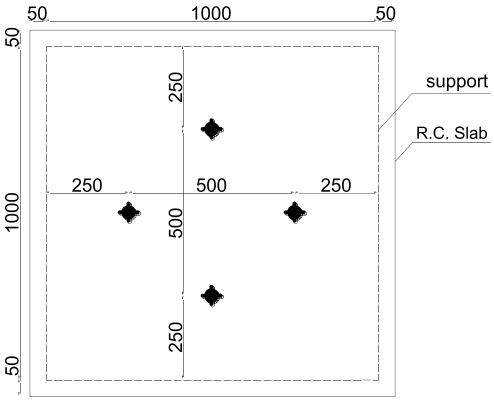
According to the definition, ductility is a structural element's ability to bend or stretch beyond its yield point without losing a lot of its strength. In order to determine the ductility index, the deflection at ultimate stresses is divided by the deflection at the initial cracking. A slab's ability to provide advance indications before experiencing complete failure is directly proportional to its ductility index value. In general, enlarging the aperture size led to a greater ductility index in comparison to the control slab. However, strengthening slabs with different openings using two welded steel mesh layers had a lower ductility index, and this is attributed to a higher first cracking deflection for strengthened specimens compared with the corresponding un-strengthened specimens. The ductility index dropped from 8.12 to 6.01 as the number of layers increased from 1 to 4. This can be attributed to the larger first cracking deflection observed with a higher number of strengthening mesh layers.

### *3.4. Cracking behavior and mode of failure*

Generally, flexural failure was the failure mode of all slabs. All



**a** Test Set-up.



**b** LVDT locations (bottom side), (measurements in mm).

**Fig. 5. a** Test Set-up.**b** LVDT locations (bottom side), (measurements in mm).

specimens' initial cracking and ultimate load values are provided in Fig. 7. The twelve tested specimens' fracture patterns are depicted in Fig. 8. The reference specimen (C0), cast without openings, showed bottom tension surface cracks. The main cracks ran along the slab's diagonals, while smaller cracks were uniformly dispersed around the slab. For the tested control slabs with openings (C15, C25, and C35), cracks began at the opening corner and extended towards the slab's edges, spreading widely and accompanied by minor, narrow, short cracks. They continued to develop until the slab's failure. Crack patterns for preceding control slabs "with and without openings" show that cracking was far more prevalent when openings were present.

As for strengthened specimens, cracks first appeared on their tension side, mostly under the four-point loads. With the rise in the applied load, there was a corresponding increase in both the quantity and breadth of the cracks. Additionally, new cracks emerged and proceeded to spread diagonally towards the borders of the slab. The results clearly demonstrate that the application of ferrocement strengthening techniques successfully restricts and minimizes the initial formation of cracks on the openings' sides of the specimens by effectively surrounding these openings with strengthening layers. Also, fewer cracks appeared at the corners of the openings, which is a result of the additional strength for the opening corners provided by the overlapping between wire mesh layers.

## 4. Finite elements analysis (FEA)

In this part, the ABAQUS/CAE 2017 non-linear finite element software is used to check and validate the experimental results for the specimens being studied in this study. The experimental and theoretical results of the simulated RC slabs were compared. The following section describes in detail the FEM approaches.

### 4.1. *Classification of elements and modeling of materials*

Using ABAQUS, the specimens were modeled as three-dimensional structures. C3D8R was used for simulating the concrete and ferrocement parts. Steel bars, welded steel mesh, and expanded steel mesh were modeled using T3D2 elements. Fig. 9 shows the modeling of all parts in ABAQUS/CAE. Metal meshes and steel bars are embedded in ferrocement layers and concrete slabs, respectively. To ensure accurate modeling, the ABAQUS software was given the experimental program's material characteristics for concrete, ferrocement, steel bars, welded steel mesh, and expanded steel mesh.

Both concrete and ferrocement materials were modeled using the damaged plasticity model. The ABAQUS concrete damage plasticity model simulates the material's inelastic behavior by combining isotropic damage elasticity, isotropic compression, and tensile plasticity concepts. Steel reinforcement behaves linearly elastically at low strain values until it reaches the yield point, at which point its behavior changes from elastic to plastic. Steel's plastic attitude is identified by its yield point and post-yield hardening. [47], [48].

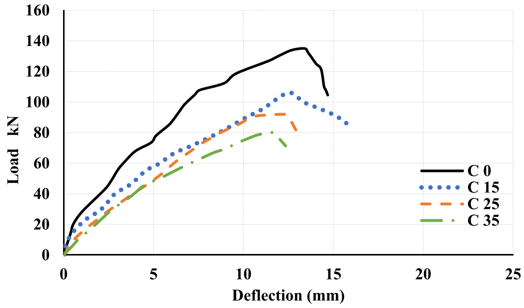
### 4.2. *Boundary conditions and load application*

The relationship between the concrete and ferrocement layers was

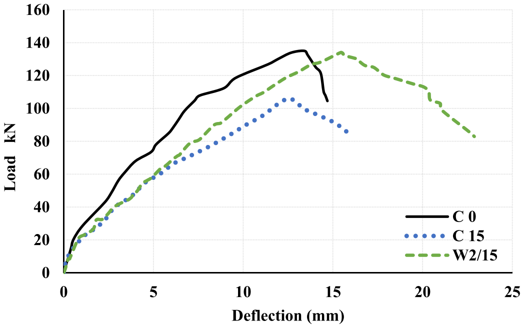
**Table 4**
Summaries of the specimens' test findings.

| Specimen ID | 1st cracking | | Ultimate | | Ductility | Pu (specimen) /Pu (control without opening) | Pu (specimen) /Pu (control with opening) |
|---|---|---|---|---|---|---|---|
| | Pcr (KN) | Δcr (mm) | Pu (KN) | Δul (mm) | Δul / Δcr | | |
| C 0 | 40 | 2.01 | 135 | 13.41 | 6.67 | 1 | – |
| C 15 | 25 | 1.60 | 106 | 12.62 | 7.89 | 0.79 | – |
| C 25 | 22 | 1.58 | 92 | 12.32 | 7.80 | 0.68 | – |
| C 35 | 15 | 1.30 | 80 | 11.48 | 8.83 | 0.59 | – |
| W2/15 | 35 | 2.36 | 134 | 15.44 | 6.54 | 0.99 | 1.26 |
| W2/25 | 31 | 2.00 | 122 | 13.85 | 6.93 | 0.90 | 1.33 |
| W2/35 | 27 | 1.88 | 107 | 12.86 | 6.84 | 0.79 | 1.34 |
| E2/25 | 36 | 2.10 | 130 | 14.72 | 7.01 | 0.96 | 1.41 |
| W1/25 | 28 | 1.70 | 115 | 13.80 | 8.12 | 0.85 | 1.25 |
| W4/25 | 34 | 2.32 | 129 | 13.94 | 6.01 | 0.96 | 1.40 |
| E2/25/EXT. | 38 | 2.58 | 138 | 16.80 | 6.51 | 1.02 | 1.50 |
| W2/25/EXT. | 35 | 2.02 | 130 | 15.05 | 7.45 | 0.96 | 1.41 |

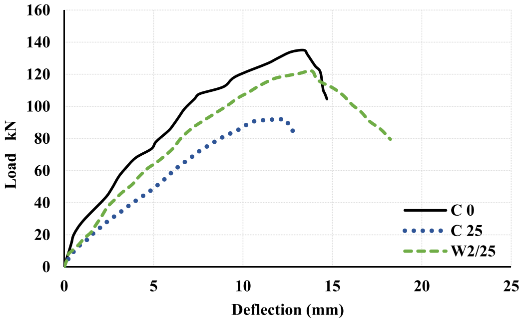
Note: Pcr: Cracking load; Δcr: Deflection corresponds to Pcr:
Pu: Ultimate load; Δul: Deflection corresponds to Pu.



