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Structural Behavior of Concrete Beams with Openings Reinforced with Innovative Composite Materials

Y. B. I. Shaheen, A. A. El Sayed

Abstract-This research aims at developing structural behavior of Ferro-cement beams with openings. To accomplish this objective, an extensive experimental program was conducted. In addition theoretical mathematical models were investigated. The experimental program comprised casting and testing of fourteen reinforced concrete beams of dimensions 200x100x2000mm.These beams are organized in six groups, Group number one is the control group in which beams are cast using conventional reinforcement where beam B1 was reinforced with two steel bars Φ12mm at the bottom and two steel bars Φ10mm at top. Number of steel stirrups 16 Φ 8mm. Beam B2 is the same as B1 but with the addition of polypropylene fibers to the concrete matrix. Group two consists of casting three beams namely B3, B4 and B5. Beam B3 was reinforced as B2 but with two openings of dimensions 10x20 cm located at equal distances from the end of the beam. Beams B4 and B5 were reinforced with two steel bars Φ 12mm at the bottom and two steel bars Φ10mm at the top with two and four layers welded steel meshes respectively. Group three comprises of casting and testing two beams B6 and B7 with two openings 10x20cm located at equal distances from the ends of beam and reinforced with one and two layers of expanded steel meshes respectively. Group four consists of casting and testing beams B8 and B9 which reinforced with one and two layers of fiber glass mesh for durability reason respectively. Group five consists of beams B10 and B11 having three openings and reinforced with four layers welded steel meshes and two layers expanded steel meshes respectively. Group six comprises beams B12, B13 and B14 with three openings and reinforced with four layers welded steel meshes, two layers expanded steel meshes and three layers welded steel meshes respectively. The test specimens were tested as simple beams under four line loadings on a span of 180cm. The performance of the test beams interms of strength, stiffness, cracking behavior, ductility, and energy absorption properties was investigated. The behavior of the developed beams was compared to that of the control beams. Two analytical models were modified and used to suit the developed composite beams one to predict the first crack load based on the well-known principles of strength of materials, and the other one to determine the ultimate strength and mode of failure based on the ultimate strength theory. The experimental results showed that high ultimate and serviceability loads, better crack resistance control, high ductility, and good energy absorption properties could be achieved by using the proposed beams. Comparison between the experimental results and the results obtained from the theoretical model showed that there is a close agreement for all beams. This agreement verified the validity of this model.

Keywords: Ferro-cement; Beams with openings; Experimental program; Structural behavior; Analytical model.

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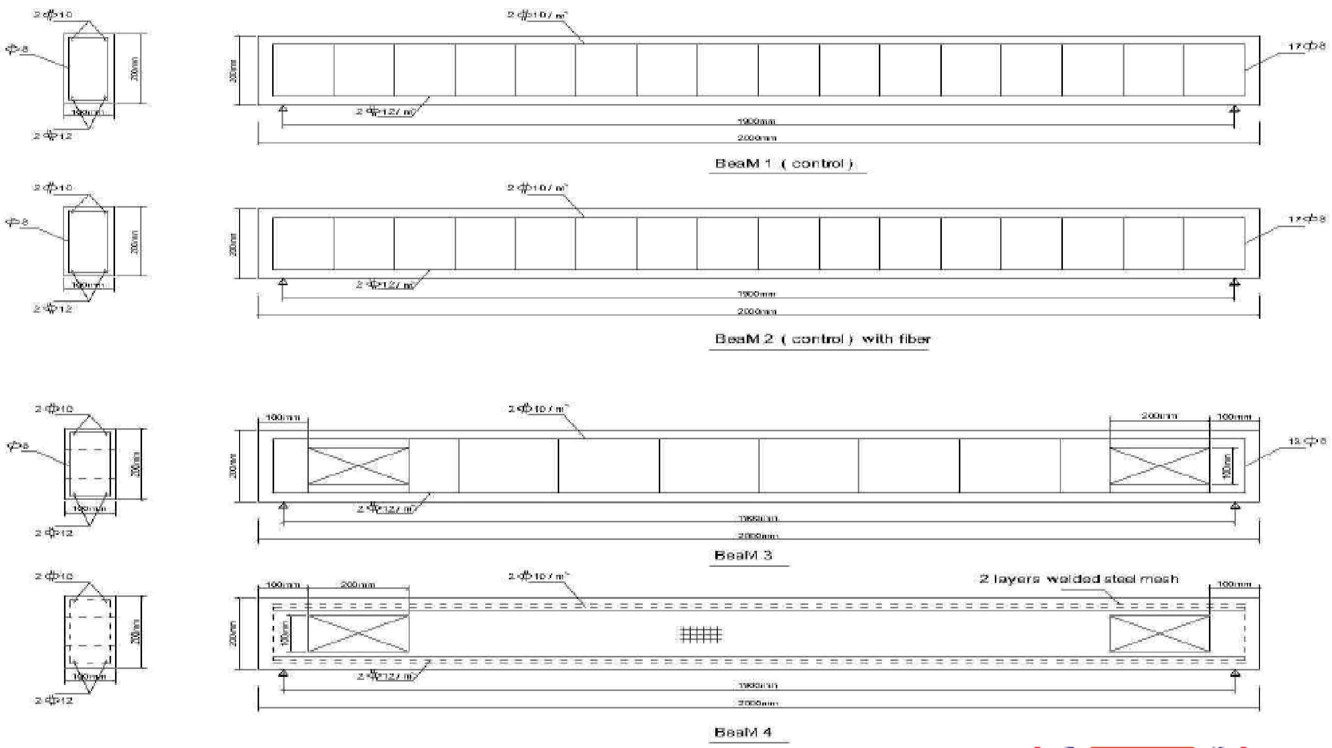
I. INTRODUCTION

Building and housing sector in both developed and developing countries are one of the most dynamic sectors. It consumes a large portion of the national resources, affects other commercial and industrial sectors and reflects the social and economic class of nations. Construction sector is a labor intensive sector, in Egypt ninety two careers and professionals depend on this vital section; moreover, 1.6 million workers are working in this sector in a regular bases which constitutes 8.3% of the total formal working force, rather than indirect employment and feeding industries related to this sector. Therefore, the need for safe, economic and sound construction techniques has increased in the past few decades to support both social and economic development. Hence novel approaches, new materials, and innovative construction methods are vital to ensure the sustainable development (Mehlab 2005). Recently, ferrocement has emerged as new construction material. ACI defines ferrocement as follows: "Ferrocement is a type of reinforced concrete commonly constructed of hydraulic cement mortar reinforced with closely spaced layers of relatively small wire diameter mesh. The mesh may be made of metallic or other suitable materials. The fineness of the mortar matrix and its composition should be compatible with the opening and tightness of the reinforcing system it is meant to encapsulate. The matrix may contain discontinuous fibers." Ferrocement differs from conventional reinforced concrete in that it consists of closely spaced, single or multiple layers of mesh or fine reinforcing bars completely impregnated with cement mortar. The result is a thin walled composite material with a much higher volume fraction of steel than conventional reinforced concrete. The mechanical characteristics displayed approximate that of a homogeneous material and are different to conventional concrete in terms of strength and deformation. The effect is not unlike that achieved with fiber glass reinforced resins. Walls are usually much thinner than conventional reinforced concrete and the maximum cover on the reinforcing is as little as 5mm with 2mm being the average recommended cover (ACI Manual of Concrete Practice 1998). The development of ferrocement technology began in the 1840s with J.L. Lambot who constructed a rowing boat using a composite of wires and cement. At the same time others were developing conventional reinforced concrete. Further development of ferrocement did not occur until the early 1940s when Pier Luigi Nervi resurrected the original ferrocement concept.

