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FLEXURAL BEHAVIOR OF FERROCEMENT FLOOR SLABS USED IN LIGHT STEEL RESIDENTIAL BUILDINGS

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ABSTRACT: This paper presents the result of an experimental investigation on the flexural behavior of ferrocement slabs used in cold formed steel residential buildings. Experimental tests were performed on eight ferrocement slabs of size 30x 600x1200 mm simply supported along their longitudinal edges on cold formed steel sections. The slabs were tested in one way flexure under two test programs involving line loading and uniform loading. Load deflection relations obtained from the tests were used to find the first crack load and the ultimate load under both test program in addition to the developed crack patterns and failure modes. It was found that under uniform loading the slabs failed in flexure mode and carried higher loads than under line loads which failed in combined shear and flexure mode. Results showed the superior behavior of ferrocement slabs over conventional reinforced concrete slabs with regard to high strength to weight ratio, improved ductility and enhanced crack performance.

Keywords: Ferrocement slabs, expanded metal, flexural strength, light steel residential buildings.

1. INTRODUCTION

The largest component of the world's building stock is, by far, low and medium rise residential buildings. Demand for these structures is growing: according to UN anticipated growth in the world population from 2017 to 2050 is 2.2 billion (United Nation 2017).

In addition to the demand for more houses, the demand for sustainability must be recognized. New construction technologies has to fully consider the balancing act between economic, environmental, and social constraints when considering construction material, means and methods, and long-term function of buildings. Innovation in building construction systems is therefore required in order to meet the challenges facing the built environment. Improved resilience, increased sustainability, and more affordable solutions are being demanded by society in the midst of increasing fiscal turmoil and more prevalent natural hazards.

To meet such challenges, it is necessary to explore the latest construction technologies, and to create innovative building systems that have the potential high performance affordable housing within reach of new markets. Beyond being affordable, these systems have to be flexible enough to suit local climate and site conditions, cultural and living habits, and spatial standards. Construction solutions also should reduce or eliminate the need for skilled personnel on the site, and ideally should be assembled with simple tools and erectable without machinery. Among the available construction systems that satisfy the previous conditions, light steel framing systems using cold formed steel (Figure 1) have proven to be a worthy alternative to traditional systems. Potential advantages of this system include high strength-to-weight, ease of production and handling, faster erection, high recycled contents, and sustainability. The flooring systems usually used with this type of construction include light timber flooring and cast-in-situ reinforced concrete with or without metal decking. Timber flooring has several disadvantages regarding its low fire resistance, high labor and material cost, its span limitations and vibrations. Cast-in-situ reinforced concrete slabs are not economical for the short to medium span ranges associated with these building types in addition to being labor intensive and time consuming.

Figure 1 Cold-formed Steel Building

For the entire building system to be efficient, structural systems used for floors and walls must also have similar advantages to the light steel framing used, i.e., ease of production and handling, faster erection, high strength to weight ratio, low cost and sustainability. A floor system which satisfies these requirements consists of thin ferrocement slabs which are prefabricated off-site from cement mortar reinforced with one or more layers of relatively small wire or expanded metal mesh. These prefabricated slabs can be easily transported to site and erected using self-tapping screw as shown in Figure 2. Compared with conventional reinforced concrete, ferrocement has higher tensile and flexural strength due to its high reinforcement ratio. In addition, because the specific surface of reinforcement in ferrocement is much higher than that of reinforced concrete, larger bond forces develop within the matrix resulting in improved ductility and crack arresting properties.

a) Prefabricated Slabs b) Erected Slabs

Figure 2 Precast Ferrocement Slabs

Review of the available literatures on general applications of ferrocement can be found in ACI (1999) and Naaman (2000). The flexural behavior of ferrocement slabs has been investigated by Hago et al (2005), Hossain et. al. (2005), Ibrahim (2011), Kulkarni et al (2013), Randhir et al (2014), Shri et al (2012) and Zakaria, et al (2016).

The present research investigates the flexural behavior of ferrocement slab panels used as pre-cast flooring elements in cold formed steel residential buildings. An experimental investigation was performed on eight ferrocement slabs of typical dimensions reinforced with expanded metal mesh. The slabs were tested in one way flexure under two loading conditions: 1) two line loads parallel to the long edge, and 2) uniformly distributed load. Each slab was tested under monotonically increasing loads to failure and the load deflection curve plotted.

