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Behavior of R.C. Deep Beam with Web Openings Strengthened With Ferrocement Overlays

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Abstract: *The main purpose of this study is to investigate the behavior of R.C deep beam with web openings retrofitted by ferrocement laminates. In order to achieve this objective, a total of fifteen simply-supported deep beams were tested under central point load. Three of them kept as reference specimens (un-strengthened specimens) and the remaining twelve beams were externally strengthened by ferrocement overlays with different strengthening schemes such as all sides of the beam and around the opening. The essential parameters that were considered include the number and the type of steel wire meshes, thicknesses of plastering mortar, mortar strength and the opening location (bending and shear zone). The experimental work confirmed that the behavior of R.C. deep beams with openings has been evidently improved by using ferrocement layer as a strengthening technique. It was observed that the ultimate load carrying capacity was reduced by 31% and 16% due to the existence of opening placed at the shear and flexural span respectively. The experimental results indicated that the ultimate failure load, ductility ratio and uncracked stiffness of strengthened specimens with openings in the shear zone were increased by about 85%, 19%, and 65% of the un-retrofitted deep beam with holes.*

Keywords: *Deep Beam, Ferrocement, Strengthening, Openings*.

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I. INTRODUCTION

R.C deep beams usually occur in several structural applications such as transfer girders, tall buildings, and water tanks. Deep beams are defined by the Egyptian code (ECP), and (ACI) [1-2] as the beams whose shear span to an effective depth is 4 or less. The opening of the web in such beams is required frequently to provide availability of mechanical or architectural requirements. The presence of such cut-outs would reduce the strength and the overall stiffness of the beam and it may lead the structure to failure under loads. Using ferrocement overlays as a strengthening technique can overcome this problem. Ferrocement is a layer of the little thickness of mortar hardened with one or more of thin steel wire meshes [3-4]. Ferrocement laminates have many advantages such as lightweight, construction without great effort, and that it can be applied quickly to the surface of the element. Several types of research were investigated to evaluate the behavior of structural elements strengthened with varies strengthening techniques. Islam et al. [5] and Zhang et al. [6] studied the influence of using FRP as externally bonded scheme to improve the behavior of RC deep beams without openings. They were reported that the use of externally bonded FRP system resulted in an increase in shear strength in the range of 40 to 79 %. Hu and Tan [7] studied experimentally the behavior and shear strength of large reinforced-concrete deep beams with web openings. It was observed that the web opening reduced the ultimate strength of a large deep beam significantly. Kumar [8] carried out experimental and numerical studies on the behavior of GFRP strengthened RC deep beam with circular openings. The results demonstrated that the strength gain caused by the GFRP sheets was in the range of 68–125%. Maadawy and Sherif [9], Abduljalil [10] reported that using FRP in retrofitted deep beams with opening gives a high effectiveness in overcoming beam strength. It was observed that the ultimate load capacities of strengthened specimens are increased in the range of 73–118%. Mohamed et al [11] presented an experimental investigation of RC continuous deep beams which contain openings retrofitted with GFRP. Test results concluded that strengthening around openings by GFRP has a significant effect on opening located in the shear region. Hawileh et al [12] studied numerically the effect of using CFRP laminates in strengthening deep beams with web opening. It was reported that the Failure load of the CFRP-strengthened FE models was up to 74% higher than that of the un-retrofitted FE models. Burningham et al [13] carried out an experimental and analytical investigation to study the effectiveness of using post-tensioned CFRP rods in repairing R.C. deep beams. The results indicated that the ultimate load capacity of the repaired beams was upgraded up 128 % compared to the nominal capacity of the control beam. Campione G. et al [14], and Mohamed. et al [15] investigated the effect of location of openings in the shear zone. The main parameters in these studies were the position of cut-outs and arrangement of reinforcement. It can be noted that the influence of the cut-outs depends on its location in the beam. Qeshta et al [16] studied the structural behavior of R.C. beams retrofitted with mesh-epoxy composite as a new strengthening system. Many researchers studied the efficiency of strengthening R.C. shallow beams with ferrocement overlays [17-20]. The results showed that ferrocement is a suitable retrofitting technique to improve beams capacity.