The development of ferrocement technology has primarily been done in the boat building industry although (ACI Manual of Concrete Practice 1998). Since the early introduction of ferrocement, the applications of the new emerging material increased to include manufacturing of structural elements such as walls, beams, slabs, and roofing systems and as repair material for different concrete elements. The applications of the ferrocement could now be found in many places all over the world. For example, prefabricated ferrocement wall panels have been used for low cost housing in Malaysia, mosque domes constructed with ferrocement are found in Indonesia and Jordan, unique and beautiful buildings with this technology are found in India, Cuba, and Bangladesh. In Malaysia, there are two companies that construct ferrocement boats. Ferrocement is a construction material that proved to have superior qualities of crack control, impact resistance, and toughness, largely due to the close spacing and uniform dispersion of reinforcement within the material. One of the main advantages of ferrocement is that it can be constructed with a wide spectrum of qualities, properties, and cost, according to customer's demand and budget. Recently, ferrocement has received attention as a potential building material, especially for roofing of housing construction (National Academy of Sciences 1973). Fahmy et al (1999 and 2008) and others have conducted many investigations and reported the physical and mechanical properties of this material and made available numerous test data to define its performance criteria for construction and repair of structural elements. ferrocement has successfully been used for many other applications such as roof systems and silos

II. EXPERIMENTAL PROGRAM

The experimental program comprised casting and testing of fourteen reinforced concrete beams of dimensions 200x100x2000mm.These beams are organized in six groups, Group number one is the control group in which beams are cast using conventional reinforcement where beam B1 was reinforced with two steel bars Φ12mm at the bottom and two steel bars Φ10mm at top. Number of steel stirrups 16 Φ 8mm. Beam B2 is the same as B1 but with the addition of polypropylene fibers to the concrete matrix. Group two consists of casting three beams namely B3, B4 and B5. Beam B3 was reinforced as B2 but with two openings of dimensions 10x20 cm located at equal distances from the end of the beam. Beams B4 and B5 were reinforced with two steel bars Φ 12mm at the bottom and two steel bars Φ10mm at the top with two and four layers welded steel meshes respectively. Group three comprises of casting and testing two beams B6 and B7 with two openings 10x20cm located at equal distances from the ends of beam and reinforced with one and two layers of expanded steel meshes respectively. Group four consists of casting and testing beams B8 and B9 which reinforced with one and two layers of fiber glass mesh for durability reason respectively. Group five consists of beams B10 and B11 having three openings and reinforced with four layers welded steel meshes and two layers expanded steel meshes respectively. Group six comprises beams B12, B13 and B14 with three openings and reinforced with four layers welded steel meshes, two layers expanded steel meshes and three layers welded steel meshes respectively. The test specimens were tested as simple beams under four line loadings on a span of 180cm, as shown in figure1. The performance of the test beams in terms of strength, stiffness, cracking behavior, ductility, and energy absorption properties was investigated.



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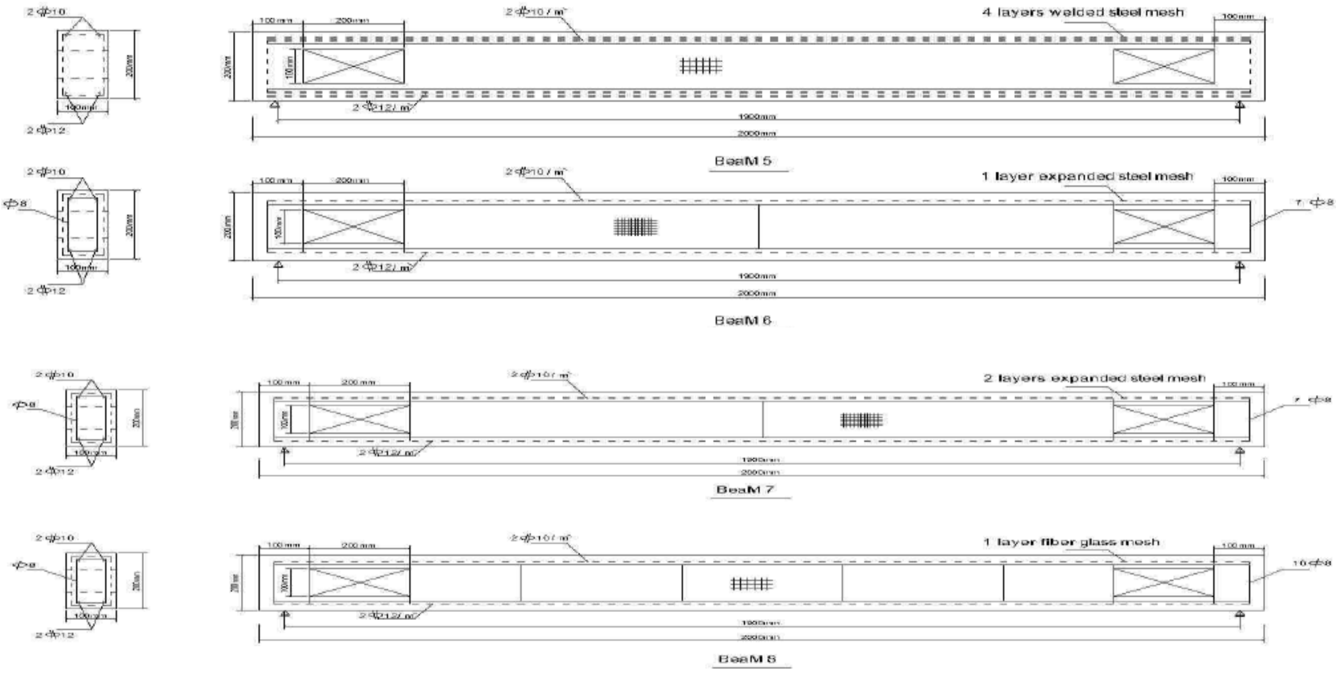

Figure1: Details of reinforcing materials of all tested beams

III. MATERIALS

A. **Cement** used was the Ordinary Portland cement, type produced by the Suez cement factory. Its chemical and physical characteristics satisfied the Egyptian Standard Specification (E.S.S. 4756-1/2009) [19].