2. EXPERIMENTAL PROGRAM

The experimental program involved testing eight ferrocement slabs with dimensions 1200x600x30 mm. The slabs were tested in simply supported conditions in the shorter direction similar to their usage in practice. All slabs were reinforced with only one bottom layer of expanded metal mesh of the type shown in Figure 3a.

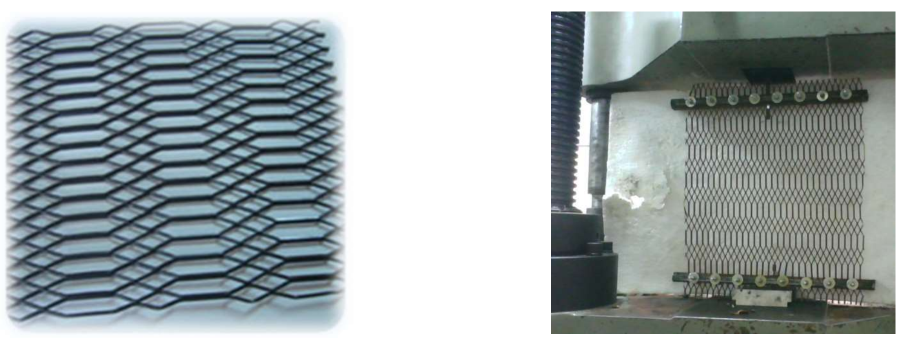
2.1 Material Specifications

2.1.1 Mortar

The mix used to cast the ferrocement specimens was developed by trial batching. The mix with the best compressive strength consisted of: (1) Ordinary Portland cement, (2) Fine aggregate composed of clean sand passing through no.8 (2.38 mm) sieve mixed with fine crushed basalt of maximum size 1 (< 10mm) in the ratio 2 to 1, and (3) water. The mixing ratio by weight were sand to cement = 2, fine crushed basalt to cement = 1 and water to cement = 0.45. At the time of casting three cube specimens of size 70x70x70 mm were cast and used to determine the cube compressive strength of the mix. All specimens were air dried for 24 hours and then immersed in water for 28 days before the test. The average cube compressive strength of the mix was found to be 28.9 MPa.

2.1.2 Mesh

The mesh use was expanded metal of the geometry shown in Figure 3a. The metal thickness was 1.2 mm with an average weight of 27.8 N/m^2. The openings dimensions were 9x45 mm for the longer opening and 9x18 mm for the shorter opening. The mesh was always positioned so that the longer opening runs parallel to the shorter direction in order to have the higher reinforcement ratio in the loaded shorter direction. Two test samples of the mesh were fixed at their ends to steel grips and tested under direct tension as shown in Figure3 b. Test results showed that the values of yield strength and ultimate strength are 18.4 MPa and 32.7 MPa, respectively.



a) Mesh Geometry b) Tension Test

Fig 3 Expanded Metal Mesh

2.2 Fabrication and Casting

The specimens were cast in rectangular moulds which consisted of a bottom steel plate with four steel angles welded around the perimeter and standing for the slab thickness of 30 mm, see Figure 4. All specimens were 600 mm in width, 1200 mm in length and 30 mm thick. The expanded metal layer was first straightened before being placed to provide a cover of 5-10 mm from the bottom plate. An exact value of this cover was practically unattainable. The materials were mixed mechanically and then cast into the mould manually without vibrators. The top surface was leveled with a trowel. The specimens were then air dried for 24 hours and cured under wet conditions for 28 days before testing.

(a) Mould (b) Cast Slab

Figure 4 Casting of Ferrocement Slab Specimens

2.3 Test Setup

All specimens were tested as simply supported slabs in the shorter direction. In order to simulate the actual supporting conditions used in practice, the ferrocement slab was connected along its longitudinal edges to a cold formed steel channel section of size 100x50x1.5 mm using self tapping screws as shown in Figure 5. Two wooden blocks were placed at the steel beam support to avoid web crippling of the channel section. The slab surface was painted with white emulsion so that cracks could be easily observed.

