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Behavior of R.C. Slab with Opening Retrofitted by Ferrocement Overlays: Experimental and Analytical Investigation

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Abstract: *This paper presents an experimental and numerical study to evaluate the effectiveness and feasibility of using ferrocement as external overlays for strengthening R.C. slab with a central opening. Twelve R.C slabs of dimension 1000 x 800 x 100 mm were cast and tested experimentally, ten of the specimens were strengthened by ferrocement laminates and the other two were kept as control specimens; with and without opening. The effects of mortar thickness, number, and type of steel wire mesh, ferrocement mortar strength, and strengthening schemes were investigated. A 3-D finite element model using ANSYS package was developed and compared with the available experimental test results to check the validity of the model. A total of 32 numerical models were analyzed to study the different parameters that not covered by the experimental investigation. This study provides information on the viability of using ferrocement laminates in strengthening R.C. slab with cut-out and showed that both flexural behavior and stiffness were significantly enhanced. It was observed that the influence of the openings is vanished by strengthening the test specimens by ferrocement. The ultimate load capacities of the strengthened specimens were increased between 186% and 80% relative to the control specimens with and without opening respectively. The finite element analysis was capable of reasonably estimate the experimental behavior.*

Keywords: *Ferrocement, R.C. Slab, Opening, Strengthening, ANSYS*

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I. Introduction

R.C structures may need to be rehabilitated during their lifetime due to many reasons. Changing of function in a building is considered one of these main reasons. In many situations, openings may be needed in slabs at locations that were not considered during the design of a building for instance air conditioning, heating or wiring ducts are often required. In these cases, cut-out in slabs become one of the most common problems confronted. To avoid stress concentration (excessive cracking) at the opening location and to improve the slab capacity to carrying any additional loads strengthening of the opening zone is required. The application of ferrocement laminates is able to overcome these problems (stress concentration at openings and slab capacity carrying additional loadings). The ferrocement is a thin layer of micro-concrete reinforced with steel wire mesh with a small diameter [1-2]. There are many advantages of ferrocement such as materials are available in most of the countries, ease of construction, less weight, and low cost of the construction materials. Cut-out of R.C. slab will reduce strength and the overall stiffness of the slab and may decrease in the ability of a structure to withstand imposed loading. It is important to investigate the strengthening technique to overcome these negative effects of openings in the reinforcements of slabs. There are numerous researchers [3,4,5] investigated the effect of using different techniques of FRP in retrofitted one way R.C. slab with openings. Enochsson et al [6] presented analytical and experimental studies to evaluate the validity of using CRFP wrapping for retrofitting two-way R.C slabs with openings. The experimental test results revealed that utilizing CFRP sheet as a retrofitting technique lead to a better performance in the overall flexural behavior of slabs. Al-Sulayvani and Al-Talabani [7] carried out an experimental investigation on circular R.C. slabs with openings strengthened by CFRP under repeated loads. The performance of the retrofitted slabs was studied for different strengthening schemes and different opening shapes. Florut et al [8] tested two-way slabs with openings near the supports, strengthened by CFRP sheets. It was observed that there was an enhancement in the flexural behavior of slabs. Thanoon [9] investigated an experimental test to repair R.C. one-way slabs using ferrocement laminates and different techniques. The researches [10, 11, 12, 13, and 16] have been carried out to investigate the Strengthening and repairing R.C. columns with ferrocement jackets. Badawy [17] carried out an experimental program to study the behavior of R.C. slabs with openings. Three variables were investigated; opening sizes, retrofitting area around the opening, the volume fraction of reinforcement, and the type of connection between mortar and R.C. slabs. The experimental results showed that the efficiency of R.C. slabs with opening using ferrocement as a strengthening technique was improved. The test results indicated that ferrocement jacket can effectively enhance the ultimate load carrying capacity. Jayasree et al [14] studied experimentally the flexural behavior of R.C. beams with a different degree of corrosion and strengthened by ferrocement overlays. Li et al [15] suggested a technique for rehabilitating reinforced concrete interior beam-column joints using ferrocement laminates with diagonal reinforcements. Paramasivam et al [18-19] investigated the effect of using ferrocement laminates in strengthening R.C.T-beams. An experimental test was investigated by Beheraa et al [20] to evaluate the validity of using ferrocement on the "U" jacket in strengthening torsional behavior of R.C. beam. Xiong et al [21] studied the effect of retrofitted R.C columns with ferrocement jacket including steel bars.

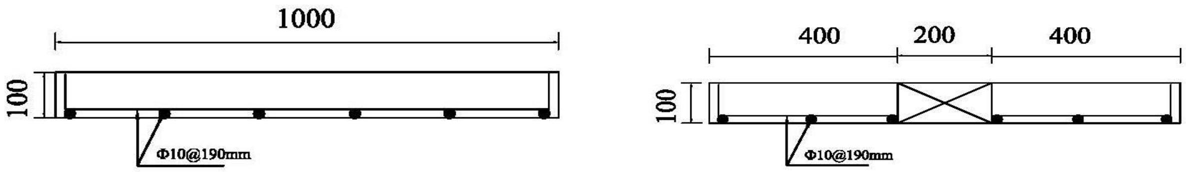
II. Experimental program

i. MATERIAL PROPERTIES

The slabs were constructed using ready-mixed concrete provided by a local supplier. The average 28-day compressive strength of concrete was 25 MPa based on testing standard concrete cubes. The mix proportions of concrete were (1:0.4:0.8) for cement: fine aggregate: coarse aggregate: and the water-cement ratio was 0.5. Deformed steel bars Φ 10 mm were used in reinforcing the concrete slabs. The average yield and ultimate strengths of the steel bars were 410 MPa and 635 MPa respectively. The ferrocement mortar consisted of sand, cement, and silica fume. Silica fume and super-plasticizer were used as admixtures to yield a workable mixable to penetrate and surround ferrocement mesh completely and having high strength mortar and high performance. In this experimental program, two different types of mortar grade were considered. The average compressive strength of mortar was 25 MPa and 40 MPa respectively. Two types of steel wire-meshes were used in this experimental work; The First type is expanded wire mesh (diamond) of 1.5 mm diameter and 30 mm x 15 mm wire spacing. The second one is galvanized steel wire mesh-fabric of the woven form with square opening 20 mm square grid and 1 mm diameter. Modulus of elasticity for expanded and square wire mesh is 85000 MPa and 138000 MPa respectively.