B. **Fine aggregate** used in the experimental program was natural siliceous sand. Its characteristics satisfy the (E.C.P. 203/2007) [17], (E.S.S. 1109/2008) [17]. It was clean and nearly free from impurities with a specific gravity 2.6 t/m^3 and a modulus of fineness 2.7.

C. **Super Plasticizer** used was a high rang water reducer HRWR. It was used to improve the workability of the mix. The admixture used was produced by Sika Group under the commercial name of ASTM (Sikaviscocrete), It meets the requirements of ASTM C494 (type A and F) [20]. The admixture is a brown liquid having a density of 1.18 kg/litre at room temperature. The amount of HRWR was 1.0 % of the cement weight.

D. **Water** was used, clean drinking fresh water free from impurities was used for mixing and curing the tested plates according to the Egyptian Code of Practices (E.C.P. 203/2007)[17].

E. **Reinforcing Materials**

A) Reinforcing Steel Bars

1. **High tensile deformed steel bars** produced from the Ezz Al Dekhila Steel - Alexandria was employed. Its chemical and physical characteristics satisfy the Egyptian Standard Specification (E.S.S. 262/2011) [21]. High tensile deformed steel bars of (nominal diameter 10 mm) were used in reinforcing all the concrete beams, yield stress was determined as 400 MPa and its tensile strength was 600 MPa.
2. **Mild steel bars** of 8 mm diameter were used in the short direction of plate. Its yield strength and its tensile strength were 240 MPa and 350 MPa respectively.

B) Reinforcing Meshes

1) Expanded Metal Mesh: Expanded metal mesh was used as reinforcement for ferrocement plates. Its chemical and physical characteristics satisfy the Egyptian Standard Specification (E.S.S. 262/2011) [23]. Table (1) shows the technical specifications, mechanical properties and photo of expanded metal mesh.

2) Welded Metal Mesh: Galvanized welded metal mesh employed which obtained from China. Its chemical and physical characteristics satisfy the Egyptian Standard Specification (E.S.S. 262/2011). Table (2) shows the technical specifications, mechanical properties and photo of welded metal mesh.

3) Polyethylene meshes: Two types of Polyethylene meshes were used, which obtained from Al Shrouk Company of synthetic fibers namely CE121 and CE131. These types of meshes are made from high density polyethylene. "Geogrid" were used. Tables (3, 4) show the properties and photos of these meshes.

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Table (1): Technical Specifications and Mechanical Properties of Expanded Metal Mesh.

Style	1532	
Sheet Size	1 × 10 m	
Weight (Kg/m^2)	1.3	
Diamond size (mm)	16 x 31	
Dimensions of strand (mm)	1.25 x1.5	
Proof Stress (N/mm^2)	199	
Proof Strain × 10^{-3}	9.7	
Ultimate Strength (N/mm^2)	320	
Ultimate Strain× 10^{-3}	59.2	

Table (2): Technical Specifications and Mechanical Properties of Welded Metal Mesh.

Dimensions (mm)	12.5 × 12.5	 
Weight (gm. /m^2)	430	
Proof Stress (N/mm^2)	400	
Ultimate Strength (N/mm^2)	600	
Ultimate Strain × 10^{-3} (mm)	1.25 × 1.5	
Proof Strain × 10^{-3}	1.17	

Table (3) Technical Specification of Polyethylene Mesh CE121 Polyethylene

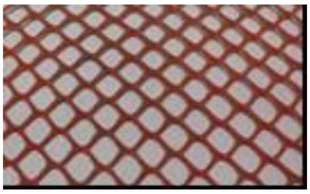
Size of opening	12x12 mm	
Thickness	3 mm	
Weight	529 g/m^2	
Tensile Strength	24.7 MPa	
Elongation in Longitudinal Direction	21%	

Table (4) Chemical and physical properties of polypropylene fibers

Absorption	Nil	
Specific gravity	0.91	
Fiber length	Single cut lengths	
Electrical conductivity	Low	
Acid & salt resistance	High	

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IV. MORTAR MATRIX

The concrete mortar used for casting plates was designed to get an ultimate compressive strength at 28-days age of (350 kg/cm^2), 35 MPa. The mix properties for mortar matrix were chosen based on the (ACI committee 549 report: 2008), and Egyptian Code Practices (E.C.P. 203/2007) [17], For all mixes, mechanical mixer in the laboratory used mechanical mixing with capacity of $0.05m^3$, where the volume of the mixed materials was found to be within this range. The constituent materials were first dry mixed; the mix water was added and the whole patch was re-mixed again in the mixer. The mechanical compaction was applied for all specimens. Mix properties by weight for the different groups are given below in Table (5).

Table (5): Constituents of Mortar

Cement	Sand /Cement	W/C	S.P./C
1	2	0.35	1%

V. SILICA FUME

Silica fume is also known as micro silica, volatilized silica, or condensed silica fume. It is a by-product from silicon metal and ferrosilicon alloy production. The material is a very fine powder with spherical particles about 100 times smaller in size than Portland cement or fly ash. The diameters range from 0.02 to 0.5 μm with an average of 0.1 μm. Silica fume contains 85 to 95% non crystalline silicon dioxide.

The first application of silica fume in the United States was conducted in Kentucky in 1982. The use of silica fume will make concrete with the following properties [20]:

- Low heat of hydration, and reduced permeability.
- Retarded alkali-aggregate reaction, and reduced freeze-thaw damage and water erosion,
- High strength, and increased sulfate resistance,.

The chemical analysis and physical properties of Silica fume shown in Table (6).

Table (6) Chemical Analysis and Physical Properties of the Silica Fume

Analysis and properties	Mass %
SiO_2	90.2
$Al2O_3$	1.7
$Fe2O_3$	0.4
CaO	2.1
MgO	1.7
Na2O	0.7
K2O	0.7
SO_3	0.5
Loss on ignition (LOI)	2.5
Specific Surface Area (cm^2/g)	200000
Specific gravity	2.21

VI. BEHAVIOR OF FERROCEMENT BEAMS

As described beams were tested under three line loadings and the deflection at each load increment was recorded at the mid span. The load deflection curves for all the tested beams were shown. The first crack initiation and propagation was also observed for each specimen. The effect of the parameters under investigation on the ultimate moment, maximum deflection at ultimate load, ductility ratio, energy absorption, and cracking behavior are discussed in the following sections**.** The experimental results of the test program and the discussions are presented. Comparisons are conducted between the results of the different test groups to examine the effect of the four parameters under investigation; existence of openings, type of reinforcing materials, numbers of layers of mesh reinforcement and volume fraction of provided steel reinforcement. The effects of these parameters on the structural response of the developed beams in terms of the strengths at first crack load, serviceability loads and their respective ultimate loads were determined. Ductility ratio, energy absorptions properties were determined. Cracking patterns of all the tested beams were detected. The results of all test specimens are listed in Table 7.