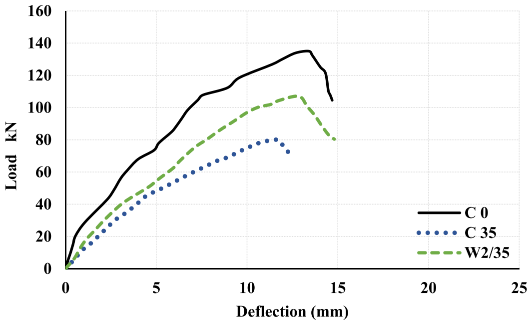
(a) Effect of opening size.



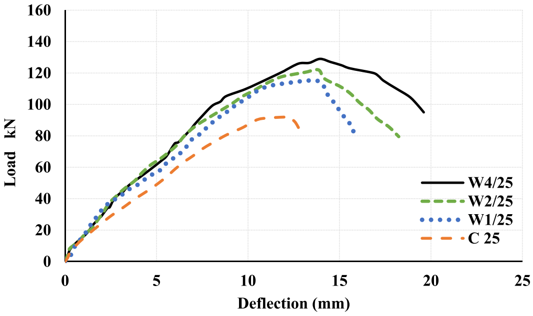
(b) Effect of using two welded steel mesh layers on strengthening the opening size of 15 cm.



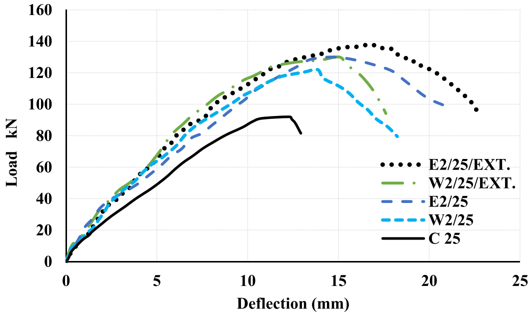
(c) Effect of using two welded steel mesh layers on strengthening the opening size of 25 cm.



(d) Effect of using two welded steel mesh layers on strengthening the opening size of 35 cm.



(e) Effect of strengthening layer numbers.



(f) Effect of strengthening mesh layer types and extension lengths.

**Fig. 6.** Load-deflection relationships for tested slabs under different study parameters.

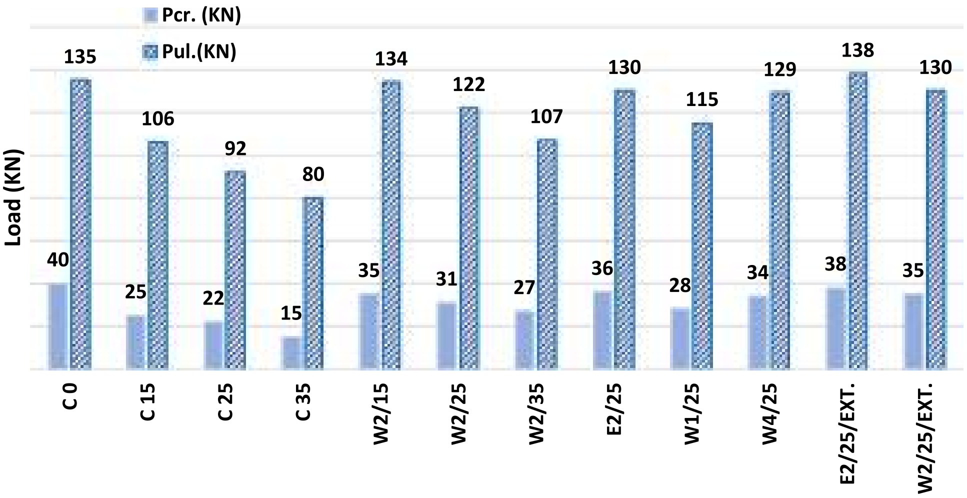
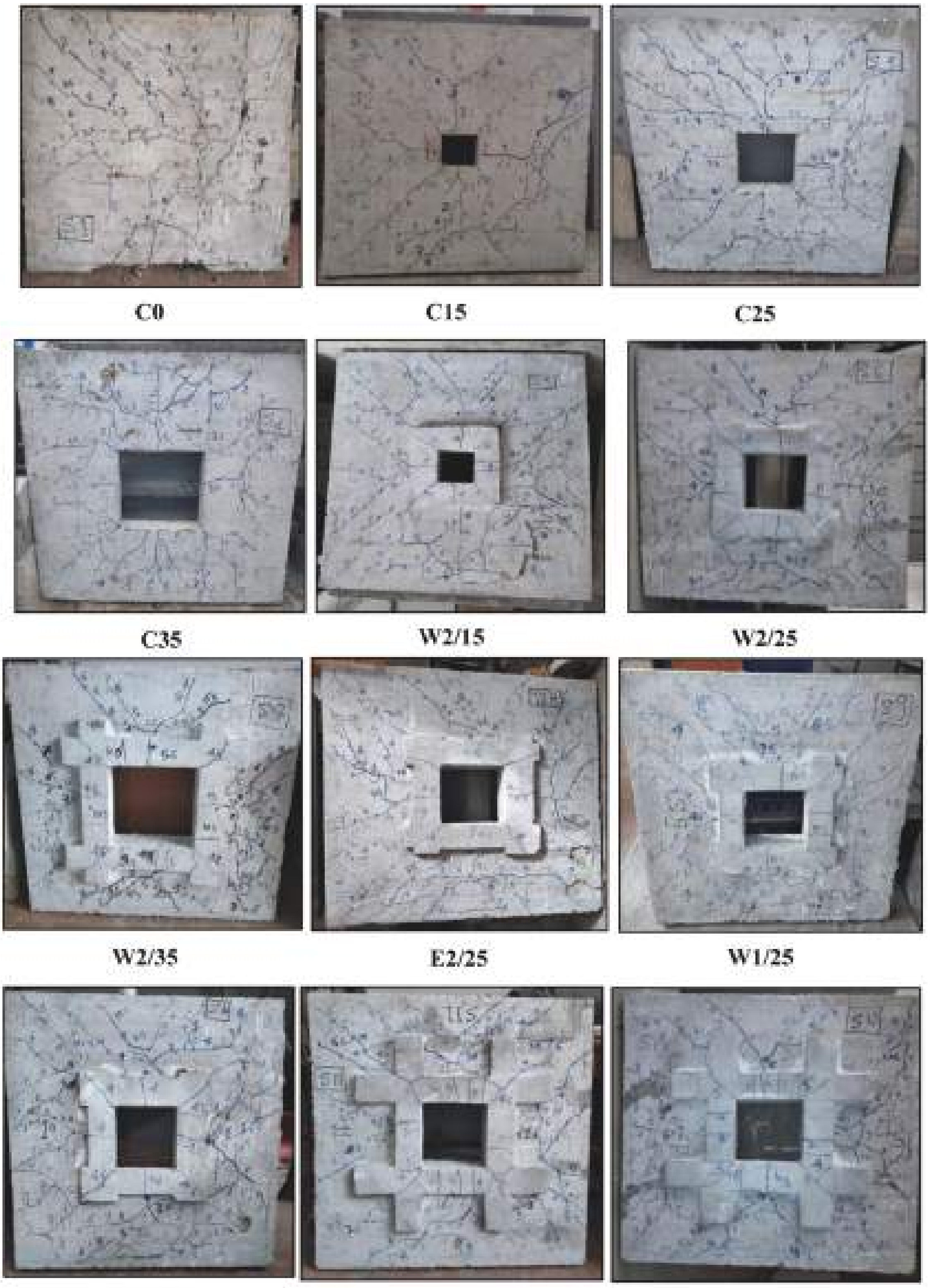