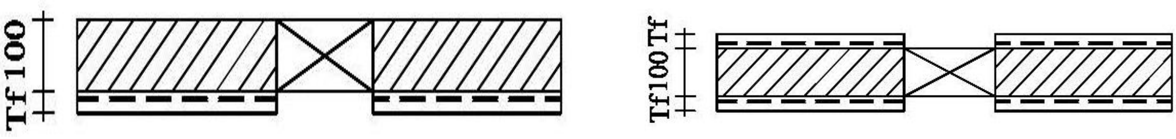
ii. TEST SPECIMENS

The experimental program was carried out twelve rectangular concrete slabs. Two slabs were kept as reference specimens with and without opening and without ferrocement retrofitting (Sc- Sco). The other ten test specimens with opening were strengthened with ferrocement laminates. The overall slab dimensions were 1000 mm (length) by 800 mm (width) and 100 mm (thick). Eleven specimens are constructed with a central opening at bending zone of size 200 x 200 mm. The test specimens have Φ10 @190mm in two directions as tension reinforcement. Figure 1 shows the typical dimensions and steel reinforcement layout of the reference specimens. Many parameters were considered as indicated in Table 1, such as; the thickness of ferrocement layer, number, and type of steel wire meshes, and characteristic strength of mortar matrix. Eight specimens were strengthened by applying one layer of ferrocement at tension face and two specimens were strengthened by applying two layers at both tension and compression face in sandwich form as shown in Figure 2. Ferrocement overlays were applied in sequent steps. Before applying the mortar, the surface of the slab was roughened and cleaned, then the wire-mesh was fixed by steel bolts to stand in its designated positions. A bonding material was applied to improve the bond between the roughening surface of slab and mortar. Finally, ferrocement matrix was cast manually while the bonding material still wet. Figure 3 shows the strengthening procedures.



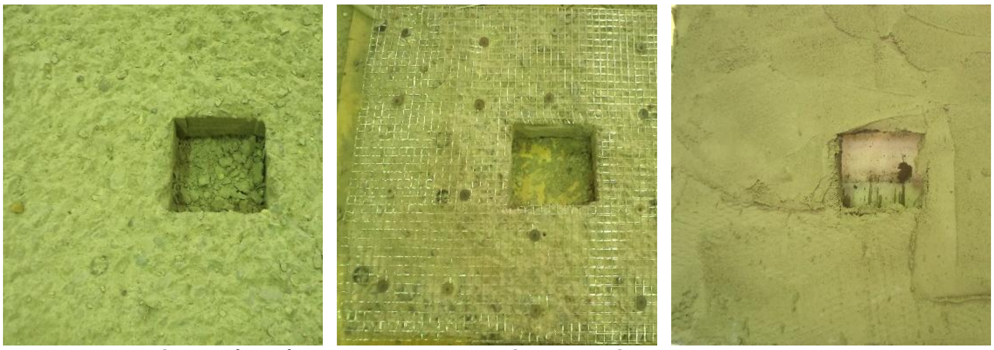
a) Details of specimen without opening control **b)** Details of Specimen with a central opening

FIGURE 1. DIMENSIONS AND REINFORCEMENT DETAILS OF CONTROL SPECIMENS



b) Applying ferrocement at tension side c) Applying ferrocement as sandwich form

FIGURE 2. STRENGTHENING SCHEMS OF SLABS WITH FERROCEMENT



1. Roughing surface of slab   2. Fixing the wire-mesh and Plastering of bonding material   3. Applying mortar

FIGURE 3. STRENGTHENING PROCEDURE

TABLE 1: DESCRIPTION OF THE TEST SPECIMENS

Specimen	Mesh type	Strengthening schem	Ferrocement thickness (mm)	Volume fraction (%) per layer	No of wire mesh per layer	Mortar strength (MPa)
Sc	-------	-------	-------	-------	-------	-------
Sco	-------	-------	-------	-------	-------	-------
S1	Expanded	Tension face	25	1.48	2	40
S2	Expanded	Tension face	25	2.23	3	40
S3	Expanded	Tension face	35	1.06	2	40
S4	Expanded	Tension face	25	1.48	2	25
S5	Expanded	Tension face	25	2.23	3	25
S6	Expanded	Tension face	35	1.06	2	25
S7	Square	Tension face	25	0.63	2	40
S8	Square	Tension face	25	0.94	3	40
S9	Expanded	Sandwich	25	1.48	2	40
S10	Expanded	Sandwich	25	2.23	3	40

iii. TEST SETUP

All the specimens were tested under the effect of four point loads and examined as simply supported conditions. One LVDT with 100 mm was used and located at the bottom side of the specimen at the corner of the cut-out, and another one was placed at the middle side of the opening or at this corresponding position in the slab without opening. Figure 4 shows the experimental test setup.