Based on the available data from the current literature review, it was observed that no technical data is available on the viability of using ferrocement overlays as strengthening technique to improve the behavior of RC deep beams with openings. The present study is aimed to evaluate the possible use of this technique as a structural engineering solution to upgrade RC deep beams containing openings. Its purpose is to provide experimental evidence that would aid practicing engineers and researchers to better understand the interrelationship between the opening location and failure mode of RC deep beams strengthened with ferrocement laminates.

II. EXPERIMENTAL PROGRAM

In this study, a laboratory research was performed on fifteen reinforced concrete deep beams. All beams were fabricated and cured with pure water at the laboratory. The experimental program was carried out at the Concrete Research and Material Properties Laboratory of the "Faculty of Engineering, Fayoum University".

MATERIALS PROPERTIES

The materials used in the preparation of tested specimens were obtained from local Egyptian sources that are commonly used in Egyptian construction. Materials include ordinary Portland cement as bonding material, crushed limestone as coarse aggregate, pure sand as fine aggregate and tap water. The average compressive strength of the concrete is 32 MPa at 28-day. Two types of mortar mix were considered to get a different cubic compressive strength. Targeted mortar grade for Type (1) and Type (2) was 30 MPa and 40 MPa respectively. Table 1 shows the composition of mortar mixes. For the determination of mortar grade, twelve stranded cubes (70x70x70 mm) were cast and tested. The compressive strength of mortar for Type (1) and Type (2) is given in Table 2. Two types of steel reinforcement were used. The first type with grade (28/45) was used with Ø 8 mm diameter as horizontal and vertical stirrups, where the second one was high-yield strength deformed bars with grade (40/60) used with Φ12 mm and Φ 16 mm diameter as top and main bottom reinforcement respectively. In this experimental investigation, two types of steel wire mesh fabric were used. The First type was expanded wire mesh with dimensions (thickness = 0.7 mm, width= 1.15 mm, angle of inclination = 65.7o and wire spacing 15x30 mm). The second type was galvanized steel wire mesh-fabric of the woven form with square opening 20 mm square grid and 0.6 mm diameter. Modulus of elasticity for both square and expanded wire mesh are 138000 MPa and 85000 MPa respectively.

TABLE 1: PROPORTIONS MORTAR MATRIX BY RATIO

Mix type	Sand/Cement	Water /Cement	Silika fume	Superplasticizer	Sika bond
Type (1)	2	0.4	------	------	-------
Type (2)	2	0.4	15% of cement	0.15% of cement	0.15% of cement

TABLE 2: MORTAR CUBES COMPRESSIVE STRENGTH

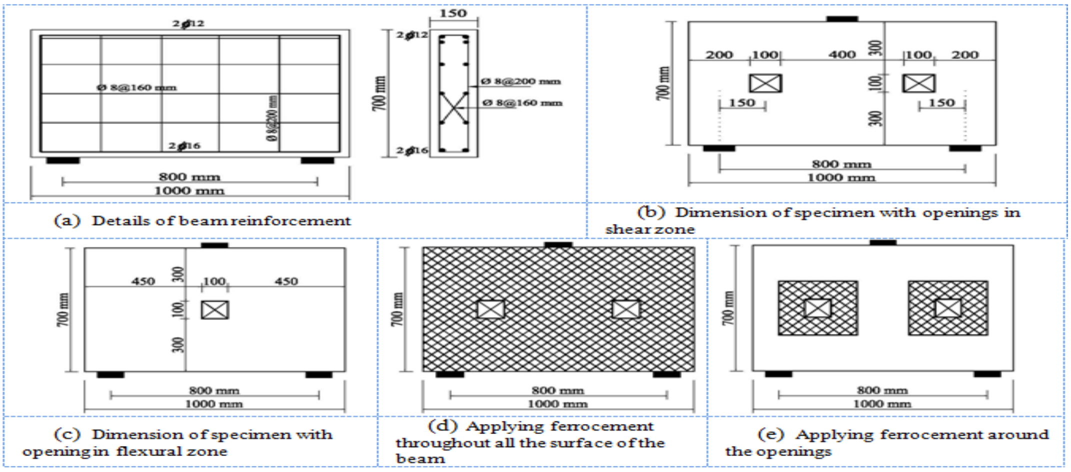
cube		1	2	3	4	5	6	average
Mortar grade (MPa)	Type (1)	31.7	30.9	32.5	30.6	31.1	30.5	31.2
	Type (2)	40.2	41.5	42.4	43.1	40.7	41.2	41.5