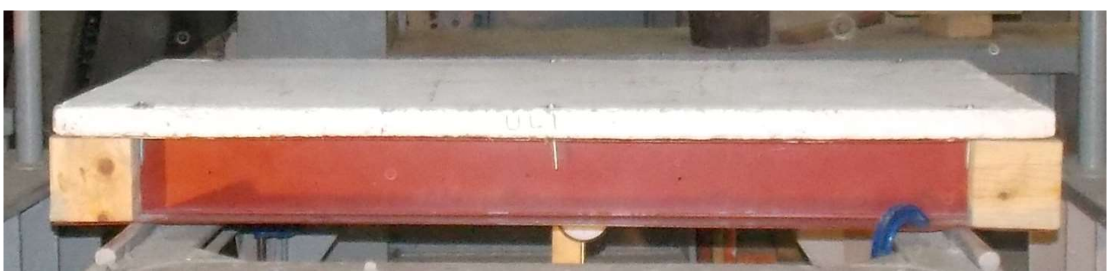


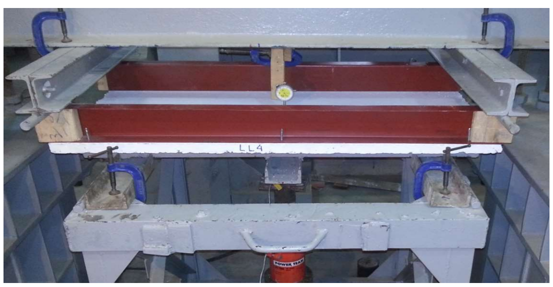
Figure 5 Edge support of tested slab

Two test programs were used in the experimental investigation. The first test program involved testing four test specimens (LL1 to LL4) under four point bending using two longitudinal line loads of length 1000 mm spaced at 200 mm as shown in Figure 6. In order to easily visualize the development of cracking patterns, the test was carried out with the slab tensile side up. The line loads were applied to the underside of the slab through two longitudinal round bars of length 1000 mm welded to two channel beams spaced at 200 mm center to center which are connected to a central transversal spreader beam as shown in Figure 6b. The loading was applied in a vertical upward direction using a hydraulic jack as shown in Fig 6a. The load was measured using an electric load cell of 100 KN capacity and was applied in increments of 2 KN. The test was terminated when the slab failed or when deflections became excessive. Deflections at the central point were measured using a dial gauge graduated in units of 0.01 mm. In the second test program four test specimens (UL1 to UL4) were tested under uniformly distributed load over an area of 400*1000 mm of the slab surface. The slab-beam assembly was placed in the normal position with the tensile side facing down and the load applied vertically downward to the upper side. The load was initially applied using steel billets with dimensions 130x130x500 mm each stacked in rows on the upper side of the slab as shown in

Figure 7a. Each row of these billets is equivalent to a uniform pressure of 10 KPa on the loaded area. Three rows of these billets were stacked to distribute the test load over the slab surface giving a total load of 30 KPa. Additional loading increments were then applied using a hydraulic jack with an electric load cell. The load was applied at increments of 3 KN until failure due to increased crack width or excessive deflections.