III. Finite Element Analysis

The test specimens, used in the experimental program, were simulated using the finite element package ANSYS 14.5 [22] and the analytical results were compared with the experimental ones to check the validity of the FE models. The verification process means that the model is trustworthy and can be used effectively to predict the influence of the other parameters not studied experimentally on the overall behavior of such slab.

i. DEFINING MATERIAL PROPERTIES

The finite element model using ANSYS 14.5 [22] was proposed to study the flexural behavior of retrofitted RC slabs with opening by ferrocement laminates. Two types of elements were used to build up the models. The three-dimensional, eight-node solid element (SOLID65), available in the ANSYS library was used to model both concrete and ferrocement mortar as shown in Figure 5.a. SOLID65 element is an eight-node solid element used to model the concrete with or without reinforcing bars. The rebar reinforcement feature of this element was used to model the mesh reinforcement behavior. Reinforcement is specified by its material, volume ratio, and orientation angles. The volume ratio is defined as the rebar volume divided by the total element volume. The orientation is defined by two angles in degrees (θ and φ) from the element coordinate system. The element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. The most important feature of this element is that it can represent both linear and nonlinear behavior of the concert. The reinforcing steel bars were adopted using (LINK180) element. Table 2 shows the material properties of elements.

ii. NUMERICAL MODELING OF SLAB AND BOUNDARY CONDITIONS

The experiment conditions have been used to describe the boundary conditions while the load application of the finite element analysis has been described to simulate the actual loading sequence. In this study, taking advantage of the symmetry in geometry and loading, the simulated model is constructed in the form of one-quarter of the slab due to the two axes of symmetry (500*400*100 mm). Thus, the boundary condition of these two edges is defined as the symmetry of displacement, which is shown in Figure 5.b. Because the specimens are simply supported on four edges that are free to lift during the tests, the proper simulation of the boundary condition as taken into account. A displacement control incremental loading was applied at four symmetrical points at 200 mm from the corner of the opening in two directions. Small initial load steps were used for detecting the first crack in the connections. Then, automatic time stepping was used to control the load step.

iii. PARAMETRIC STUDY

Verified models were used to investigate the variables which not considered by the experimental program. A total of 32 numerical simulations has been conducted using ANSYS (14.5) package. Four main parameters with regard to the main properties of ferrocement were studied, namely: the characteristic strength of mortar, thickness of ferrocement layer, strengthening schemes, and percentage of wire mesh reinforcement in the ferrocement cover layer. In this numerical analysis, four different thicknesses of the mortar layer (15, 20, 25,30mm), three different types of mortar strength (40, 60, and 75 Mpa), two values of volume fraction (1.5 and 3%), and two strengthening schemes (tension side or sandwich form) were considered. The description of suggested extra models is listed in Table 3.