**Fig. 7.** Cracking and ultimate load for all specimens.

defined using tie constraints, with the master surface representing the bottom of the concrete slab and the slave surface representing the top of the ferrocement layer. The translational movement in the z-direction of the four edges of all modeled slabs was restricted. To simulate the experimental testing, the load acted as pressure on the upper surface of the studied specimens, impacting a specific region of 150 × 150 mm, as illustrated in Figs. 10 & 11.



C0
C15
C25
C35
W2/15
W2/25
W2/35
E2/25
W1/25
W4/25
E2/25/Ext
W2/25/Ext

**Fig.8.** Crack pattern for the tested slabs (bottom faces).

### 4.3. *Meshing of models*

A mesh sensitivity analysis is a process in ABAQUS that evaluates the impact of mesh sizes or element types on simulation results. It helps determine the appropriate level of refinement for reliable results, balancing accuracy and efficiency while minimizing computational costs. W. Mansour [49] utilized different mesh sizes in FE simulation to achieve convergence and numerical outcomes. A moderately fine mesh with 30 mm element size was chosen due to its good accuracy and less computing power. In this study and to obtain more precise results in balance with the time consumed in the analysis, a moderately finer mesh was applied for concrete and ferrocement modelling with maximum

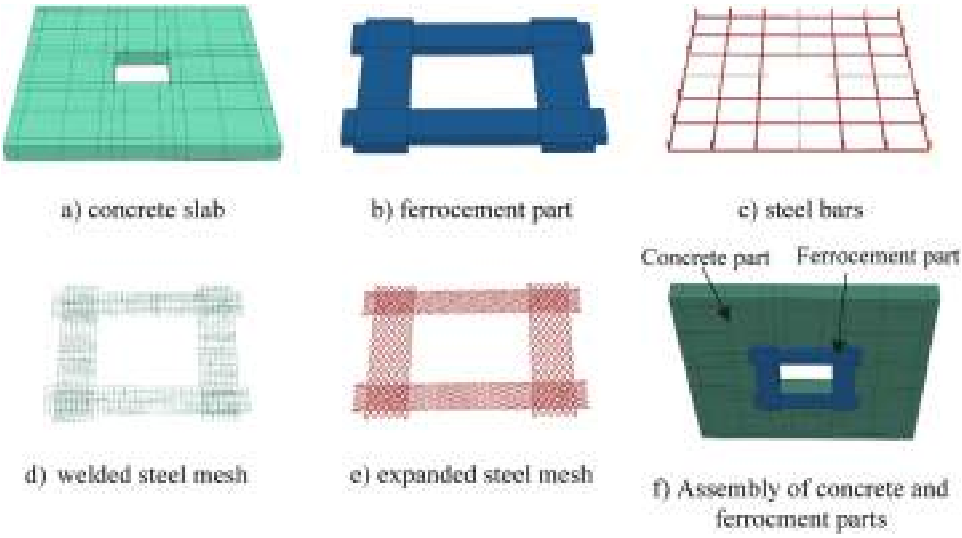


**Fig. 9.** . Modeling of all parts in ABAQUS/CAE.

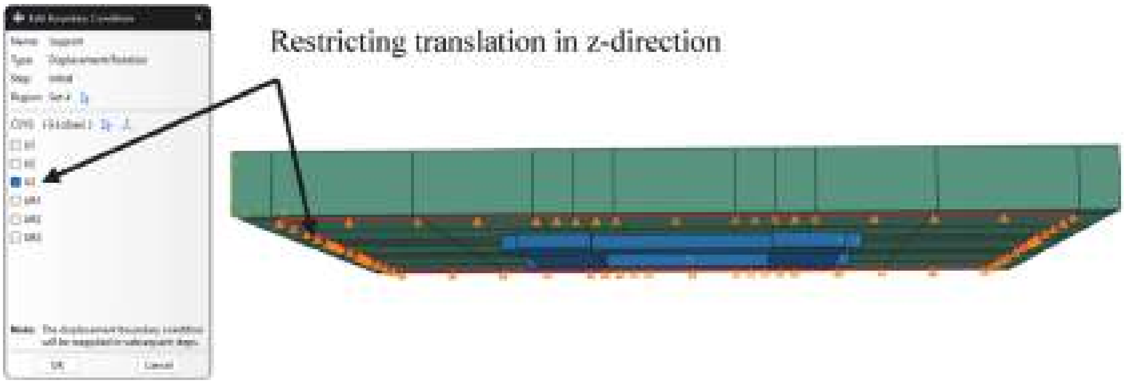


**Fig. 10.** Boundary condition for supports.

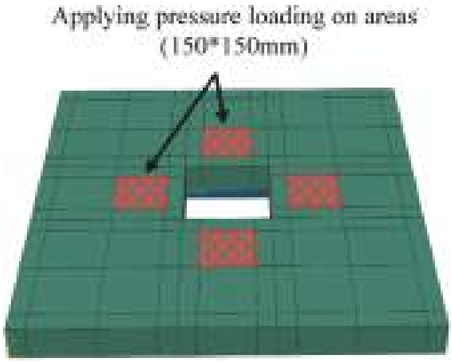


**Fig. 11.** Load condition.

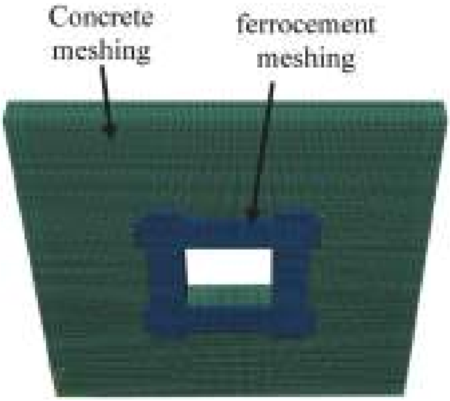


**Fig. 12.** Mesh configuration.

mesh sizes of 20 and 10 mm, respectively, as shown in Fig. 12. Also, the maximum mesh sizes for steel bars, welded steel mesh, and expanded steel mesh were 20, 12.5, and 16 mm, respectively.