III. TEST SPECIMENS

Through this experimental program, fifteen RC deep beams were prepared and tested for this investigation. Three beams with and without openings were considered as control specimens, where the remaining twelve with cut-outs were retrofitted with ferrocement overlays. Dimensions of all specimens were 1000 mm length with 800 mm effective length, 150 mm width and the overall height was 700 mm. A clear cover of 15 mm was preserved at the top and bottom of the beam whereas a clear cover of 10 mm was preserved on the beam's vertical sides. The experimental program consisted of two groups. The first series consisted of eleven RC beams with two square openings of dimensions 100*100 mm, one in each shear region and were placed symmetrically about the mid-point of the beam. The second group contained three specimens of one opening (100*100 mm) in the middle of the beam. No additional reinforcement was used around the openings to simulate the sawn-up situation. Thorough laboratory program ten specimens were strengthened by applying the ferrocement overlays throughout the surface of the beam whereas two specimens were externally strengthened by wrapping the ferrocement around the opening and extended 100 mm or 150 mm beyond the cut-out. Many parameters were considered throughout this study as follows; the thickness of ferrocement layer, number and type of wire meshes, the compressive strength of mortar, location of the openings, and strengthening schemes as listed in Table 3. Fig. 1 shows the dimensions, reinforcement detailing, and strengthening schemes of the test specimens.

IV. STRENGTHENING PROCEDURE

The application procedure of ferrocement laminates was performed in consecutive steps. Roughening and cleaning the surface of the beam, then fixing the steel wire mesh by bolts. A bonding material is applying on the beam sides to give high adhesion between the mortar layer and old concrete. Finally applied the mortar layer with a desired thickness. Fig. 2 shows the application procedure of ferrocement laminates.



(a) Details of beam reinforcement

(b) Dimension of specimen with openings in shear zone

(c) Dimension of specimen with opening in flexural zone

(d) Applying ferrocement throughout all the surface of the beam

(e) Applying ferrocement around the openings

FIG. 1 DIMENSIONS, REINFORCEMENT DETAILS, AND STRENGTHENING SCHEMES OF THE TEST SPECIMENS.

Roughing the surface of the specimen

Fixing the steel wire-mesh by steel bolts

Plastering of bonding material

Surface treatment of mortar after application

FIG. 2 STRENGTHENING PROCEDURE

V. TEST SETUP

A total of fifteen R.C. deep beam specimens with identical dimension and reinforcement were constructed. The supports were placed at 100 mm from each end of the beam. Then the effective span became 800 mm. The beams were examined as simply supported beams under single loading point until failure. Reaction frame (Loading Frame) was used in the test program to apply the vertical load to the beam through a hydraulic jack of 1000 kN capacity. The load was transmitted through a load cell and circular steel stub directly at the center of the beam. One LVDT linked to the data acquisition system was placed on the tension side of the beam to estimate corresponding deflections. The stroke of LVDT used in the test was +/- 100 mm with 0.1 sensitively. Fig 3 shows a photo of the experimental setup.