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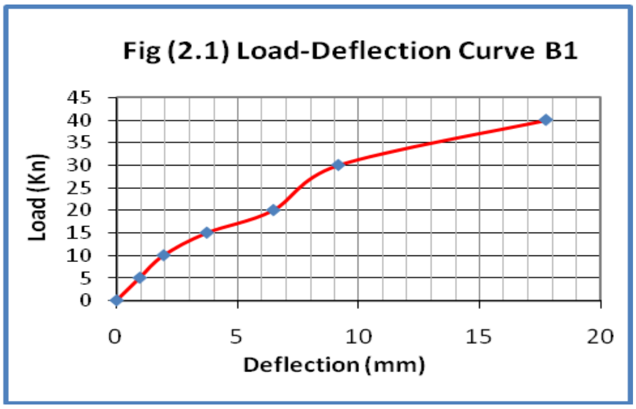
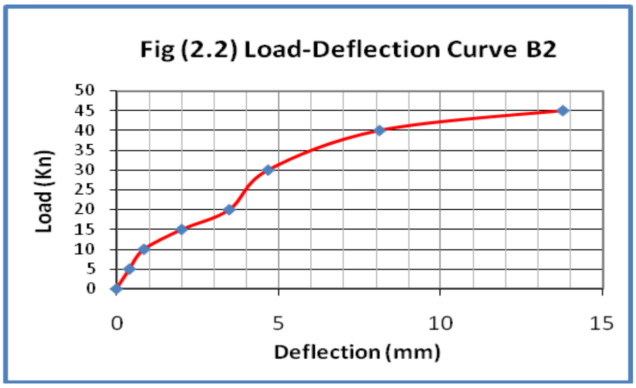
Table (7) First crack, serviceability, ultimate loads, ductility ratios and energy absorption properties of all the tested beams.

Series No.	Beam No.	Volume Fraction%	F.C.,KN	P.serv, KN.	P.ult, KN.	def.F.C., mm	max.def, mm	duct.ratio	Energy.abs, KN.mm
1	control B1	3.197	10	24.216	40	1.94	17.72	9.134021	447.125
	control B2	3.292	15	38.49	45	2.01	13.78	6.855721	435.55
2	Beam B3	3.48	10	18.8	27	1.5	15	10	271.6
	Beam B4	2.544	15	18.874	30	3.95	14	3.544304	250.45
	Beam B5	2.862	10	14.795	36	1.17	18	15.38462	348.3
3	Beam B6	2.756	10	11.027	40	5.52	32	5.797101	638.15
	Beam B7	3.287	15	29.324	45	3.29	17	5.167173	487
4	Beam B8	3.428	10	5.686	25	1.95	18	9.230769	286.1
	Beam B9	4.11	10	18.733	28	3.55	20	5.633803	376.75
5	Beam B10	3.025	15	20.028	32	4.87	19	3.901437	405.7
	Beam B11	3.475	20	22.7	38	5.85	19	3.247863	463.4
6	Beam B12	3.477	20	25.65	33	5.42	13.57	2.50369	302.5
	Beam B13	3.645	15	31.09	32	3.25	13.74	4.227692	326.54
	Beam B14	4.095	20	26.676	40	5.41	14.57	2.693161	349.225

Figures 2.1-2.14 show the load deflection curves for all tested beams. The table shows the obtained results for the first crack load, service load, and ultimate load, deflection at ultimate load, ductility ratio, and energy absorption. Ultimate load and deflection at ultimate load were measured and obtained during the test, while the first crack load, service load, ductility ratio and energy absorption were determined from the load-deflection diagram for each tested beam. The first crack load was determined from the load deflection curve at the point at which the load-deflection curve started to deviate from the linear relationship. The Service load, or flexural serviceability load, is defined in this investigation as the load corresponding to deflection equal Span/250. Figures 3, 4, 5, 6 and 7 show first crack load, serviceability load, ultimate load, ductility ratio, and energy absorption for all tested beams respectively.





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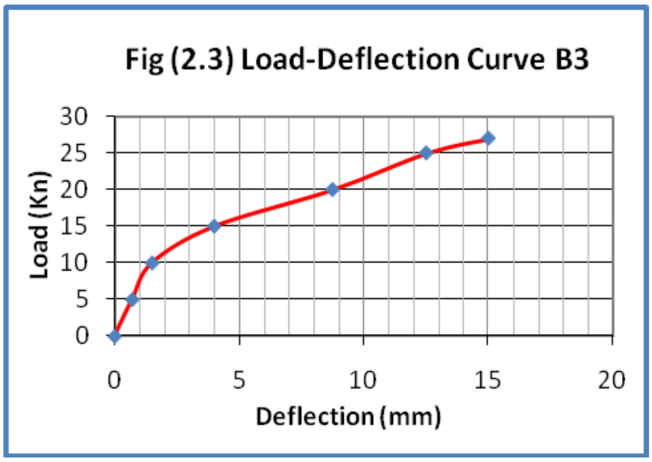