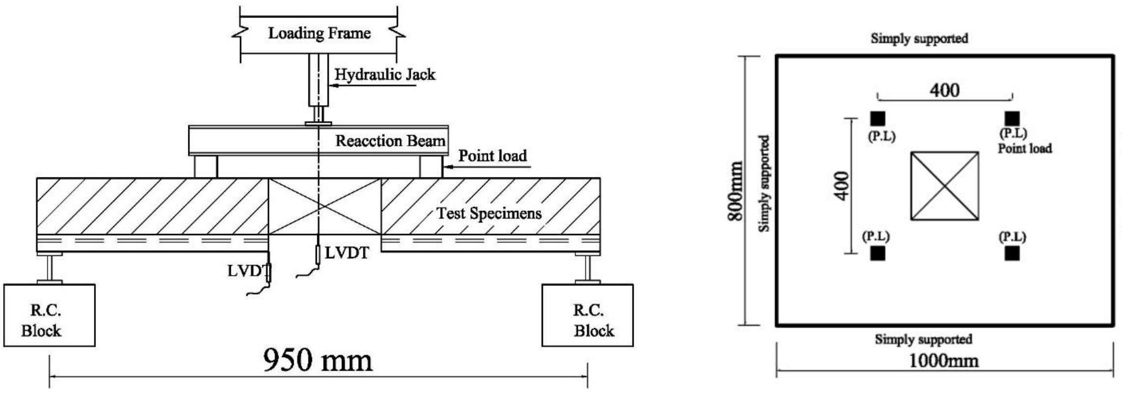


FIGURE 4. TEST SETUP

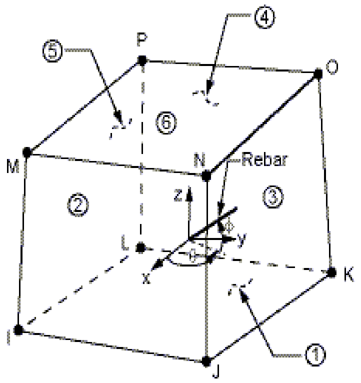


FIGURE 5.a. SOLID65 3-D REINFORCED CONCRETE SOLID ELEMENT

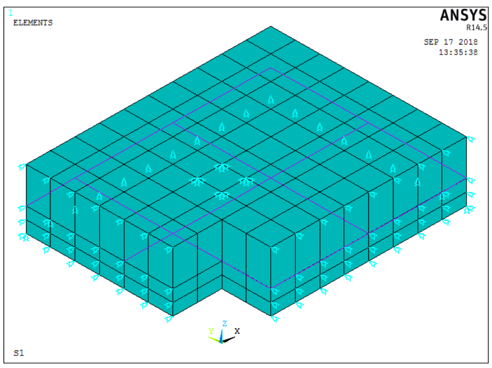


FIGURE 5.b. ANSYS NUMERICAL MODEL

TABLE 2: MATERIAL PROPERTIES FOR THE ELEMENT

Material	Element type	Material properties	
Concrete	Solid 65	Elastic modulus (Ex)	$4400\sqrt{fcu}$ MPa
		Uniaxial crushing stress (fcu`)	25 MPa
		Uniaxial tensile stress (ft)	$0.6\sqrt{fcu}$ MPa
		Poisson's ratio (υ)	0.20
		Shear coefficient for open shear (ßt)	0.20
		Shear coefficient for closed shear (ßc)	0.8
Longitudinal reinforcement	Link 180	Elastic modulus (Ex)	200000 MPa
		Yield stress (fy)	410 MPa
		Tensile Strength	628 MPa
		Poisson's ratio (υ)	0.30
Mortar and wire mesh	Solid 65	Elastic modulus (Ex)	24100 MPa
		Uniaxial crushing stress (fcu)	(40-60-75) MPa
		Uniaxial tensile stress (ft)	$0.6\sqrt{fcu}$ MPa
		Poisson's ratio (υ)	0.20
		Shear coefficient for open shear (ßt)	0.1
		Shear coefficient for closed shear (ßc)	0.8
		Yield stress (fy)	370 MPa
		Poisson's ratio (υ)	0.30
		Elastic modulus for expanded wire mesh	68000 MPa
		Elastic modulus for square wire mesh	132000 MPa

TABLE 3 DESCRIPTION OF PROPOSED EXTRA MODELS

Group	Model	Mesh type	Strengthening Scheme	Ferrocement thickness (mm)	Volume fraction (%) per layer	Mortar grade (MPa)
Group 1	S1, S2, S3, and S4	Expanded	Tension face	15, 20, 25, and 30	1.5	40
Group 2	S5, S6, S7, and S6	Expanded	Tension face	15, 20, 25, and 30	3	40
Group 3	S9, S10, S11, and S12	Expanded	Tension face	15, 20, 25, and 30	1.5	60
Group 4	S3, S14, S15, and S16	Expanded	Tension face	15, 20, 25, and 30	3	60
Group 5	S17, S18, S19, and S20	Expanded	Tension face	15, 20, 25, and 30	1.5	75
Group 6	S21, S22, S23, and S24	Expanded	Tension face	15, 20, 25, and 30	3	75
Group 7	S25, S26, S27, and S28	Expanded	Sandwich form	15, 20, 25, and 30	1.5	60
Group 8	S29, S30, S31, and S32	Expanded	Sandwich form	15, 20, 25, and 30	3	60

IV. Results and Discussion

iv. RESULTS OF EXPERIMENTAL PROGRAM

The results obtained from the tested specimens are discussed in the following sections. The load versus the deflection values, failure load, and crack pattern were observed and initial stiffness, ductility ratio, and energy dissipation were calculated.

LOAD DEFLECTION RELATIONSHIP

Figures 6 to 9 show a compassion between the applied loads and the corresponding central deflection curves of the tested specimens. The deflection and the load carrying capacity indicated the efficiency of using such method of strengthening and proved that restoring of the original ultimate moment. Strengthened control slab with opening possessed a higher ultimate load compared with the one without opening. It was found that increasing the mortar grade resulted in increasing the ultimate load and decreasing the deflection. The results indicated a better behavior for slabs strengthened using ferrocement with grade 40 MPa as shown in Figures 6 and 7. It can be realized that from Figure 8 using square wire mesh as ferrocement reinforcement led to enhancement in ultimate load, and exhibited a better performance. By comparing the load-deflection curves in Figure 9, it can be seen that specimens strengthened in a sandwich form failed in a brittle mode once the slab reached its ultimate load capacity. This is characterized by a sharp drop in the load versus deflection plot immediately after the ultimate load is reached. It can be concluded that using two ferrocement laminates in a sandwich form resulted in considerably higher resisting in flexural capacity than that obtained when the flat laminate is attached to the tension side of the slab.

ULTIMATE LOAD CAPACITY

The experimental results of the test specimens are presented in Table 4. It is clearly seen that the control specimens experienced the lowest ultimate load of 170kN and 109 kN for the control specimens Sc, and Sco; respectively. It was observed that the ultimate of the specimen (Sco) with an opening has 56% lower than that of the specimen (SC) without opening. From the experimental results, it can be seen that the failure load of the retrofitted specimens is ranging from 111 % to 186 % higher than that of the un-strengthened slab with the opening based on the strengthening Scheme. The ultimate load capacities of the test specimens having mortar grade 40 MPa (S1, and S2) is 8% and 32% higher than that of specimens with mortar grade 25 MPa (S4, and S5) respectively.

DUCTILITY, ENERGY ABSORPTION, AND STIFFNESS

As the result of the experimental test, the initial stiffness, ductility (δu/δy), and energy dissipation of the test specimens were calculated and listed in Table 4. The uncracked stiffness was calculated as the slope of the linear elastic stage (pre-cracking stage). It was observed that the ductility indexes of the retrofitted specimens were lower than that of solid slab without opening. It can be realized that increasing ferrocement thickness causes an increase in both initial stiffness and energy dissipation. The use of strengthening technique of applying of two layers of ferrocement laminates in both tension and compression sides as a sandwich form resulted in markedly higher stiffness than that obtained from flat laminate in tension side. It was observed that the average increase in uncracked stiffness, ductility ratio, and energy absorption of the strengthened specimens are measured by 204%, 10%, and 42% of the reference specimen with the opening.