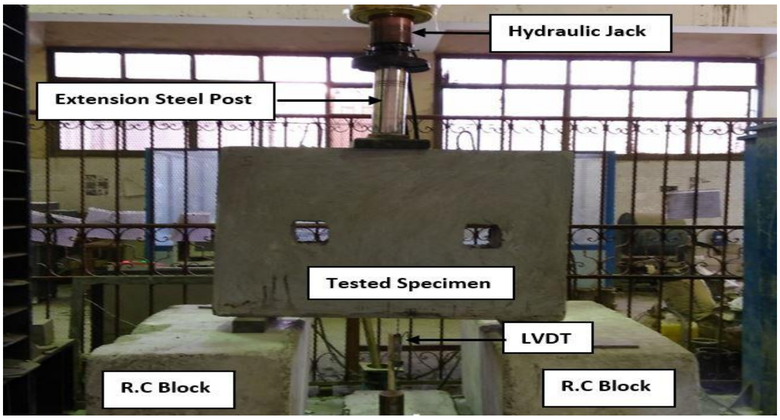


FIG. 3 TEST SETUP

TABLE 3: SPECIMENS PROPERTIES

Specimen	Opening location	No. of Opening	strengthening scheme	Mesh Type	No. of wire meshes	Ferrocement thick. (mm)	Mortar grade (MPa)
B0	Without opening	-------	-------	-------	-------	-------	-------
B1	150 mm near support	2	-------	-------	-------	-------	-------
B2	Middle of Span	1	-------	-------	-------	-------	-------
B3	150 mm near support	2	Wrapping ferrocement throughout the surface of the beam	Expanded	2	20	40
B4	150 mm near support	2		Expanded	3	20	40
B5	150 mm near support	2		square	2	20	40
B6	150 mm near support	2		square	3	20	40
B7	150 mm near support	2		Expanded	2	30	40
B8	150 mm near support	2		square	2	30	40
B9	150 mm near support	2		Expanded	2	20	30
B10	150 mm near support	2		Expanded	2	30	30
B11	Middle of Span	1		Expanded	2	30	40
B12	Middle of Span	1		square	2	30	40
B13	150 mm near support	2	Extend 100 mm around the opening	Expanded	3	20	20
B14	150 mm near support	2	Extend 150 mm around the opening	Expanded	3	20	20

VI. EXPERIMENTAL RESULTS AND DISCUSSION

CRACKING PATTERN AND MODE OF FAILURE

Two failure modes have been noticed in the experimental program [7, 9, 10, 15, and 21]. The first mode is a typical shear failure by diagonal cracks appeared through the loading point to supports. This mode of failure was observed at R.C deep beams with or without a hole at the flexural zone. The second mode was observed at R.C deep beams containing openings at the shear region. This was observed through a sudden collapse owing to diagonal cracking along the two critical paths which link the loading point to the support with the furthest corners of the hole. Fig 4 shows, photographically, crack patterns for all tested specimens. From the photos, it can be seen that the cracks started at the corners of the opening. These cracks propagated toward the support and loading points. New diagonal cracks were established with growing wide and extension of the existing cracks simultaneously with increasing the applied load. Moreover, in some cases, it was observed that crushing and spallation of the concrete at load and reaction point zones appeared due to bearing stresses or anchorage failure at end supports. The concrete cracks emerged and gradually increased approaching failure load. Rupture of the ferrocement laminate is supposed to occur if the strain in the ferrocement reaches its design rupture strain before the concrete reaches its maximum usable strain.