## 4.4. *Comparison of experimental and numerical findings*

The load-displacement curves for all tested specimens showed excellent agreement between theoretical and experimental results, as shown in Fig. 13 and Table 5. The finite element model accurately described the load-deflection relationship of the experimental results. The experimental and FEM results for the first cracking and ultimate loads showed great agreement, with a ratio of 0.74 to 1.18 for the first cracking load and 0.95 to 1.04 for the ultimate load. The comparison of each slab's load versus average deflection in experimental and FEM data is shown in Fig. 13. Also, all slabs' failure patterns are illustrated in Fig. 14, which shows a similar pattern for the same slabs assessed experimentally.

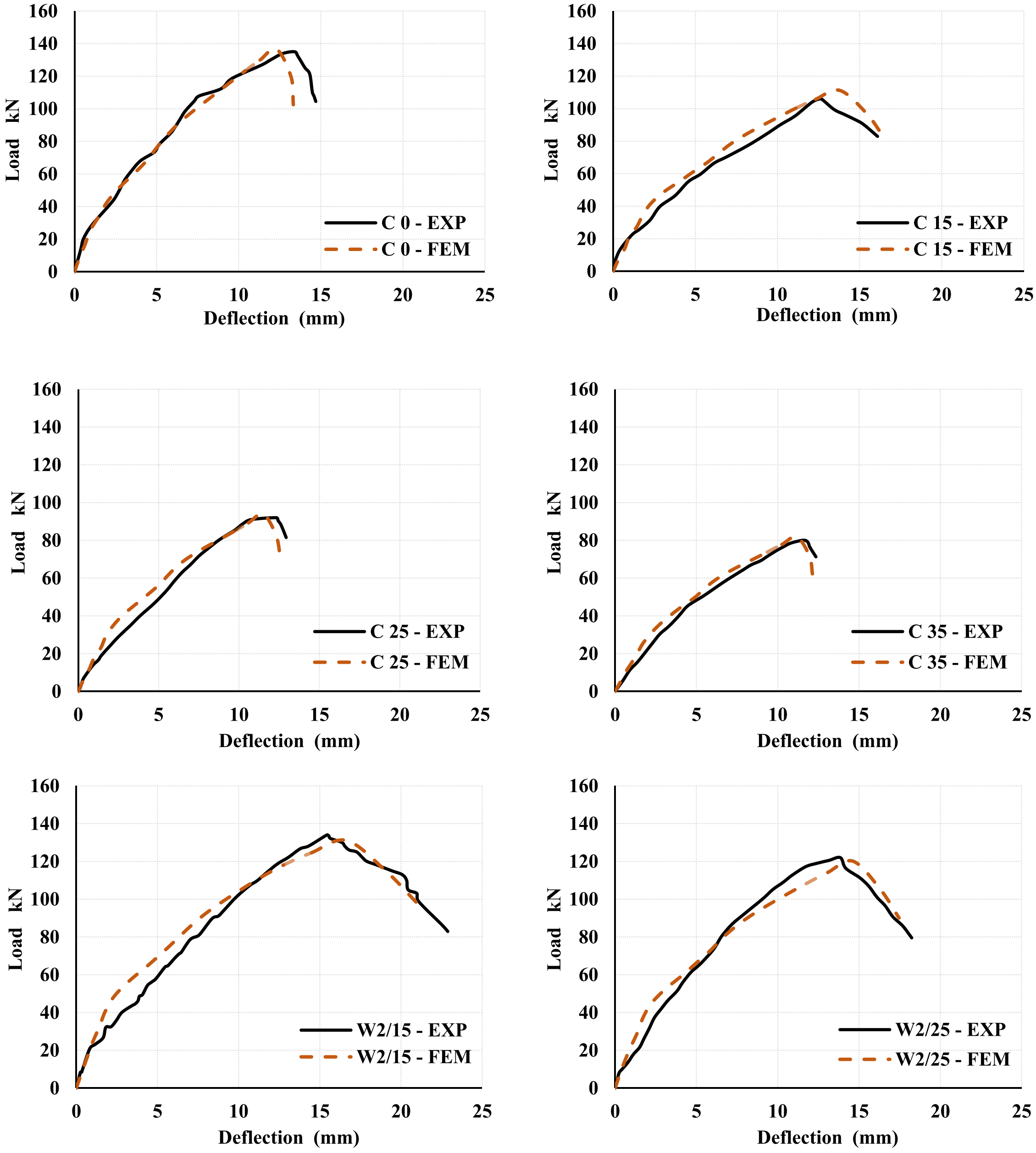


**Fig.13.** Comparison between experimental and FEM curves (load versus deflection).

## 5. Summary and conclusions

Throughout this research, ferrocement technology was utilized to strengthen R.C. slabs with various opening sizes. Ferrocement layers were constructed around the opening on the slab's underside. A total of twelve square slabs were prepared and tested up to failure: one reference specimen without an opening, three control specimens with different opening sizes, and eight specimens with openings strengthened using different ferrocement schemes. The test variables pertaining to the strengthening techniques under consideration were the number, type, and extension length outside the opening of steel mesh layers. The following inferences could be deduced from the investigating findings:

1. Creating openings in existing R.C. slabs decreased load-carrying ability by a range of 21.5 % to 40.7 % compared with the reference specimen without an opening, according to the opening sizes (15, 25, and 35 cm).
2. When steel mesh layers are increased from 1 to 4, the ultimate load rises by 25 % to 40 % compared to the un-strengthened control specimen of the same opening size (C25), and as a result of increasing slabs' capacity, the ultimate deflection increases by a range between 12 % and 13 %.
3. The study used welded and expanded steel mesh layers for strengthening slabs. Both types improved flexural behavior, increasing ultimate load by 41 % to 50 % for expanded type and 33 % to 41 % for welded type. Expanded steel mesh type resulted in a higher ultimate load of 6–7 % compared to welded steel mesh layers for slabs with openings.
4. Increasing the extension length of ferrocement strengthening layers for specimens E2/25/EXT. and W2/25/EXT to be twice the extension length for specimens E2/25 and W2/25 resulted in a higher ultimate load of 6–7 %, which showed a slight effect of increasing the extension length outside the opening edge.