CRACKING PATTERN AND MODE OF FAILURE

Figure 10 shows the cracking patterns of the test specimens after the completion of the test. It can be observed that all the test specimens failed in flexure failure mode. Cracks have appeared on the tension side of the slab failure accompanied by vertical cracks. Also, slight cracks appeared in the whole slab for control specimen without opening (Sc). In the case of the slabs with a central cut-out, the crack pattern was diagonal and propagated from the corner of the opening to the edge of the slab. Spalling of concrete was seen on the surface of the slab and increased gradually until the load approached almost its ultimate value.

v. COMPASSION BETWEEN EXPERIMENTAL AND FINITE ELEMENT RESULTS

Figure 11 shows the comparison between the load-deflection relationship for experimental and numerical results. The ultimate load and deflection for both experimental and FE results are summarized in Table 5. The average difference and the standard deviation ranging for the ultimate load from the experimental and analytical model are 1.01 and 0.032 respectively. It can be seen that the numerical results are in a good agreement with the experimental ones and the finite element modeling is quite accurate in representing the tested slab specimens. The nonlinear numerical analysis show close behavior with those obtained from the experimental study. The comparison between the experimental results with the finite element models shows that both models are in good agreement with each other, and shows compatibility between the two solutions. Thus the developed finite element model can be used successfully to extend the work for studying the behavior of R.C. slabs with cut-out strengthened with ferrocement overlays.

TABLE 4: SUMMARY OF THE TEST RESULTS

Specimen	Ultimate Load (kN)	Ultimate Deflection (mm)	%Increase in ultimate load above control specimen with opening (Sco)	Ductility ratio	Energy absorption (kN.mm)	Initial stiffness (kN/mm)
Sc	170	19.00	56.0	1.7	3272	15.40
Sco	109	21.00	0.0	1.30	2035	7.20
S1	198	15.00	81.7	1.14	3012	18.20
S2	249	19.50	128.4	1.08	3368	17.00
S3	240	15.00	120.2	1.33	3150	19.50
S4	183	16.50	67.9	1.26	2903	11.50
S5	188	19.00	72.5	1.42	3156	16.50
S6	152	18.00	39.4	2.27	2490	13.00
S7	182	18.00	67.0	1.74	3170	19.30
S8	230	18.50	111.0	1.63	3662	20.10
S9	273	9.75	150.5	1.30	4067	38.46
S10	312	9.25	186.2	1.10	3020	45.70

TABLE 5: COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL RESULTS

Specimen	Ultimate Load (kN)			Ultimate Deflection (mm)		
	EXP	ANSYS	EXP./ANSYS %	EXP	ANSYS	EXP./ANSYS %
Sc	170	163	104	19.00	18.50	103
Sco	109	112	97	21.00	22.00	95
S1	198	193	103	15.00	17.50	86
S2	249	242	103	19.50	18.50	105
S3	240	247	97	15.00	16.50	91
S4	183	188	97	16.50	18.00	92
S5	188	192	98	19.00	17.50	109
S6	152	147	103	18.00	17.00	106
S7	182	178	102	18.00	16.50	109
S8	230	220	105	18.50	16.00	116
S9	273	285	96	9.75	11.50	85
S10	312	302	103	9.25	10.00	93
	Average		101 %	Average		99
	Standard deviation		0.032	Standard deviation		0.098

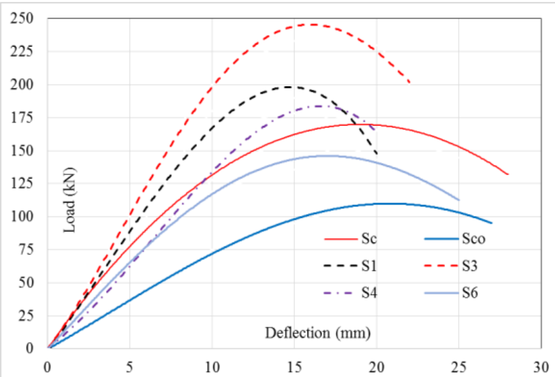


FIGURE 6. EFFECT OF FERROCEMENT THICKNESS

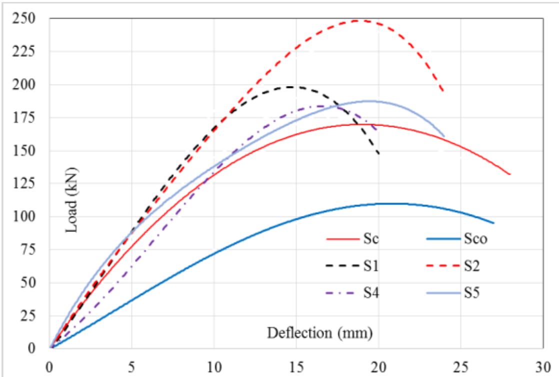


FIGURE 7. EFFECT OF NUMBER OF WIRE MESH PER LAYER

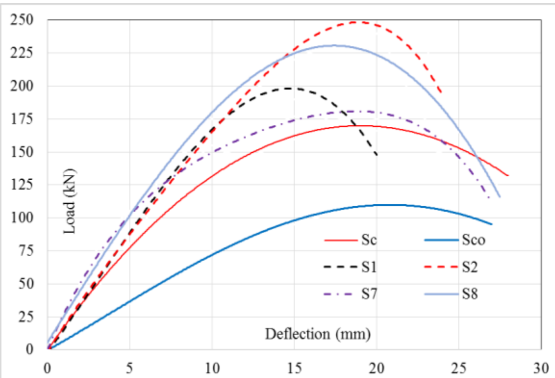


FIGURE 8. EFFECT OF TYPE OF WIRE MESH

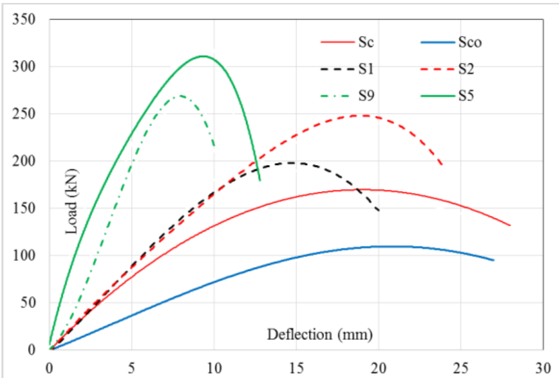


FIGURE 9. EFFECT OF STRENGTHENING SCHEMES

vi. PARAMETRIC STUDY RESULTS

The results of the 32 numerical models will be discussed in detail through the following sections.