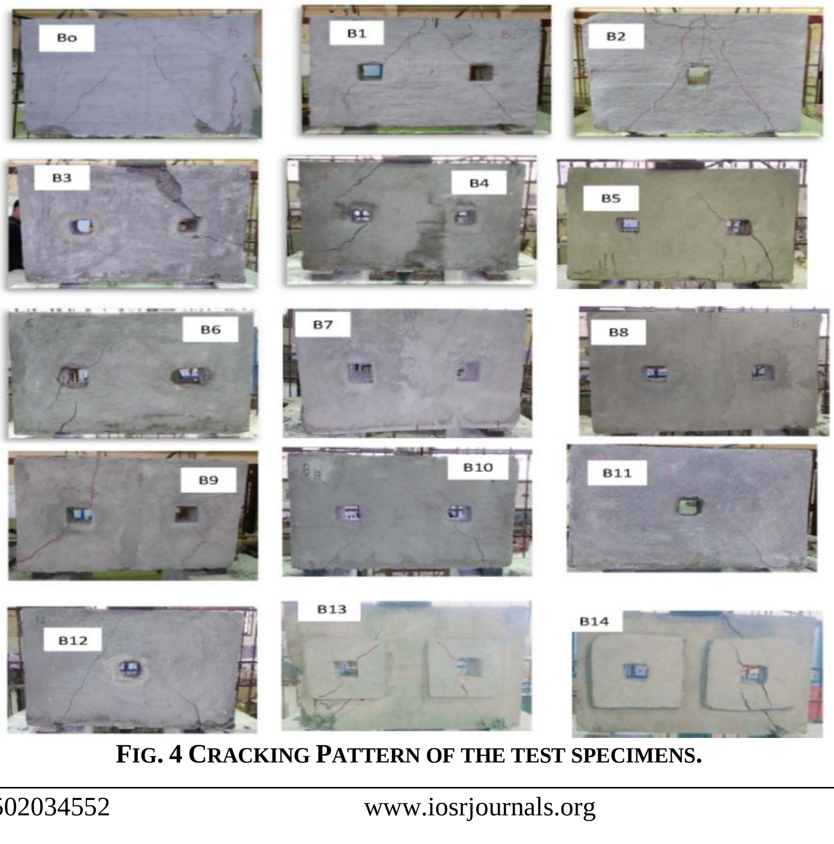


FIG. 4 CRACKING PATTERN OF THE TEST SPECIMENS.

LOAD- DEFLECTION CURVE

Fig. 5 shows load vs. mid-span deflection curves for the test specimens to investigate the efficiency of using ferrocement laminates as a strengthening method. It can be shown that the trend of the curves for samples displays an initial linear stage and later gradually non-linear behavior occurs due to cracks. The structural performance of R.C. deep beams including a hole depends mainly on the presence and position of the hole on the degree of the interruption of the natural load path. Specimen B1 shows lower stiffness, nearly similar to the ultimate deflection of specimen B2 but with a lower ultimate load. Comparing the results of strengthening specimens, it appeared that using ferrocement wrapping significantly enhanced the shear response of R.C. deep beam with openings. Increasing the volume fraction of reinforcement led to an increase in the ultimate load and a decrease in the deflection. Furthermore, using expanded wire mesh as ferrocement reinforcement shows a more effective than that of square wire mesh with the same volumetric ratio. The results indicated that wrapping the ferrocement at 100 mm extend around the opening is effective and practical than that of wrapping all the surfaces of the beam.

ULTIMATE LOAD CAPACITY

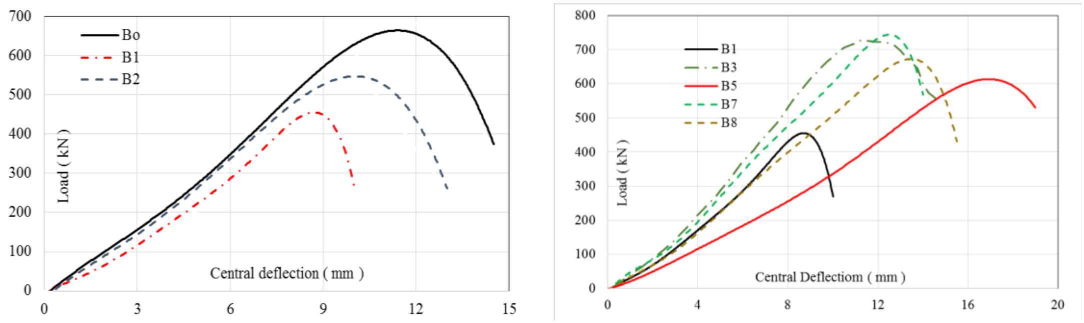
Table 4 gives a summary of the experimental results for the test specimens. The presented data showed that, the control specimens with holes (B1 and B2) had the lowest ultimate load (460 and 560 kN) respectively. The presence of openings of beams B1 and B2 cause a decrease in the ultimate load by 31 % and 16 % respectively compared with the control beam without opening (Bo). It can be seen that the existence of cut-outs particularly in the shear region produces earlier cracks at openings and decreases first crack load, yield load, and ultimate load. In some cases, the shear capacity for strengthened beams with openings transcends the beam original ultimate load. The results indicated that wrapped R.C. deep beams with a hole by ferrocement layer lead to a significant improvement in the ultimate strength by 41 %. The ultimate load capacity and the first crack load were improved in the beam (B3) having mortar grade Type (2) by 30 %, and 25% respectively more than that of the beam (B9) having mortar grade Type (1). It was observed that the first cracks appear at loads about 70% of the ultimate load capacities. The first crack load, yield load, and ultimate load carrying capacity of strengthened deep beams were increased by 65%, 73%, and 85% respectively compared to that of the un-retrofitted with a hole near support.