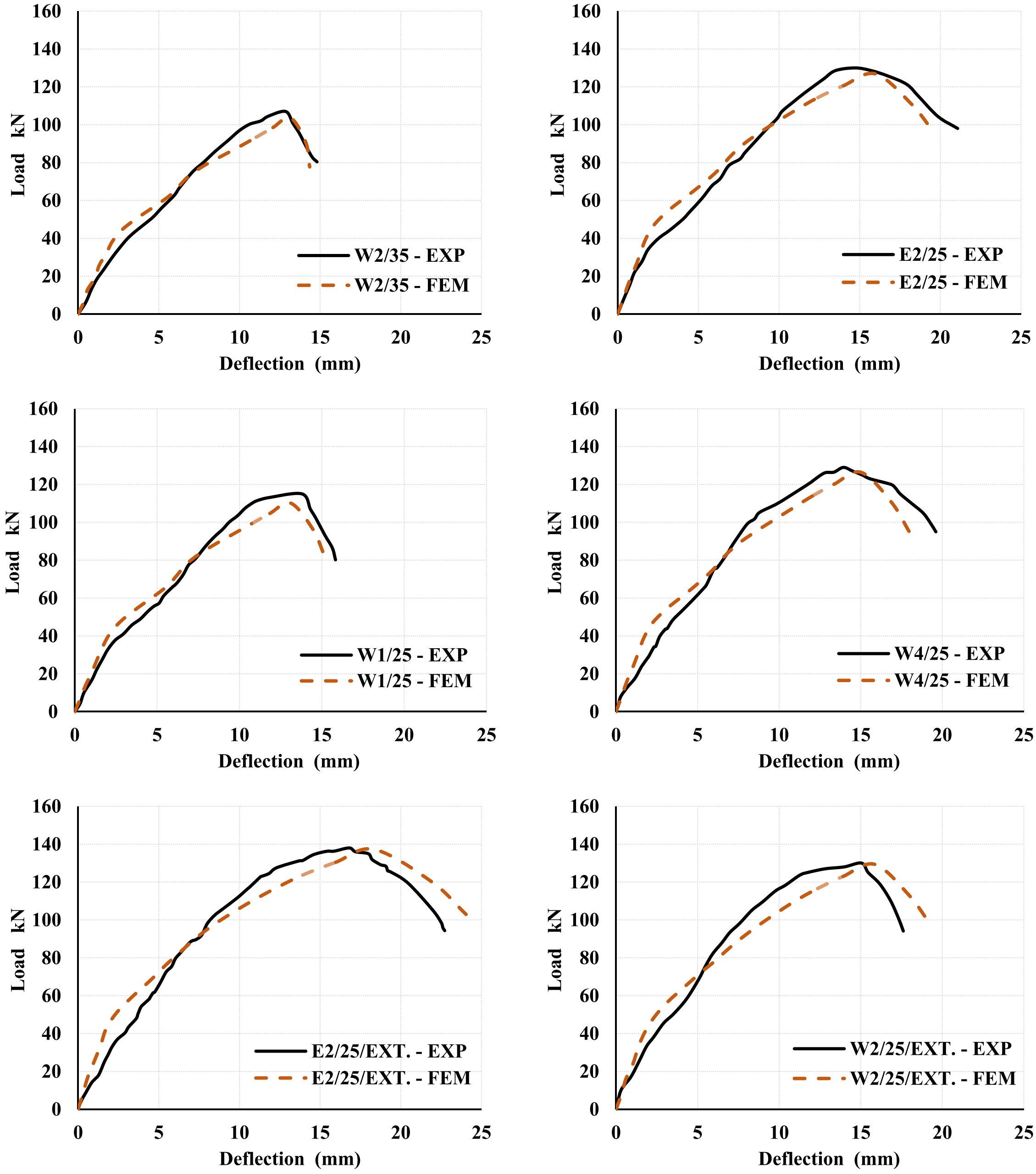
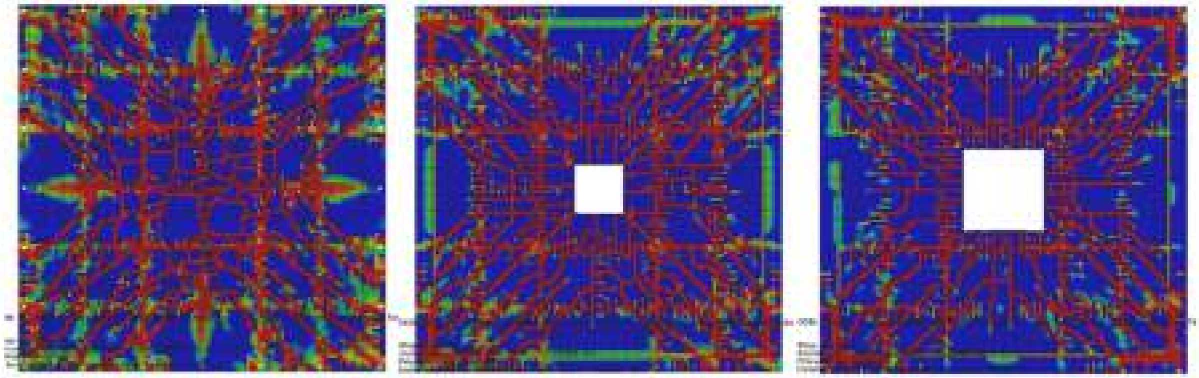


**Fig.13.** (*continued*).

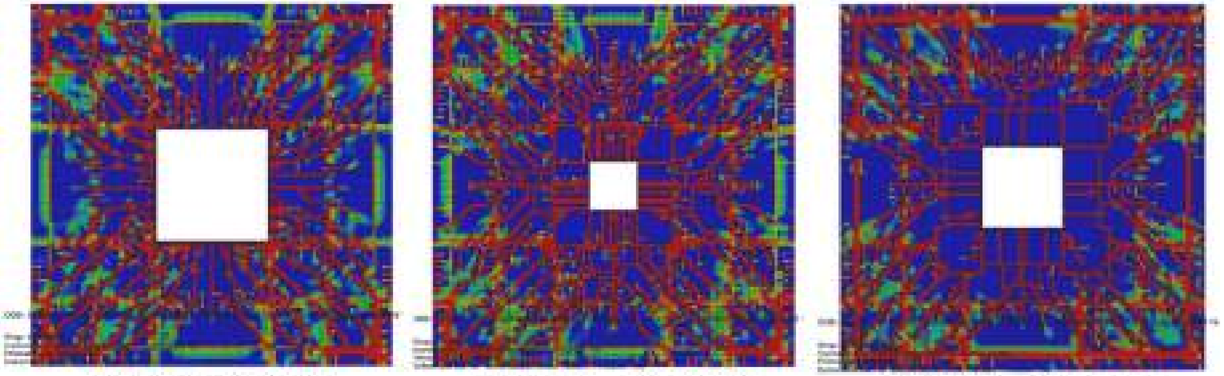
**Table 5**
Comparison between the experimental and numerical findings.