LOAD DEFLECTION BEHAVIOR

Figure 12 shows the load-deflection relationship at the opening corner for the eight groups. All the strengthened slabs exhibit higher ultimate loads compared to the control slab with opening. The ultimate strength is considerably enhanced by increasing the ferrocement laminate thickness. The retrofitted slabs were not only restored the original ultimate load but also showed higher ultimate load compared to the control specimen. Also, increasing the mortar compressive strength causes a decrease in deflection and increases the ultimate load carrying capacity. Increasing the wire mesh layers did not considerably contribute in reducing the overall deflection, however, the total deflection of the strengthened slab is still lower than that of the control specimen with opening. Table (5) summarizes the ultimate failure load and the corresponding deflection for all the tested specimens. It can be noticed that using two ferrocement layers in sandwich form resulted in higher ultimate load compared to strengthened slab with only one layer at the tension face.

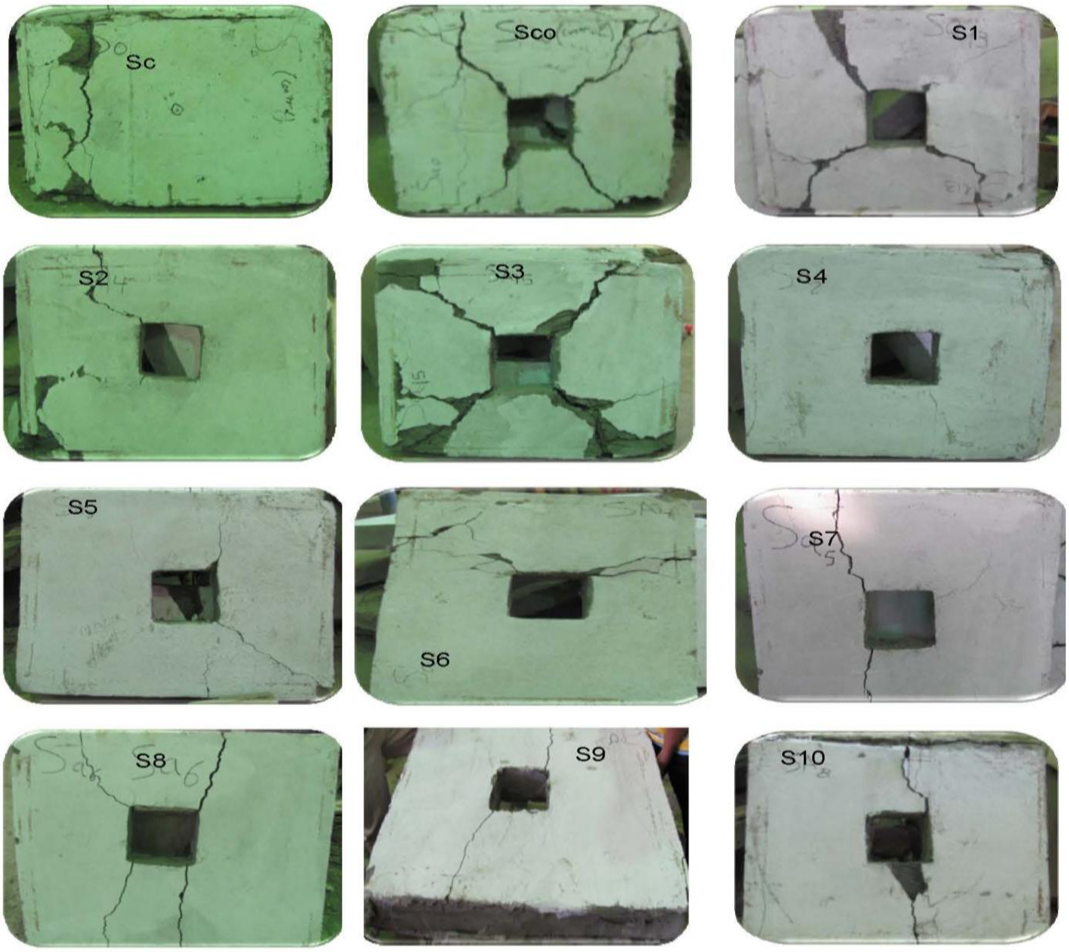


FIGURE 10. CRACKING PATTERN OF THE TEST SPECIMENS

ULTIMATE LOADS, STIFFNESS AND ENERGY ABSORBATION

Table 6 shows the ultimate load, ultimate deflection, initial stiffness, and energy dissipation of the suggested numerical models. It can be seen that the uncracked stiffness increases with increasing ferrocement thickness and number of wire meshes. All strengthened specimens have large values of stiffness than that of the reference slab with cut out, which lead to less ductile behavior due to retrofitting by ferrocement overlays. It can be noticed that the ultimate load increases while the deflection decreases with increasing both of thickness and strength of mortar. Strengthening slab by ferrocement laminates of thickness 30 mm lead to increasing the total slab thickness and consequently increases the load-carrying capacity up to 222%. It was found that the increased thickness of ferrocement from 15 mm to 30 mm resulted in increasing the average percentage of stiffness from 128 % to 171%. The increase of volume fraction percentage from 1.5 to 3 for retrofitted groups resulted in increasing the average gain in the ultimate capacity of the slabs from 78% to 98 %. The gain in energy absorption was affected by the thickness of the strengthening layer and the mortar grade. It was found that applying ferrocement in a sandwich form type enhanced ultimate load, stiffness, and energy absorption compared with that in tension face only.