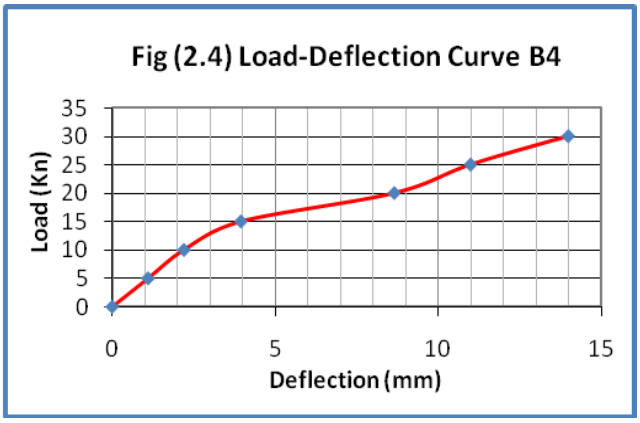

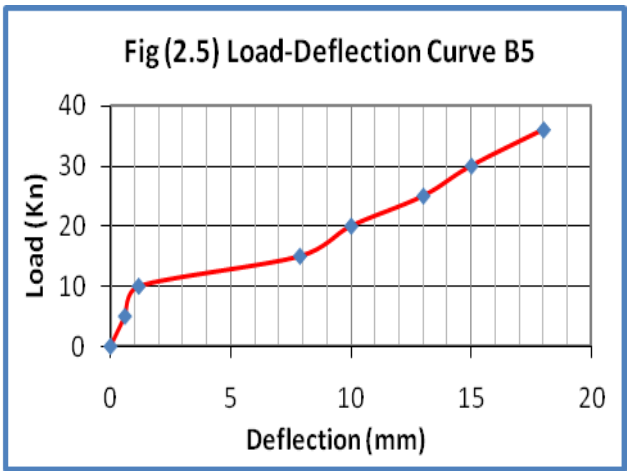

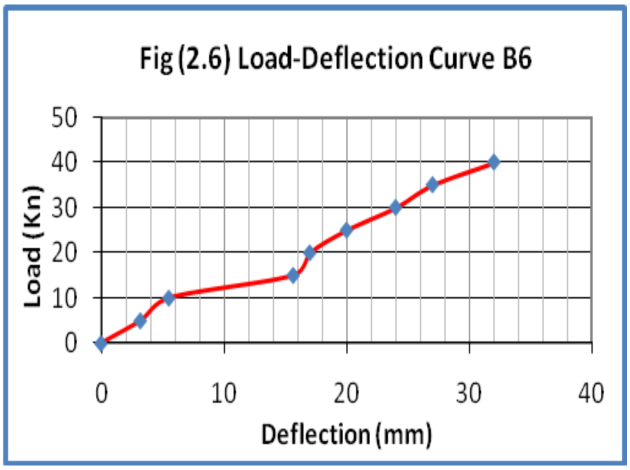

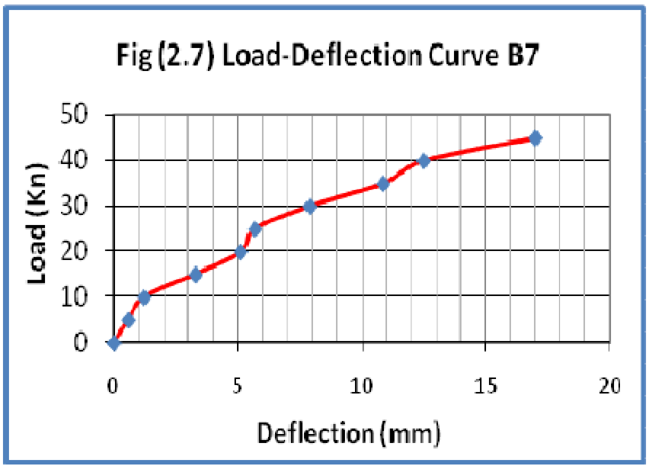

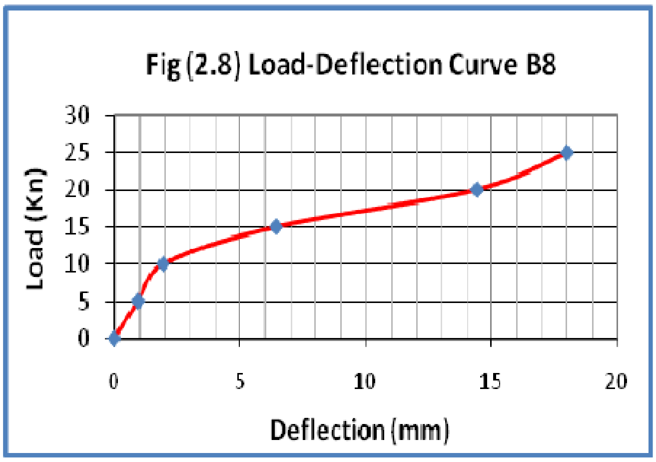

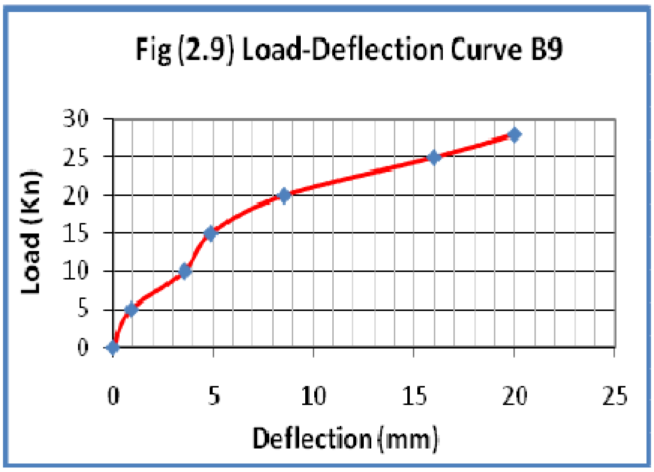

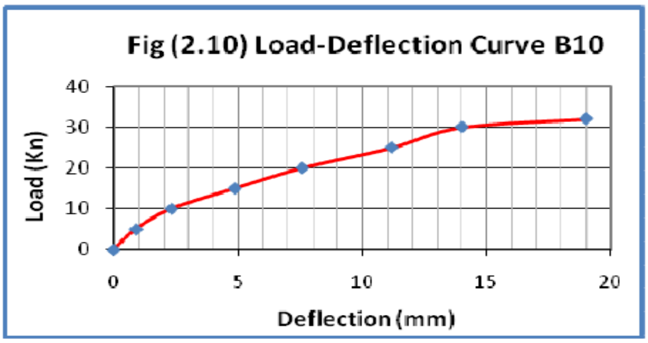

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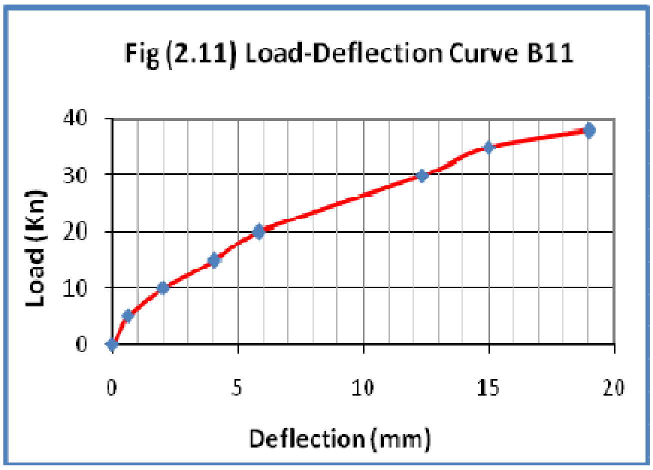

Fig (2.11) Load-Deflection Curve B11

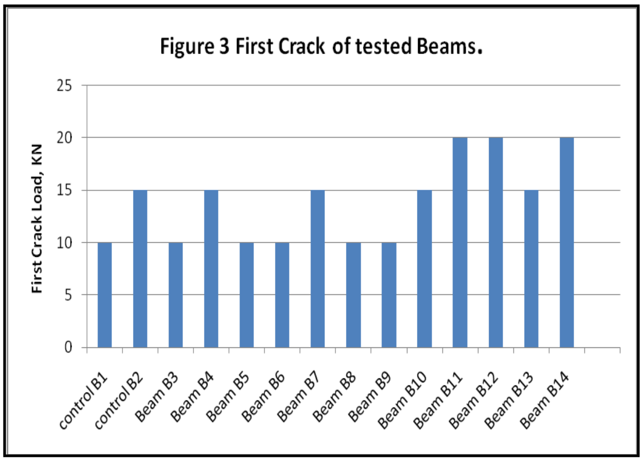

Figure 3 First Crack of tested Beams.