| Specimens ID | First crack load (kN) | | $P_{exp.}/P_{FEM}$ | Ultimate Load (kN) | | $P_{exp.}/P_{FEM}$ |
|---|---|---|---|---|---|---|
| | $P_{exp.}$ | $P_{FEM}$ | | $P_{exp}$ | $P_{FEM}$ | |
| C 0 | 40 | 33.87 | 1.18 | 135 | 136.71 | 0.99 |
| C 15 | 25 | 27.54 | 0.91 | 106 | 111.25 | 0.95 |
| C 25 | 22 | 23.24 | 0.95 | 92 | 93.90 | 0.98 |
| C 35 | 15 | 20.26 | 0.74 | 80 | 81.86 | 0.98 |
| W2/15 | 35 | 32.44 | 1.08 | 134 | 131.05 | 1.02 |
| W2/25 | 31 | 29.73 | 1.04 | 122 | 120.12 | 1.02 |
| W2/35 | 27 | 25.66 | 1.05 | 107 | 103.66 | 1.03 |
| E2/25 | 36 | 31.40 | 1.15 | 130 | 126.87 | 1.02 |
| W1/25 | 28 | 27.26 | 1.03 | 115 | 110.14 | 1.04 |
| W4/25 | 34 | 31.29 | 1.09 | 129 | 126.37 | 1.02 |
| E2/25/EXT. | 38 | 33.97 | 1.12 | 138 | 137.24 | 1.01 |
| W2/25/EXT. | 35 | 32.02 | 1.09 | 130 | 129.34 | 1.01 |

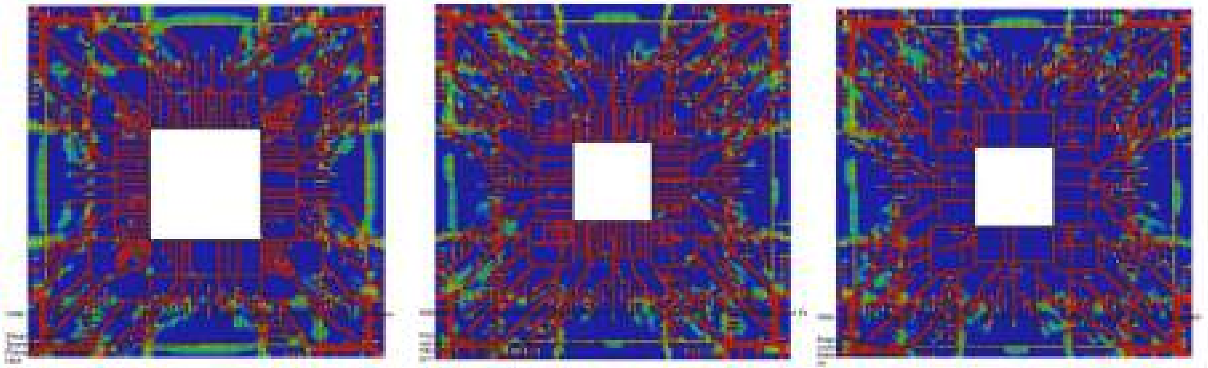
5. Generally, increasing the opening size results in a higher ductility index relative to the reference slab. However, strengthening slabs with different openings using two welded steel mesh layers had a lower ductility index, and this is attributed to a higher first cracking deflection for these strengthened specimens. Increasing layer numbers from 1 to 4 led to a lower ductility index from 8.12 to 6.01 due to higher first cracking deflection for bigger numbers of strengthening mesh layers.
6. Openings in RC slabs increased cracks, particularly at corners, while strengthening techniques reduced crack formation around openings due to effective reinforced layers like ferrocement.
7. Precise agreement was observed between the finite element model and the experimental results, with the model accurately representing the load-deflection relationships.



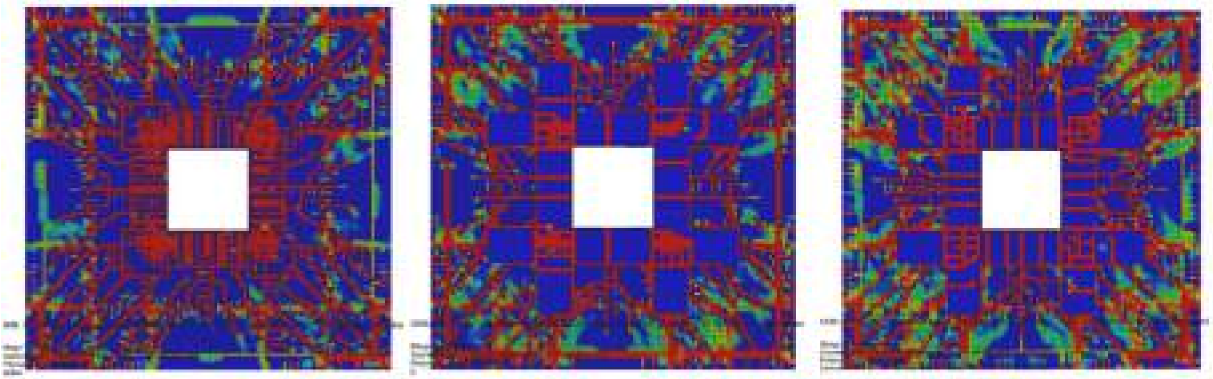
**C 0 (Pu=136.71 kN)** **C 15 (Pu=111.25 kN)** **C 25 (Pu=93.90 kN)**



**C 35 (Pu=81.86 kN)** **W2/15 (Pu=131.05 kN)** **W2/25 (Pu=120.12 kN)**



**W2/35 (Pu=103.66 kN)** **E2/25 (Pu=126.87 kN)** **W1/25 (Pu=110.14 kN)**



**W4/25 (Pu=126.37 kN)** **E2/25/Ext. (Pu=137.24 kN)** **W2/25/Ext. (Pu=129.34 kN)**

**Fig.14.** Failure pattern of FEM for all slabs.

## 6. Limitations to the ferrocement technique

There were general limitations to the ferrocement technique [18–21], and it was taken into account during the experimental program of this study as follows:

a) Ferrocement components are susceptible to shrinkage cracks due to their higher cement content, and to overcome this issue, a 7-day uninterrupted curing period was applied.
b) Incomplete mortar coverage can lead to the corrosion of steel meshes; therefore, complete mortar coverage was prioritized during the construction process.

Additionally, it is recommend to use admixtures to enhance the workability and flowability of the ferrocement.