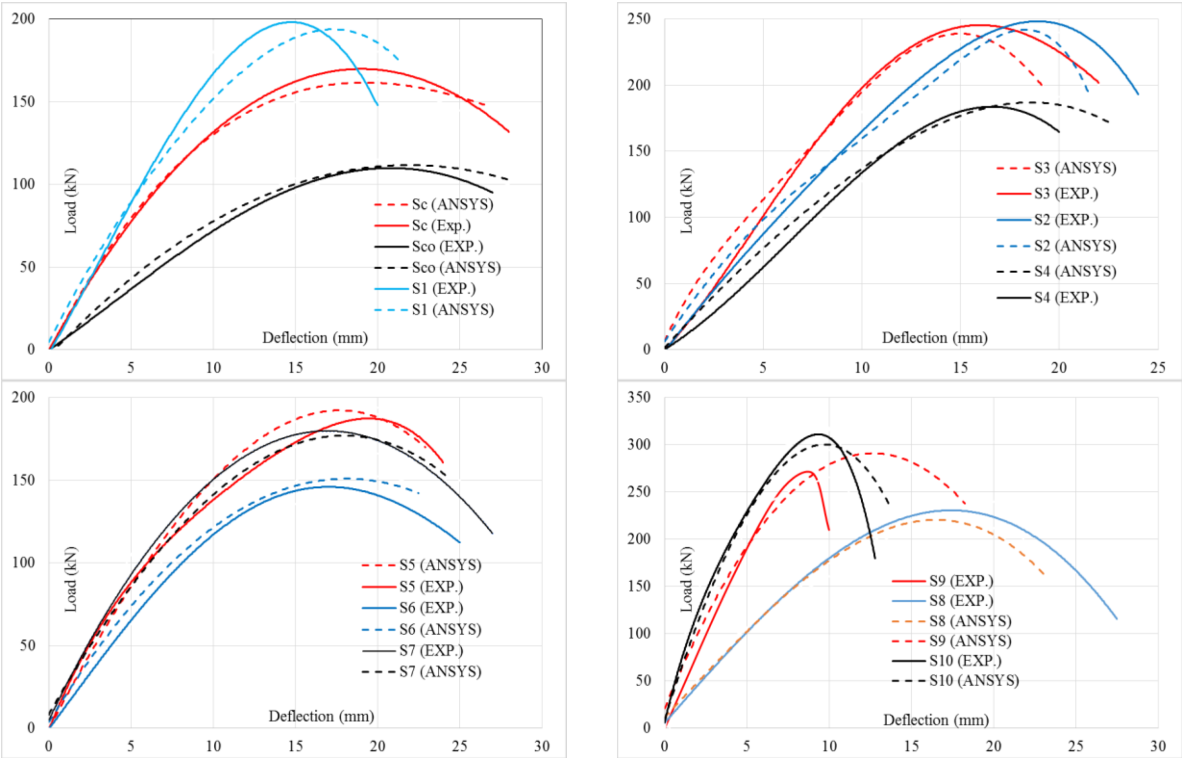


FIGURE 11. LOAD-DEFLECTION CURVES FOR EXPERIMENTAL VERSUS NUMERICAL MODELS

TABLE 6 RESULTS OF SUGGESTED EXTRA MODELS

Group	Model	Ultimate load (kN)	Ultimate deflection (mm)	Pu/Pu(Sco)	Initial stiffness (kN/mm)	Energy absorption (kN.mm)
Control Specimen	Sco	112	18.50	----	7.65	1938
Group 1	S1	165	15.00	147	16.7	2259
	S2	177	15.00	158	17.3	2388
	S3	205	18.00	183	18.2	2619
	S4	215	18.00	192	19.0	2755
Group 2	S5	185	15.00	165	17.5	2425
	S6	215	18.00	192	18.4	2672
	S7	227	16.50	203	19.7	2818
	S8	244	18.00	218	20.8	3035
Group 3	S9	180	18.00	161	17.41	2635
	S10	190	18.00	170	18.0	2811
	S11	210	19.00	188	18.9	3098
	S12	217	17.00	194	21.5	3116
Group 4	S13	198	17.00	177	18.3	2824
	S14	210	16.50	188	19.2	3082
	S15	232	16.50	207	20.5	3410
	S16	249	17.50	222	21.8	3644
Group 5	S17	183	17.00	163	18.3	2749
	S18	195	18.00	174	19.7	2957
	S19	215	17.00	192	20.6	3222
	S20	225	16.50	201	21.9	3434
Group 6	S21	197	18.00	176	19.3	2924
	S22	212	18.00	189	20.9	3195
	S23	238	18.50	213	22.4	3482
	S24	248	18.50	221	24.3	3736
Group 7	S25	230	10.50	205	33.8	2478
	S26	256	11.00	229	39.2	2816
	S27	300	10.25	268	44.5	3229
	S28	345	12.00	308	50.1	3591
Group 8	S29	255	10.50	228	36.0	2637
	S30	290	9.50	259	41.8	2371
	S31	330	10.50	295	48.4	3437
	S32	365	10.00	326	54.7	3703