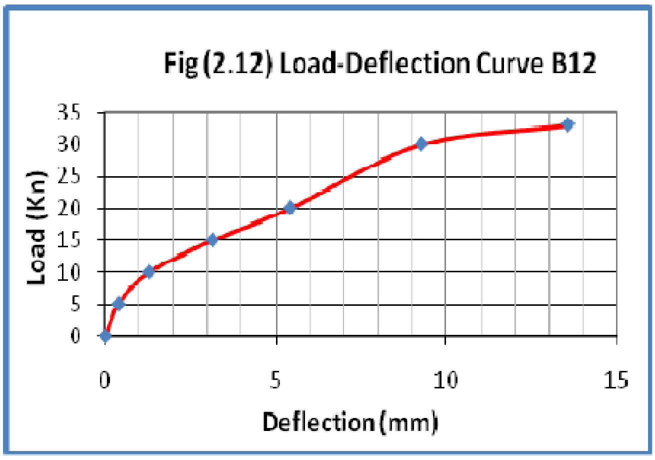

Fig (2.12) Load-Deflection Curve B12

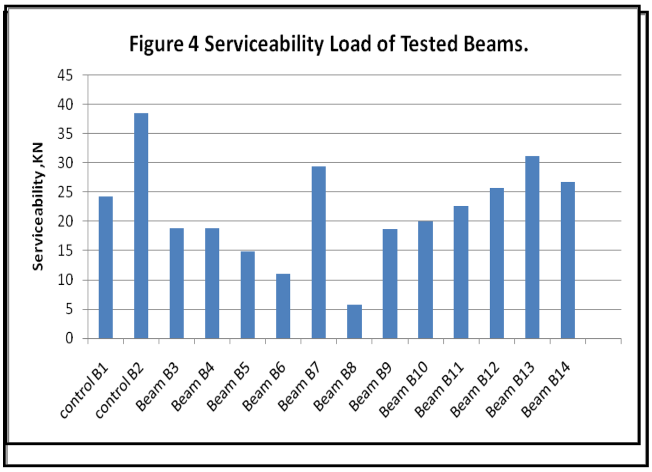

Figure 4 Serviceability Load of Tested Beams.

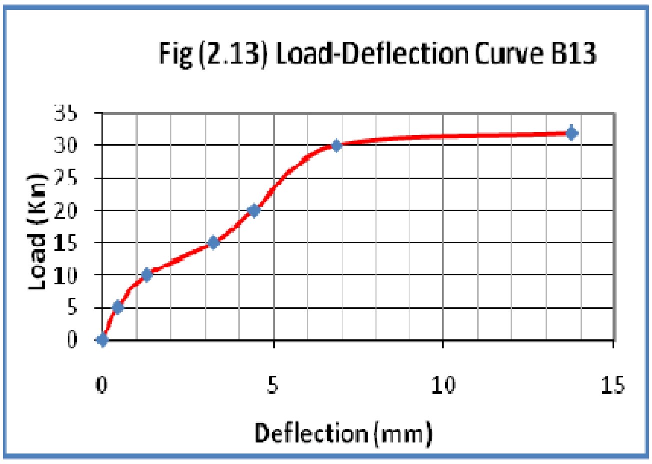

Fig (2.13) Load-Deflection Curve B13

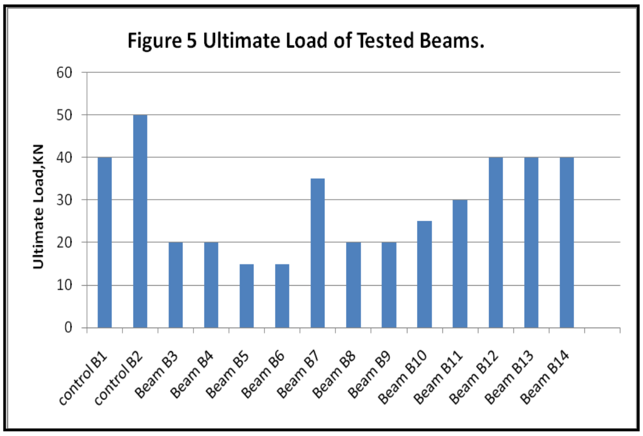

Figure 5 Ultimate Load of Tested Beams.

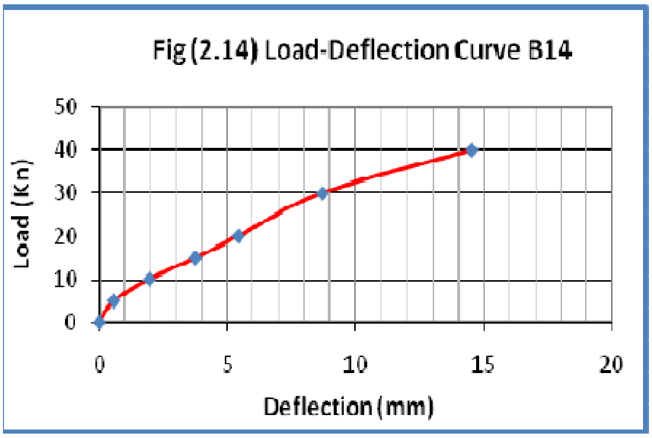

Fig (2.14) Load-Deflection Curve B14

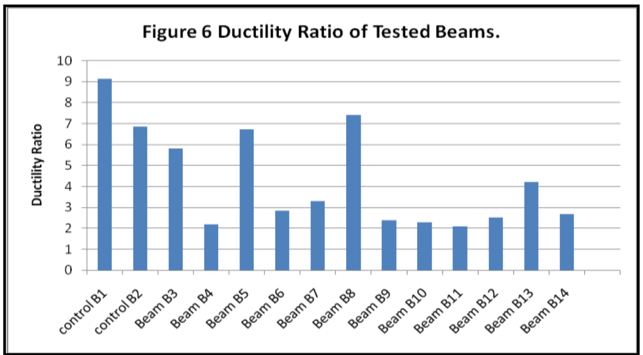

Figure 6 Ductility Ratio of Tested Beams.

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4.1 Behavior of the Test Specimens

The Behavior of the conventional reinforced concrete and that reinforced with closely spaced wire steel mesh differs as a result of the uniformity of reinforcement distribution along the section, geometry of reinforcement, type of reinforcement, specific surface area, volume fraction of reinforcement, and number of openings. These parameters have effects on the serviceability load and deflection control, cracking behavior, ultimate strength, ductility ratio, and energy absorption properties.