## 7. Recommendations for future studies

It is recommended that future studies investigate the impact of unforeseen openings in reinforced concrete slabs under various parameters, such as special concrete types, reinforcement ratios, opening shapes, locations, and loading patterns. To gather sufficient data for approval in codes of practice, further research on ferrocement materials for strengthening and repairing reinforced concrete elements using various mesh types and percentages is necessary. Strengthening the whole tension face of slabs, rather than just the openings, can be beneficial. Studies should also explore the effects of high temperature, fire, and durability on the behavior of reinforced concrete slabs with openings strengthened using ferrocement techniques. Additionally, studies should be conducted on the dynamic effects of strengthened two-way R.C. slabs and the effect of strengthening openings next to columns to enhance punching shear failure using the ferrocement technique. It is also recommended to conduct further studies on the use of non-metallic reinforcing materials.

Engineers and practitioners should consider using ferrocement as an external reinforcement for strengthening structural members or restoring damaged slabs. Ferrocement is a durable material with high tensile strength, close-spaced reinforcement, and improved resistance to crack development and corrosion. Ferrocement slabs offer reduced maintenance costs, design flexibility, and ease of repair, resulting in cost savings and efficient maintenance and restoration of reinforced concrete elements.

## CRediT authorship contribution statement

**Mahmoud Elnagar:** Data curation, Formal analysis, Investigation, Resources, Writing – original draft. **Gamal Khaleel:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – review & editing. **Khaled El-Sayed:** Conceptualization, Data curation, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Mohamed H. Makhlouf:** Conceptualization, Data curation, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

[1] Elsehsah Abdelrahman, Madkour Hany, Farah Khalid. Structural behavior of RC slabs with opening strengthened with F.R.P. Int Res J Eng Technol (IRJET) 2018; Vol. 05(Issue 08).
[2] Mahlis M, Shoeib AE, Abd Elnaby S, Sherif A. The effect of cutting openings on the behavior of two-way solid loaded slabs. Structures 2018;vol. 16:137–49. https://doi.org/10.1016/j.istruc.2018.09.002.
[3] Banu N, Taranu Dragos. Traditional solutions for strengthening reinforced concrete slabs. Bul Inst Politeh Din lasi Sect Constr Arhit 2010;vol. 56(3):53.
[4] Madan CS, Panchapakesan K, Anil Reddy PV, Joanna PS, Rooby J, Gurupatham BGA, Roy K. Influence on the flexural behaviour of high-volume fly-ash-based concrete slab reinforced with sustainable glass-fibre-reinforced polymer sheets. J Compos Sci 2022;vol. 6(6):1–21. https://doi.org/10.3390/jcs6060169.
[5] Chinnasamy Y, Joanna PS, Kothanda K, Gurupatham BGA, Roy K. Behavior of pultruded glass-fiber-reinforced polymer beam-columns infilled with engineered cementitious composites under cyclic loading. J Compos Sci 2022;vol. 6(11). https://doi.org/10.3390/jcs6110338.
[6] Seliem HM, Seracino R, Sumner EA, Smith ST. Case study on the restoration of flexural capacity of continuous one-way RC slabs with cutouts. J Compos Constr 2011;vol. 15(6):992–8. https://doi.org/10.1061/(asce)cc.1943-5614.0000232.
[7] Khajehdehi R, Panahshahi N. Effect of openings on in-plane structural behavior of reinforced concrete floor slabs. J Build Eng 2016;vol. 7:1–11. https://doi.org/10.1016/j.jobe.2016.04.011.
[8] Chand Dewangan H, Kumar Panda S, Kumar Hirwani C. Numerical deflection and stress prediction of cutout borne damaged composite flat/curved panel structure. no. December 2020 Structures 2021;vol. 31:660–70. https://doi.org/10.1016/j.istruc.2021.02.016.
[9] Philip RE, Andrushia AD, Nammalvar A, Gurupatham BGA, Roy K. A comparative study on crack detection in concrete walls using transfer learning techniques. J Compos Sci 2023;vol. 7(4). https://doi.org/10.3390/jcs7040169.
[10] Nageswara Rao DK, Ramesh Babu M, Raja Narender Reddy K, Sunil D. Stress around square and rectangular cutouts in symmetric laminates. Compos Struct 2010;vol. 92(12):2845–59. https://doi.org/10.1016/j.compstruct.2010.04.010.
[11] El-Mawsly EH, El-Kashif KFO, Shawky AA, Abdalla HA. Experimental and numerical investigation on strengthening of RC flat slabs with central opening. Case Stud Constr Mater 2022;vol. 16(February):e00974. https://doi.org/10.1016/j.cscm.2022.e00974.
[12] Afefy HM, Fawzy TM. Strengthening of RC one-way slabs including cut-out using different techniques. Eng Struct 2013;vol. 57:23–36. https://doi.org/10.1016/j.engstruct.2013.09.013.
[13] Shehab HK, Eisa AS, El-Awady KA. Strengthening of cutouts in existing one-way spanning R. C. flat slabs using CFRP sheets. Int J Concr Struct Mater 2017;vol. 11 (2):327–41. https://doi.org/10.1007/s40069-017-0186-7.
[14] Abdulrahman BQ, Wu Z, Cunningham LS. Experimental and numerical investigation into strengthening flat slabs at corner columns with externally bonded CFRP. Constr Build Mater 2017;vol. 139:132–47. https://doi.org/10.1016/j.conbuildmat.2017.02.056.
[15] Madan CS, Munuswamy S, Joanna PS, Gurupatham BGA, Roy K. Comparison of the flexural behavior of high-volume fly ashbased concrete slab reinforced with GFRP bars and steel bars. J Compos Sci 2022;vol. 6(6):1–17. https://doi.org/10.3390/jcs6060157.
[16] Zheng X, Wan B, Huang P, Huang J. Experimental study of hybrid strengthening technique using carbon fiber laminates and steel plates for reinforced concrete slabs. Constr Build Mater 2019;vol. 210:324–37. https://doi.org/10.1016/j.conbuildmat.2019.03.100.
[17] Shbeeb NI, Al-Akhras NM, Shannag MJ, Alfendi HR. Strengthening of lightweight reinforced concrete slabs using different techniques. IES J Part A Civ Struct Eng 2012;vol. 5(1):16–27. https://doi.org/10.1080/19373260.2012.652936.
[18] Burakale AS, Attarde PM, Patil MD. Ferrocement construction technology and its applications-a review. Int Res J Eng Technol 2020;vol. 07(07):4178–89.
[19] B. Tabraiz, Ferro-cement technology and prospective developments in durability and sustainability, M.Sc. thesis, Politecnico di Torino, 2019.
[20] Batra A, Ghangas S, Kumar L, Saxena H. A review study of application of ferro-cement. Int Res J Eng Technol 2017;vol. 4(6):1592–7.
[21] Maharashtra GOF. Ferrocement technology. Maharashtra Eng Res Inst 2018;(1): 1–152.
[22] Cheah CB, Ramli M. The structural behaviour of HCWA ferrocement-reinforced concrete composite slabs. Compos Part B Eng 2013;vol. 51:68–78. https://doi.org/10.1016/j.compositesb.2013.02.042.
[23] Erfan AM, Abd Elnaby RM, Elhawary A, El-Sayed TA. Improving the compressive behavior of RC walls reinforced with ferrocement composites under centric and eccentric loading. Case Stud Constr Mater 2021;vol. 14:e00541. https://doi.org/10.1016/j.cscm.2021.e00541.
[24] Rajguru RS, Patkar M. Torsion behavior of strengthened RC beams by ferrocement. Mater Today Proc 2022;vol. 61:138–42. https://doi.org/10.1016/j.matpr.2021.06.329.
[25] Soman M, Mohan J. Rehabilitation of RC columns using ferrocement jacketing. Constr Build Mater 2018;vol. 181:156–62. https://doi.org/10.1016/j.conbuildmat.2018.05.206.
[26] Masud MM, Kumar A. Strengthening of circular RC column through external confinement using ferrocement. Indian J Sci Technol 2016;vol. 9(30). https://doi.org/10.17485/ijst/2016/v9i30/99208.
[27] Naser FH, Al Mamoori AHN, Dhahir MK. Effect of using different types of reinforcement on the flexural behavior of ferrocement hollow core slabs embedding PVC pipes. Ain Shams Eng J 2020. https://doi.org/10.1016/j.asej.2020.06.003.
[28] Ahmed TI, Afify MR. Feasibility of using ferrocement and GFRP for strengthening bearing walls with openings. J Build Pathol Rehabil 2020;vol. 5(1):1–10. https://doi.org/10.1007/s41024-019-0070-8.