DUCTILITY INDEX, ENERGY ABSORPTION AND INITIAL STIFFNESS

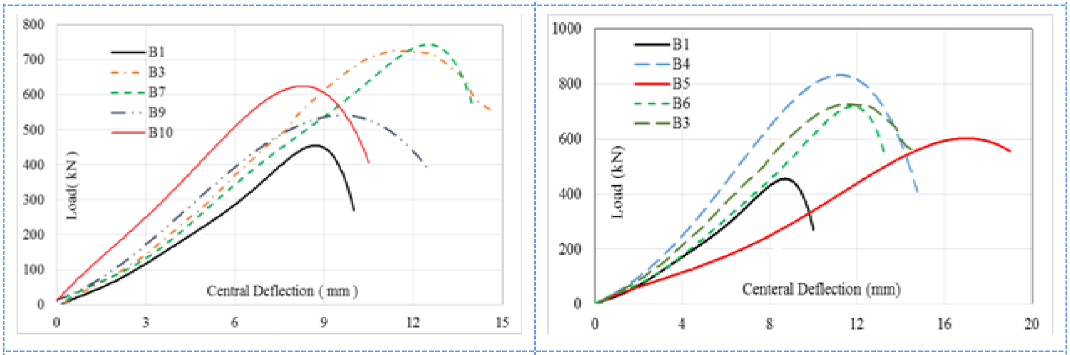
From the experimental results, ductility ratio, initial stiffness, and energy dissipation were calculated and reported in Table 5. From the obtained data, it can be realized that initial stiffness, ductility, and energy absorption increased by increasing the wire mesh layers and the mortar strength with respect to the thickness of ferrocement layer. The improvement in the mechanical behavior of strengthened R.C. deep beams was affected by the volumetric ratio. It can be indicated that ductility ratio, initial stiffness, and energy dissipation were improved in the specimen (B3) having mortar strength 40 MPa by 30%, 18%, and 50% respectively more than that of the specimen (B9) having mortar strength 30 MPa. It appears that the relatively high strength plastering mortar type had a significant influence on improving the mechanical characteristics of strengthening beam. It was observed that the average of ductility ratio, initial stiffness, and energy dissipation were measured as 3.7%, 25%, and 133% of the un-strengthened specimen (B1).

TABLE 4: SUMMERY OF TEST RESULTS

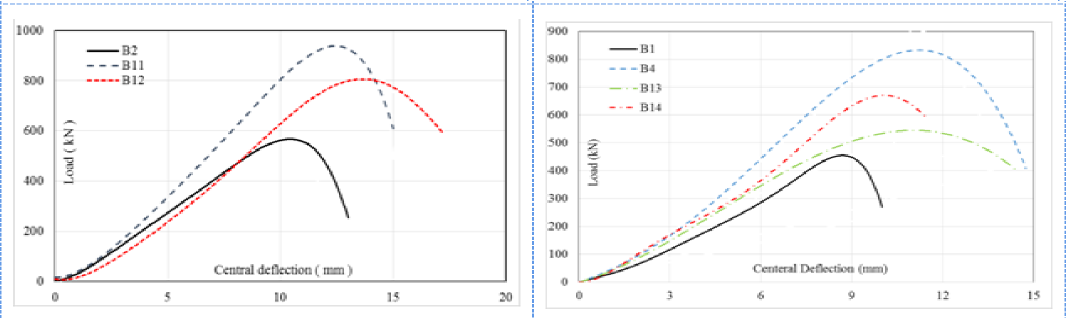
Specimen	First Crack		Yield		Ultimate		$\frac{P_u}{P_u(Bo)}$
	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	
Bo	514	8.25	533	8.5	670	11.75	1.00
B1	340	7	407	8	460	9.25	0.69
B2	387	6.25	510	8.75	560	9.75	0.84
B3	564	8.25	622	9	728	11	1.09
B4	520	7.5	705	8.75	850	11.25	1.27
B5	390	11.5	507	13.5	624	16	0.93
B6	530	9	667	10.75	740	12	1.10
B7	512	8.5	564	9.25	752	12.75	1.12
B8	334	7	593	11.75	679	14.25	1.01
B9	465	7	537	8.25	550	8.5	0.82
B10	397	4.75	548	6.5	658	7.75	0.98
B11	573	9.25	790	9.75	944	13	1.41
B12	600	9.75	689	11	822	14.25	1.23
B13	403	6.5	444	8	578	11.5	0.86
B14	495	7.5	584	8.5	685	11.0	1.02



(a) The effect of the opening location (b) The effect of the thickness of ferrocement



(c) The effect of the mortar strength (d) The effect of types and number of wire mesh.