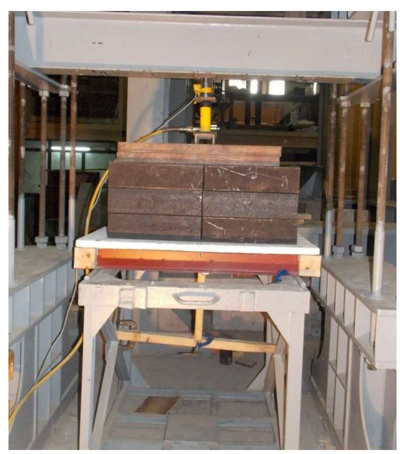
3. TEST RESULTS

The load deflection relationships for the eight test specimens are plotted in Figure 8 for the line load tests program and in Figure 9 for the uniform loading test program. For both cases, the load deflection behavior is characterized by three stages [2]. In the initial stage the matrix and the mesh act as one elastic composite section and the behavior is nearly linear up to the initiation of the first crack. Although micro-cracks are inherent in the mortar matrix even before it is loaded, the term first crack load appears frequently in the literature on ferrocement, it corresponds to the state when the original micro-cracks widen, propagate and progressively join together under load so that they are visually detected. Such a definition is quite general since it is not associated with a specific value of an average crack width. Nevertheless it can be used as a serviceability limit state. The second behavior stage is a transitional stage which is associated with a cracked matrix so that the behavior is also nearly linear but with a smaller slope since the steel has not reached its yield strength. In the third stage the matrix ceases to be effective and the mesh reaches its yield strength. This stage is associated with the cracks increasing in number and width and the slab suffering from excessive deformations till failure. The beginning of this stage can be detected from the load deflection curve when the slope changes considerable from nearly linear. The load at the beginning of this stage is termed the yield load while the load at its end is termed the ultimate load.



(a) Long Direction (b) Short Direction

Figure 6 Test Setup for Line Loads



(a) Steel Billet Loading (b) Hydraulic Jack Loading

Figure 7 Test Setup for Uniform Loads

Table (1) shows the test results of the eight specimens. The Table shows the first crack load, the ultimate load with the corresponding deflection and moment values. Figure 10 shows the comparison of load deflection results for both test programs.

Table (1) Summary of Test Results

	Slab ID.	First Crack			Final Load		
		Load	**Deflection**	**Moment**	**Load**	**Deflection**	**Moment**
		KN	**mm**	**KN.mm**	**KN**	**mm**	**KN.mm**
Line Loading	LL1	7.8	2.02	683	26	19.64	2275
	LL2	7.8	1.95	683	24	19.66	2100
	LL3	7.8	2.76	683	30	23.06	2625
	LL4	7.8	2.94	683	24	20.21	2100
Uniform Loading	UL1	14.3	3.43	1269	51.5	22.66	4580
	UL2	11.7	2.53	1038	54.6	18.67	4846
	UL3	12.6	3.43	1118	45.6	25.06	4047
	UL4	12.6	3.43	1118	42.6	28.61	3781

3.1 First Crack Load

The four specimens tested under line load had the same first crack load at 7.8 KN while the four specimen tested under uniform load had different values of first crack load ranging between 11.7 and 14.3 KN with an average of 12.8 KN; i.e., 64 % larger than the corresponding line load value.. The corresponding deflection value at the first crack load in both cases is about 3 mm which is close to a deflection serviceability limit of span/180. These results indicate that ferrocement slabs will not crack under service loads.

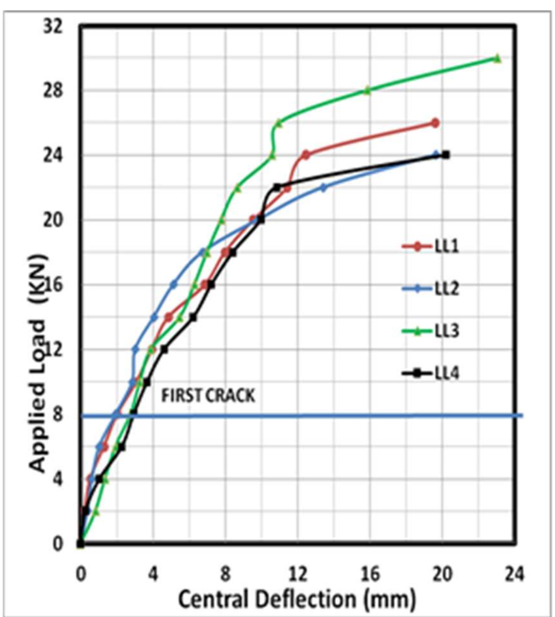


Figure 8 Load - Deflection Curves (Line Loading)

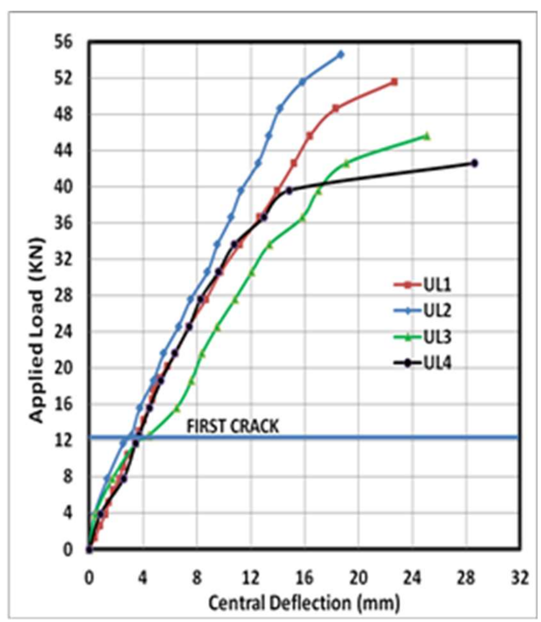


Figure 9 Load-Deflection Curves (Uniform Loading)