[29] Ashraf M, Halhalli V. Flexural behaviour of SCC ferrocement slabs incorporating steel fibers. Int J Eng Res Technol 2013;vol. 2(10):557–61.

[30] Erfan AM, Ahmed HH, Mina BA, El-Sayed TA. Structural performance of eccentric ferrocement reinforced concrete columns. Nanosci Nanotechnol Lett 2020;vol. 11 (9):1213–25. https://doi.org/10.1166/nnl.2019.3008.

[31] Majeed FH. Estimating the behavior of ferrocement strengthened RC columns using artificial neural networks. Int J Appl Eng Res 2018;vol. 13(1):732–6.

[32] Al-Kubaisy MA, Zamin Jumaat M. Flexural behaviour of reinforced concrete slabs with ferrocement tension zone cover. Constr Build Mater 2000;vol. 14(5):245–52. https://doi.org/10.1016/S0950-0618(00)00019-2.

[33] Mazan DA. Experimental study of behavior of reinforced concrete one-way slabs strengthened and repaired by ferrocement at tension Zone. Iraqi J Civ Eng 2017; vol. 11(3):52–67. https://doi.org/10.37650/ijce.2017.172894.

[34] Desayi P, Nanda Kumar N, El-Kholy SA. Strength and behaviour of ferrocement in shear. Cem Concr Compos 1992;vol. 14(1):33–45. https://doi.org/10.1016/0958-9465(92)90037-V.

[35] Murali G, Amran M, Fediuk R, Vatin N, Raman SN, Maithreyi G, Sumathi A. Structural behavior of fibrous-ferrocement panel subjected to flexural and impact loads. Materials 2020;vol. 13(24):1–22. https://doi.org/10.3390/ma13245648.

[36] Shaheen YBI, Eltehawy EA. Structural behaviour of ferrocement channels slabs for low cost housing. Chall J Concr Res Lett 2017;vol. 8(2):48. https://doi.org/10.20528/cjcrl.2017.02.002.

[37] Minde P, Bhagat D, Patil M, Kulkarni M. A state-of-the-art review of ferrocement as a sustainable construction material in the Indian context. Mater Today Proc 2023; (April). https://doi.org/10.1016/j.matpr.2023.03.250.

[38] Londhe C, Minde P. Ferrocement: cost effective & sustainable construction material for low-cost urban housing in India. Gis Sci J 2021;vol. 8(3):1633–8.

[39] Kaish ABMAmrul, Alam MR, Jamil M, Wahed MA. Ferrocement jacketing for restrengthening of square reinforced concrete column under concentric compressive load. Procedia Eng 2013;vol. 54:720–8. https://doi.org/10.1016/j.proeng.2013.03.066.

[40] Samah Badawy, Elsayed Mahmoud, Elsayed Alaa. Using ferrocement laminates in strengthening flexural behavior of RC slabs with opening. Life Sci J 2015;12(5): 146–52.

[41] Elsayed M. Numerical analysis of strengthening R.C slabs with opening using ferrocement laminates. Int J Eng Res Technol 2015;vol. 4(06):412–6.

[42] Shaheen YBI, Mahmoud AM. Structural behavior of RC channel slabs strengthened with ferrocement. Struct Eng Mech 2023;vol. 86(6):793–815. https://doi.org/10.12989/sem.2023.86.6.793.

[43] Chkheiwer Aqeel H, Mazen DAbdullah. Flexural behavior of high strength RC slabs with opening strengthening with wire mish and steel fibers. Kufa J Eng 2017;8(3).

[44] Sivanantham P, Pugazhlendi D, Gurupatham BGA, Roy K. Influence of steel fiber and carbon fiber mesh on plastic hinge length of RCC beams under monotonic loading. J Compos Sci 2022;vol. 6(12). https://doi.org/10.3390/jcs6120374.

[45] Sivanantham P, Gurupatham BGA, Roy K, Rajendiran K, Pugazhlendi D. Plastic hinge length mechanism of steel-fiber-reinforced concrete slab under repeated loading. J Compos Sci 2022;vol. 6(6):1–19. https://doi.org/10.3390/jcs6060164.

[46] ABAQUS Documentation User's Guide: ABAQUS User's Guide: Dassault Systèmes, Simulia Corp, Providence, 2021.

[47] Shaheen Yousry Bauomy I, Etman Zeinab Abd El khaleq, Kandil Doha Elmetwally Abdelmonem. Performance of light weight ferrocement composite walls. Chall J Concr Res Lett 2023;14(3):69. https://doi.org/10.20528/cjcrl.2023.03.002.

[48] Noha Yehia Elwakkad, Tayeh Bassam A, Hekal Ghada Mousa, Heiza Khaled Mohamed. Experimental and numerical investigation of the behavior of self-curing R.C. flat slabs (September) Case Stud Constr Mater 2022;17:e01457. https://doi.org/10.1016/j.cscm.2022.

[49] Mansour W. Numerical analysis of the shear behavior of FRP-strengthened continuous RC beams having web openings. 2021 Eng Struct 2020;vol. 227 (November):111451. https://doi.org/10.1016/j.engstruct.2020.111451.