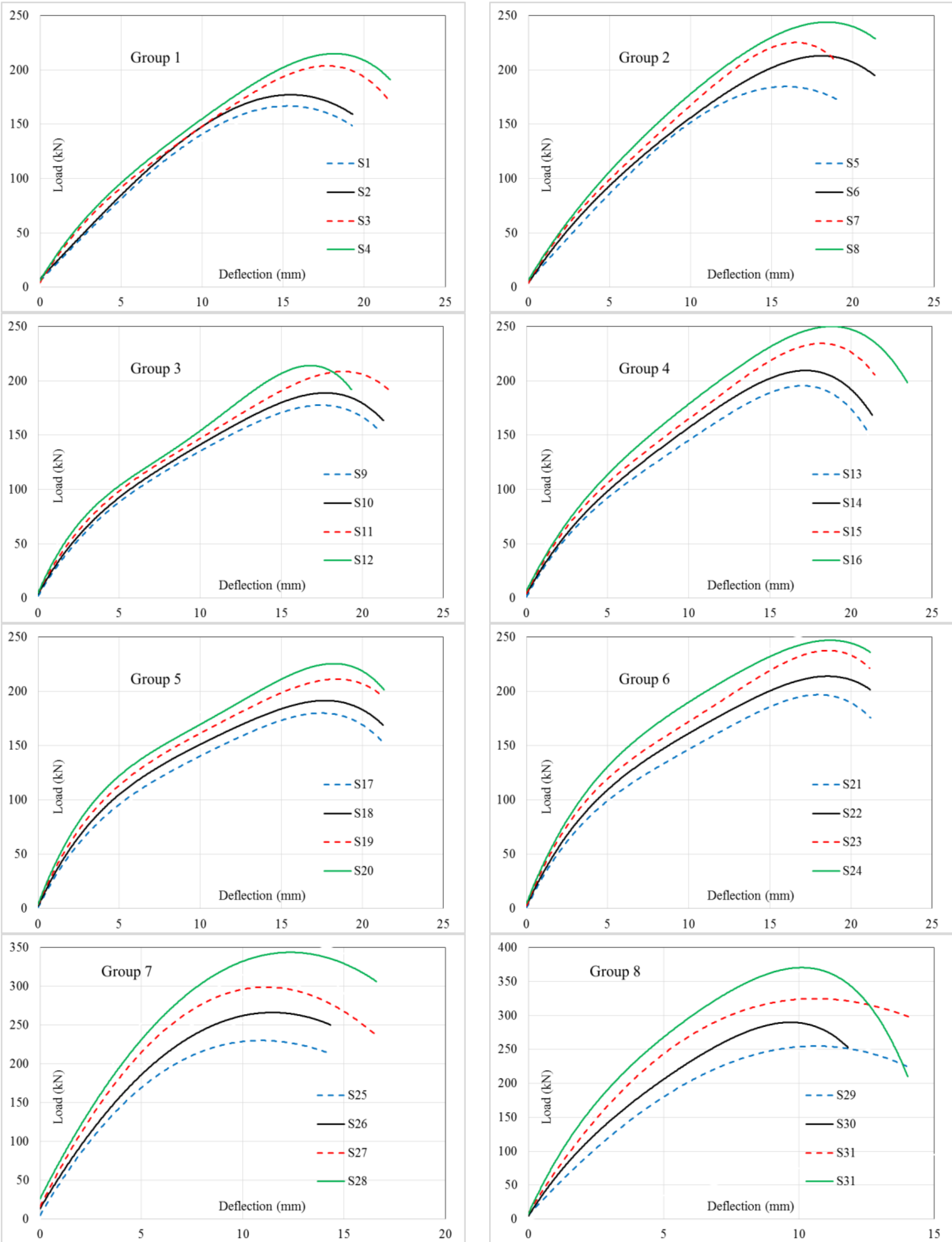


FIGURE 12. LOAD-DEFLECTION CURVES FOR ANALYTICAL MODELS

V. Conclusion

The results of the experimental investigation on the flexural behavior of R.C. slab with opening strengthened by ferrocement laminates were presented. The main findings of this investigation can be summarized as follows:

1. R.C slab with a central cut-out of 5% of the total area exhibits reduction in its flexural strength by about 56%.
2. Influence of ferrocement retrofitting on the flexural behavior of two way R.C. slab with opening is significant and very effective in terms of flexural behavior, ultimate load, and stiffness.
3. The presence of a hole produces earlier cracks at the opening location.

4. Strengthening the slabs by using ferrocement overlay improves the load strength and stiffness of all specimens.
5. The cracking pattern of the vertically loaded specimens indicated a high-stress concentration occurred at the edge of the opening.
6. Increasing mortar grade from 25 MPa to 40 MPa with an increasing number of wire meshes resulted in a significant improvement in the ultimate load and stiffness.
7. Using square wire mesh as reinforcement for the ferrocement overlays instead of expanded wire mesh exhibited a better performance in ultimate load, ductility, strain energy, and stiffness.
8. Applying the ferrocement layer as a sandwich form gives the best results in enhancing the ultimate load although the ductility was decreased.
9. The better roughening surface of the slabs and the bond between the mortar and old concrete surface must be ensured to achieve the suitable strength of the retrofitted slab.
10. The nonlinear numerical analysis based on 3D models created by ANSYS is a sturdy and relatively economical tool which can be successfully used to simulate the real behavior of RC slabs retrofitted by ferrocement overlays.

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