(e) The effect of strengthening opening at flexural zone. (f) The effect of strengthening schemes

FIG. 5 LOAD – CENTRAL DEFLECTION CURVES FOR THE TEST SPECIMENS

TABLE 5: DUCTILITY RATIO, INITIAL STIFFNESS, AND ENERGY ABSORPTION FOR TESTED SPECIMENS

Specimen	Load (kN)		Deflection (mm)		Ductility Ratio	Initial Stiffness (kN/mm)	Energy Dissipation Capacity (kN-mm)
	At Yield	At Ultimate	At Yield	At Ultimate			
Bo	533	670	8.5	11.75	1.38	63	5626
B1	407	460	8	9.25	1.16	51	2318
B2	510	560	8.75	9.75	1.11	58	4009
B3	622	728	9	11	1.22	69	6363
B4	705	850	8.75	11.25	1.29	81	6431
B5	507	624	13.5	16	1.19	38	6180
B6	667	740	10.75	12	1.12	62	4809
B7	564	752	9.25	12.75	1.38	61	5550
B8	593	679	11.75	14.25	1.21	50	5632
B9	537	550	8.25	8.5	1.03	65	4250
B10	548	658	6.5	7.75	1.19	84	4090
B11	790	944	9.75	13	1.33	81	7903
B12	689	822	11	14.25	1.30	63	8794
B13	444	578	8	11.5	1.43	56	4461
B14	584	685	8.5	11.0	1.29	68	4081

VII. CONCLUSION

In this research, fifteen deep beam samples (with and without web opening) were fabricated and tested until failure. The following general conclusions can be derived based on the experimental results.

1. The presence of opening at shear region produces earlier cracks, and failure compared to similar beam without opening. Structural response of the beam is not influenced by the cut-out at mid-span section.
2. A hole placed at near supports interrupts the load path from loading point to the support thus it decreases the capacity of the beam and first crack load. So it is preferable to locate it at any point away from the loading path.
3. The existence of opening at shear zone decreases the first load by 34%, the ultimate load by 31%, the initial stiffness by 19%, and the ductility ratio by 16% and the strain energy by 59 % compared with the solid deep beam.
4. Wrapped R.C. deep beam with openings by ferrocement overlays lead to an enhancement in the capacity of the beam in the first crack load and the ultimate load and improve the ductility of the strengthened deep beam. It was observed that the first crack load, yield load, and ultimate load carrying capacity of strengthened deep beams were increased by 65%, 73%, and 85% respectively compared to the un-retrofitted with a hole near support.
5. The pronounced enhancements of the R.C. deep beams including openings mechanical characteristics ensure the efficiency of the rehabilitation of beams using ferrocement techniques. It was observed that the average of ductility ratio, initial stiffness, and energy dissipation were measured as 3.7%, 25%, and 133% of the un-strengthened specimen (B1).
6. Strengthening RC deep beam with web opening at middle of span (flexural zone) by ferrocement laminate lead to improve the first crack load and ultimate load capacity by 55% and 69% respectively compared to the unstrengthened beam with opening (B2). The ultimate strength of retrofitted specimen is 41% higher than that of control specimen without opening (Bo).
7. All retrofitted beams have a higher peak load and initial shear crack than the control specimen with a hole.
8. The effect of the number of wire mesh and the mortar strength is essentially important to increase the first crack load, the ultimate load, and to develop the enhanced beam characteristics. The experimental results indicated that the ultimate failure load of the test specimen (B4) with three layers of wire mesh and having mortar grade 40 MPa were 41% and 52% higher than that of un-retrofitted control specimens (Bo and B1) respectively.
9. The test results indicated that wrapping the ferrocement around the opening is more practical and economical than that of applying ferrocement over all the surfaces of the beam. The ultimate failure loads of the test specimen (B14) which applying wrapping the ferrocement at 150 mm around the opening was were 49% higher than that of un-strengthened beam with cut-out.

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