4.1.1 Deformation Characteristics

The plotted central deflection of the test specimens against the applied load is shown in Figures 2.1- 2.14. It can be seen from these Figures that the load-deflection relationship of the test specimens can be divided into three stages as follows:

a) Elastic behavior until the first cracking. The load-deflection relationship in this stage is linear. The slope of the load-deflection curve in this stage varies with different types of the test specimens. The end of this stage is marked by the deviation from linearity. The extent of this stage varied with the type and number of layers of the steel meshes.

b) In the second stage, the slope of the load-deflection curve changes gradually due to the expected reduction in the specimens' stiffness as the result of multiple cracking. The gradient of the load-deflection curve increases with the increase of the volume fraction of the reinforcement.

c) In the third stage, large plastic deformation occurred as the result of yielding of the reinforcing bars and the steel meshes in the ferrocement beams. This stage was terminated by failure of the test specimens.

The load-deflection relationship for the control specimens was linear up to a load of 10kN approximately after which the relation became nonlinear. For this group of specimens, the transition from the second to the third stages, as explained before, was not distinct, while the first crack load occurred at a load equal 15KN for beam B2 due to the effect of polypropylene fibers used. At failure, the mid-span deflection reached 17.72mm and 13.78mm for beams B1 and B2 respectively. For group 2, beams B3, B4 and B3 with two openings located near the ends of beams, the deflection at first crack loads were 1.5mm, 3.95mm and 1.17mm respectively while the maximum deflections at their respective ultimate loads reached 15mm, 14mm and 18mm respectively. For group 3, beams B6 and B7 provided with two openings at their ends , the deflections at first crack loads were 5.52mm and 3.92mm respectively. While the recorded maximum deflections reached at their respective ultimate loads were 32mm and 17mm respectively. For group 4, beams B8 and B9 with two and three openings, the deflections at first crack loads were 1.95mm and 3.55mm respectively. While the measured maximum deflections reached 18mm and 20mm respectively. For group 5, beams B10 and B11 provided with three openings, the deflections at first crack loads were 4.87mm and 5.85mm respectively. While the measured maximum deflections reached 19mm and 19.5mm respectively. For group 6, which comprises three beams with three openings, beams B12, B13 and B14, the deflections at first crack loads were 5.42mm, 3.25mm and 5.41mm respectively. While the measured maximum deflections reached were 13.57mm, 13.74mm and 14.57mm respectively.

4.2 Behavior of ferrocement beams with openings

Three beams were tested under four lines loadings and the deflection at each load increment was recorded at two points on the tested beams to draw the load-deflection curves; crack initiation and propagation was also observed for each test specimen. The effect of the parameters under investigation on the ultimate moment, maximum deflection at ultimate load, ductility ratio, energy absorption, and cracking behavior are discussed in the following sections.

4.3 Ultimate Load

It is clear from Table7 that employing welded galvanized steel mesh, fiber glass mesh and expanded metal mesh in reinforcing ferrocement beams with openings in series designations 2, 3, 4, 5 and 6 is very effective in increasing their ultimate load than the other reinforcements formation. The ultimate load of beam B4, volume fraction of reinforcement of reinforcement 2.544% is much higher than that of beam B3, Vr equal 3.48%. It is interesting to note that the ultimate load of beam B5, Vr equal 2.862% is greater than that of beam B4 as result of increasing the number of layers of welded steel mesh. The ultimate load of beam B7 which reinforced with two layers of expanded metal mesh, Vr equal 3.287% is greater than that of beam B6, Vr equal 2.756%. It is significant to note that employing fiber glass mesh as reinforcement, beams B8 and B9 decreased the ultimate load by approximately 38%. Comparing the reached ultimate loads of beams B10 and B11 with three openings that there is much increase in ultimate load of beam B11, Vr equal 3.4747% approximately 16% compared with that of beam B10, Vr equal 3.0251%. Comparing the ultimate loads reached for beams B12, B13 and B14 with three openings were 33, 38 and 40 KN respectively. It is interesting to note that the effect of employing irrespective of the type of mesh used is significant in in increasing the ultimate loads reached.

4.3.1 Deflection and Ductility Ratio

All tested beams with openings showed typical three-stage load versus mid-span deflection relationship. Under initial loading the load-deflection response was linear up to cracking load. The second stage is defined by cracking section behavior with the steel reinforcement behaving linear elastic. Transition into third phase of behavior is marked by yielding of the tensile reinforcement and non-linear material behavior. After yielding of tension steel, beam behavior is defined by large increase in deformation with little increase in applied load. All tested beams showed large deflection at ultimate loading, which is an indication of high ductility. Figures 2.1- 2.14 show the load central deflection curves for all the tested beams. Table 7, summarized comparison of deflections at serviceability loads based on CP110. It is interesting to note that the value of deflection according to serviceability load for beams in series 2, 3, 4, 5 and 6 was beyond the limit 7.2 mm and this is predominant. Table 7 summarized comparison of the serviceability loads based according to span/250.

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It is interesting to note that higher serviceability loads could be obtained for beams with openings in series 2, 3, 5 and 6. It is interesting to note from Table 7 that the highest ductility ratio was found to be 15.385 for beam B5 in series designation 2, reinforced by steel bars and four layers of welded galvanized steel mesh . Ductility ratio for beams in series designation 1 was varied from 9.134 for beam 1 to 6.856 for beam B2, reinforced with conventional reinforcement. While ductility ratio for beams in series designation 2 beams B3, B4 and B5 which provided with two openings and reinforced with steel bars, two and three layers of welded steel mesh respectively and their ductility ratios were 10, 3.544 and 15.385 respectively. For series designation 3 beams B6 and B7, which reinforced with one layer and two layers of expanded steel mesh respectively, their calculated ductility ratios were 5.797 and 5.167 respectively. For series designation 4 beams B8 and B9, which reinforced with one layer and two layers of fiber glass mesh respectively, their calculated ductility ratios were 9.231 and 5.634 respectively. For series designation 5 beams B10 and B11, which reinforced with four layers welded steel mesh and two layers of expanded steel mesh respectively, their calculated ductility ratios were 3.901 and 3.248 respectively. For series designation 6 beams B12, B13 and B14, with three openings and reinforced with three layers welded steel mesh, four layers welded steel mesh and two layers of expanded steel mesh respectively, their calculated ductility ratios were 2.504, 4.228 and 2.693 respectively. Irrespective of the type of reinforcing materials, it is significant to note that increasing the volume fraction of reinforcement decreasing the obtained ductility ratio.