3.2 Ultimate Load

The four specimens tested under line load had their ultimate load in the range 24 –30 KN with an average value of 26 KN while the four specimen tested under uniform load had their ultimate load in the range 42.6 – 54.6 KN with an average of 48.6 KN; i.e., 87 % larger than the corresponding line load value. The associated shear force at mid section is 13 KN for the line load case. Considering the small thickness of these slabs, the ultimate load values in both cases are very high. These results also indicate that ferrocement slab can carry much higher total loads under uniform loading than under line loading.

Investigation of the corresponding flexural moment in each case as stated in Table (1) shows that slabs failed at an average moment value of 2275 KN.mm under line loads compared with an average moment value of 4314 KN.mm under uniform load. These results suggest that the failure mode under line loading is not pure flexure but more of a combined flexure and shear mode so the moment capacity is substantially reduced under line loading as compared to uniform loading.

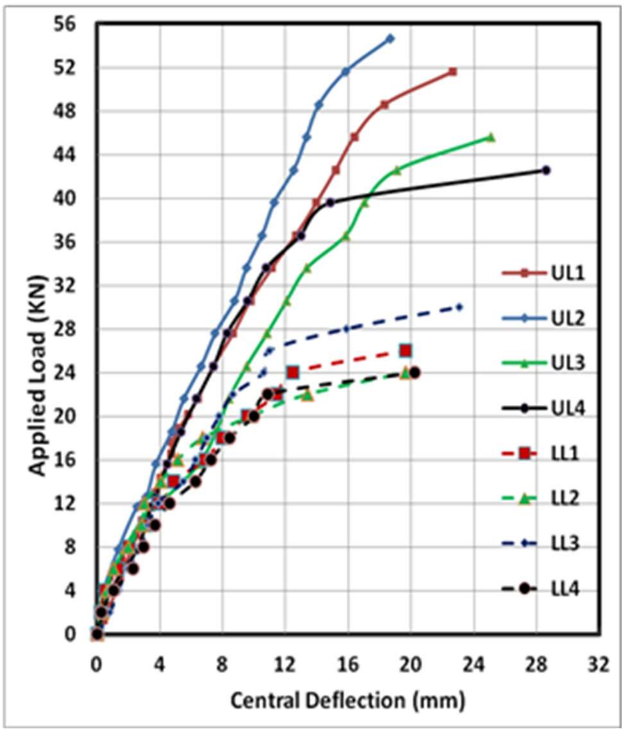


Figure 10 Comparison of Load Deflection Curves under Line Loading and under Uniform Loading

3.3 Ductility

The ratio of the average ultimate load to the average first crack load is 3.33 for line loading and 3.80 for uniform loading. This result shows the improved ductility of ferrocement slabs over conventional reinforced concrete slabs where the average ultimate load to the average first crack load is usually less than 2 (Ibrahim (2011)).

3.4 Crack Patterns

Figure 11 and 13 show the crack patterns formed in the tension side of the ferrocement slabs at ultimate loads for line loading and uniform loading, respectively. For slabs tested under line loading, longitudinal cracks initiate in the vicinity of the line loads. As the loading is increased, old cracks propagate longitudinally along the surface and vertically through the slab and new longitudinal cracks develop. At ultimate loads cracks are spread all over the tensile surface and some cracks increase in width considerably leading to excessive deflections in the slab and mesh rupture in the reinforcement as shown in Figure 12 for line loading and Figure 14 for uniform loading.