4.3.2 Energy Absorption

The experimental results given in Table 7 proved that as the volume fraction for beams increase, energy absorption increased also. It is interesting to note from Table 7 that the highest energy absorption was found to be 638.15 KN.mm for beam B6 in series designation 3, reinforced by steel bars and one layer of expanded steel mesh. Energy absorption for beams in series designation 1 was varied from 447.125 for beam B1 to 435.55 KN.mm for beam B2, reinforced with conventional reinforcement. While energy absorption for beams in series designation 2 beams B3, B4 and B5 which provided with two openings and reinforced with steel bars, two and three layers of welded steel mesh respectively and their energy absorption were 271.6, 250.45 and 348.3 KN.mm respectively. For series designation 3 beams B6 and B7, which reinforced with one layer and two layers of expanded steel mesh respectively, their energy absorption were 638.15 and 487 KN.mm respectively. For series designation 4 beams B8 and B9, which reinforced with one layer and two layers of fiber glass mesh respectively, their calculated energy absorption were 286.1 and 376.75KN.mm respectively. For series designation 5 beams B10 and B11, which reinforced with four layers welded steel mesh and two layers of expanded steel mesh respectively, their calculated energy absorption were 405.7 and 463.4 KN.mm respectively. For series designation 6 beams B12, B13 and B14, with three openings and reinforced with three layers welded steel mesh, four layers welded steel mesh and two layers of expanded steel mesh respectively, their calculated energy absorption were 302.5, 326.54 and 2.69349.225 KN.mm respectively. Irrespective of the type of reinforcing materials, it is significant to note that increasing the volume fraction of reinforcement increasing the reached energy absorption. High ductility and energy absorption properties are very useful in dynamic applications.

VII. FAILURE MODES

For all series designation of all the tested beams flexural failure occurred. Failure of the test specimens occurred due to reaching the ultimate stress of the reinforcing steel mesh. However, none of mesh bars was ruptured, which indicates that the strain in the steel mesh did not reach the ultimate strain of the steel mesh. After the end of each test, the specimen was removed from the testing machine and the mortar cover was removed to expose the reinforcing steel mesh. The visual investigation of the steel mesh confirmed that none of the bars has ruptured. The reinforcing steel meshes did not rupture for this designation. Cracks differed in width, number, and propagation directions according to the physical properties of each designation. In the next section the crack patterns and distributions are discussed for each designation separately.

5.1 Cracking Patterns

Figures 8.1- 8.14 show side views of tensile crack patterns of all the tested beams with and without openings. For designation (1), flexural cracks developed near the mid-span of the specimens of this designation. With the increase of the load, the cracks propagated vertically and new flexural cracks were developed rapidly. As the specimens approached their failure load, the cracks started to propagate wider. The crack width was observed; it was observed that the cracks were very wide as result of employing steel bars.

For designation (2) beams 3, 4 and 5, it is interesting to note that vertical flexural cracks started to develop close to the center of the span. As the load increased, more cracks started to develop and the crack at mid-span started to propagate vertically towards the top surface of the specimen, while most of the developed cracks did not continue propagating. The crack widths were much less than those of designation (1). This could be attributed to the effect of steel mesh in controlling the crack width. For series designation 3, beams B6 and B7, which was reinforced with one layer and two layers of expanded metal mesh flexural cracks were less than series 1. It is interesting to note that very fine vertical cracks were developed than the previous designation and the cracks were uniformly distributed along the middle 2/3 of the span. The observed crack widths were much less than those of designation 1. This could be attributed to the effect of steel mesh in controlling the crack width. For beams in series designation 4, B8 and B9, which were

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reinforced with one and two layers of fiber glass mesh 8, the flexural cracks started to turn diagonally as the load approached the failure load and one diagonal crack developed near the end. For series designation 5, beams B10 and B11, which reinforced with four layers of welded steel mesh and two layers of expanded steel mesh respectively. At failure, very narrow flexural cracks were developed compared with beams in the previous series. For series designation 6, beams with three openings, B12, B13 and B14, which were reinforced with three layers of welded steel mesh, four layers with welded steel mesh and two layers of expanded steel mesh respectively. The number of developed cracks was more than the previous designations and the cracks were uniformly distributed along the whole of the span. The observed crack widths were much less than those of the previous series.

Figure 8.1 Cracking pattern of Beam B1

Figure 8.2 Cracking pattern of Beam B2

Figure 8.3 Cracking pattern of Beam B3

Figure 8.4 Cracking pattern of Beam B4

Figure 8.5 Cracking pattern of Beam B5

Figure 8.6 Cracking pattern of Beam B6

Figure 8.7 Cracking pattern of Beam B7

Figure 8.8 Cracking pattern of Beam B8

Figure 8.9 Cracking pattern of Beam B9

Figure 8.10 Cracking pattern of Beam B10

Figure 8.11 Cracking pattern of Beam B11

Figure 8.12 Cracking pattern of Beam B12

Figure 8.13 Cracking pattern of Beam B13

Figure 8.14 Cracking pattern of Beam B14

VIII. CONCLUSIONS

The test results of the current experimental program showed that the developed ferrocement beams with openings and reinforced with innovative reinforcing materials achieved high strength, better deformation characteristics, crack resistance, high ductility and energy absorption properties. Irrespective of the type and number of steel mesh layers and number of openings had better mechanical properties than conventional reinforced concrete beams. The results also demonstrated that ferrocement concrete beams with openings showed fine crack widths at failure without spalling of concrete cover that is predominant. Within the scope, parameters, theoretical and analytical investigation considered in this research and based on the test results and observations of the experimental investigation; the following conclusions and recommendations may be drawn as follows:

1. Saving in the total reinforcing steel weight ranging could be achieved by utilizing welded galvanized steel mesh, expanded metal mesh and fiber glass mesh for durability reason. The saving in the steel weight ranged from 20% to 30%.
2. The beams incorporating ferrocement forms and high strength mortar matrix achieved higher first crack load, serviceability load, ultimate load, and energy absorption compared to the control test specimen irrespective of the type of steel mesh and number of steel mesh layers.
3. Beam B5 with two openings at both ends of the beam and reinforced with four layers of galvanized welded steel mesh and steel bras without using stirrups, volume fraction of reinforcing materials, 2.862% showed the high ductility ratio, 15.385 of all the tested beams.
4. Beam B6 with two openings at both ends of the beam and reinforced with one layer of expanded metal mesh and steel bras without using stirrups, volume fraction of reinforcing materials, 2.756% showed the energy absorption, 638.15 KN.mm of all the tested beams.

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5. Increasing the number of the steel mesh layers in the ferrocement forms increases the first crack load, service load, ultimate load, and energy absorption. On the other hand it decreases the ductility of the beam.
6. Employing steel mesh in reinforcing concrete beams with openings, irrespective of the type of steel mesh and numbers of openings is significant in strengthening the matrix surrounding the openings and consequently improving strength, deformation characteristics and cracking behavior with great saving of reinforcement.
7. All. tested beams with openings reinforced with various types of steel meshes showed at failure cracking control without spalling of concrete cover that is predominant due to the result of reducing stress concentration around the openings.
8. The theoretical methods for first crack and ultimate load calculations provide good prediction for these loads and the beam's mode of failure.
9. The developed beams utilizing beams with openings reinforced with innovative reinforcing materials could be successfully used as an alternative to the traditional reinforced concrete beams, which can be of true merit in both developed and developing countries besides its anticipated economic and durability merits. Further research needs to be conducted to reach sound recommendations for practical use especially for the beams provided with four and five openings.

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