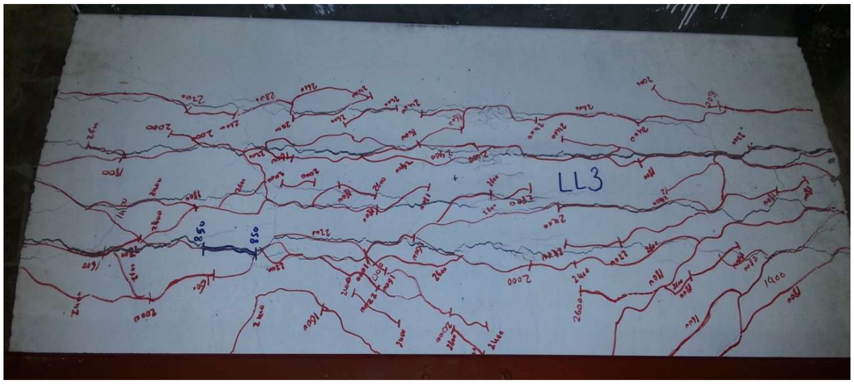


Figure 11 Crack Patterns Under Line Loading

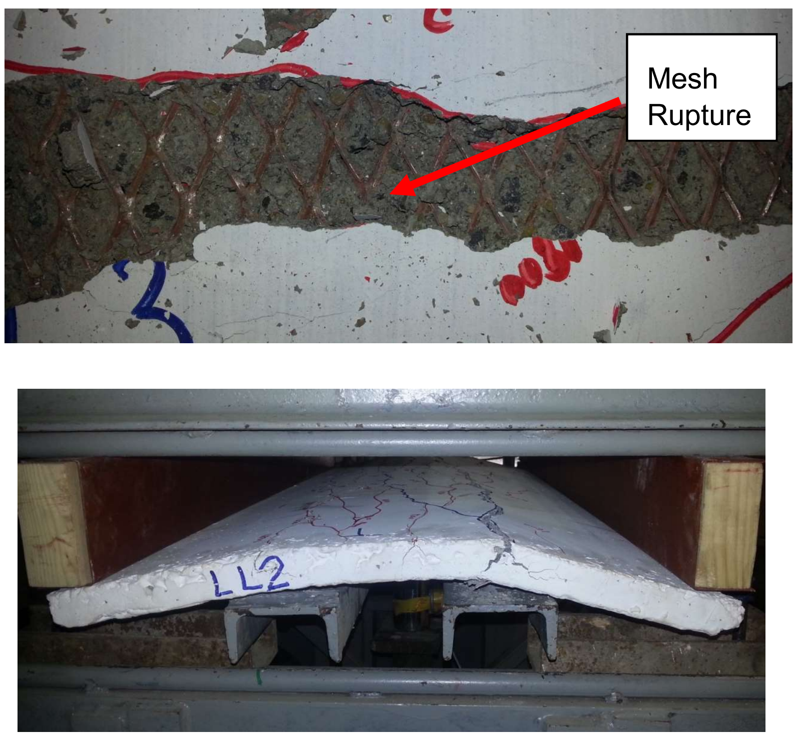


Figure 12 Slab Deflection and Mesh Failure at Ultimate Line Load

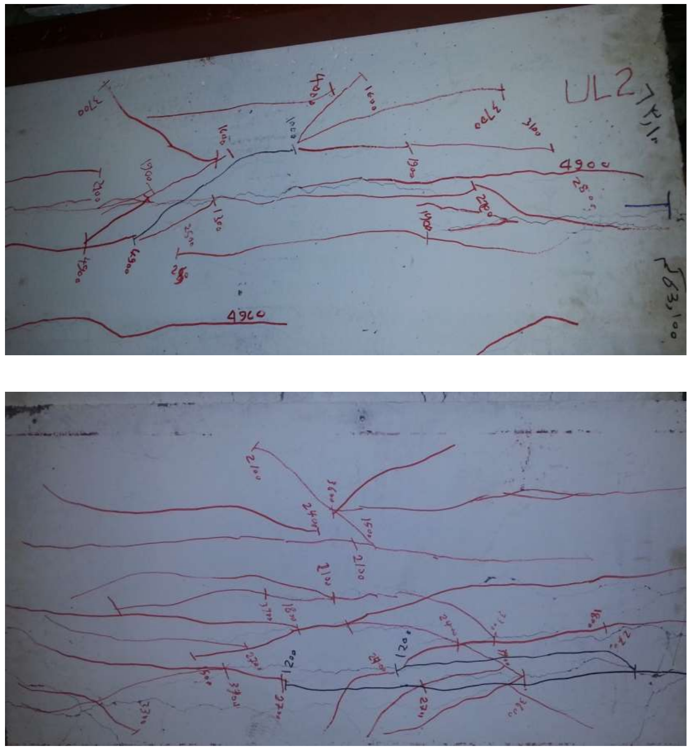


Figure 13 Crack Patterns Under Uniform Load

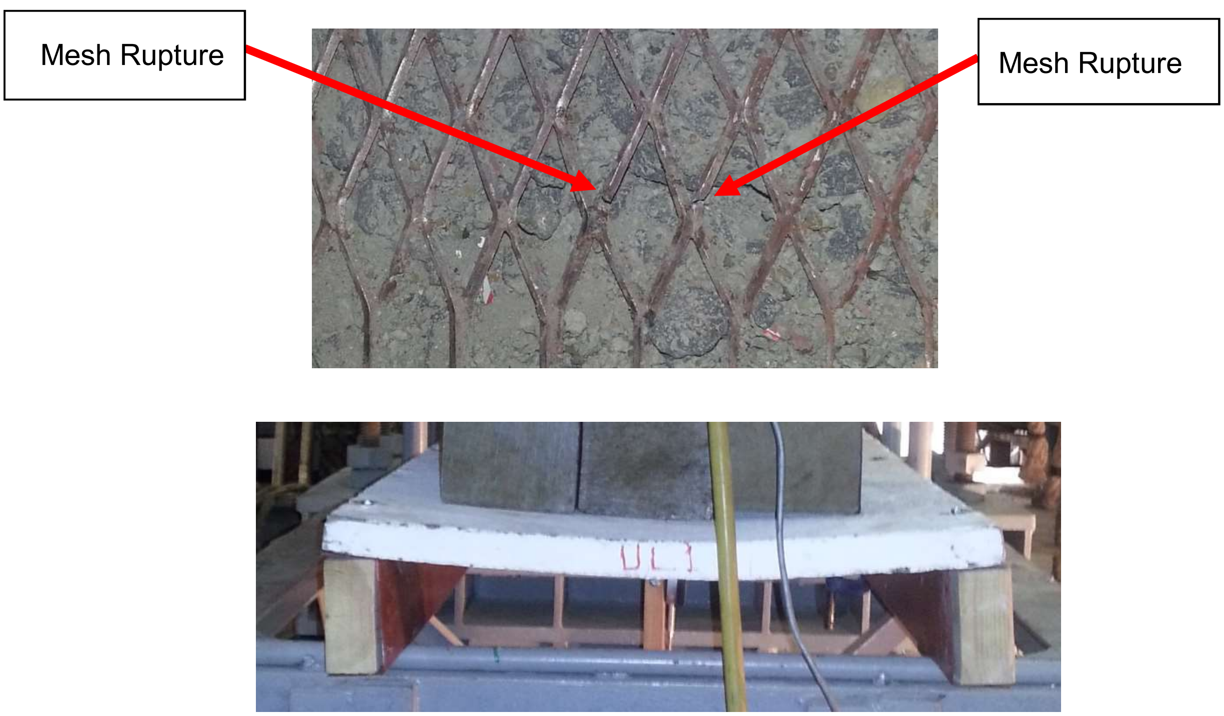


Figure 14 Slab Deflection and Mesh Failure at Ultimate Uniform Load

4. Conclusions

Based on the reported test results, the following conclusions can be stated:

1. The average first crack load and average ultimate load under uniform loading are 64 % and 87 % higher than the corresponding values under line loading.
2. Ferrocement slabs fail mainly due to pure flexure under uniform loading since the shear stresses at section of maximum bending are small. On the other hand, the slabs fail due to combined flexure and shear under line loading.
3. The ratio of the average ultimate load to the average first crack load is 3.33 for line loading and 3.80 for uniform loading. This result shows the improved ductility and enhanced crack performance of ferrocement slabs over conventional reinforced concrete slabs.
4. Ferrocement slabs present an efficient building system for residential and light commercial applications due to high strength to weight ratio, improved ductility and crack behavior, ease of production and handling, faster erection, low cost and sustainability.

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