FERROCEMENT COMPOSITE BEAMS UNDER FLEXURE

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Abstract - *Ferrocement is a thin, versatile construction material, with several unique properties and suitable for wide range of applications in Civil Engineering. Generally concrete structures are designed for static loads but sometimes dynamic loads like blasts etc. Prefabricated elements are used in construction industry as an alternative system to overcome the formwork problems in addition to getting better quality control. The prefabricated elements made of reinforced concrete are extremely heavy and difficult to transport, placing in position and to construct. Because of its good structural performance and low cost ferrocement is used in construction industry. Ferrocement is suitable for the construction of roofing/floor elements, precast units, manhole covers, and construction of domes, vaults, grid surface and folded plates. So finding the flexural behavior of ferrocement is necessary. Therefore, the flexural strength is determined by varying the meshes in the U-section and varying the thickness of the beam. An experimental and finite element analysis on flexural behavior of ferrocement U-shape channel section reinforced with wire mesh with varying number of wire mesh layers is presented. Finite element analysis of U-shape ferrocement channel were carried out. The finite element analysis (FEA) has been also used to model the ferrocement U-shape channel for various span and thickness. Ferrocement U-shape channel with varies thickness and number of mesh layers analyzed in Ansys. The obtained results indicated the acceptable accuracy of FE simulations in the estimation of experimental values. Such models can thus be used as quick, simple, and inexpensive methods to calculate the optimal deflection of ferrocement channels for various spans and sizes of tensile reinforcement.*

Key Words: ferrocement, ANSYS WB 17.0, flexural strength.

1. INTRODUCTION

"Ferrocement is a type of thin wall reinforced concrete constructed of hydraulic cement mortar reinforced with closely spaced layers of continuous and relatively small size wire mesh". Mesh may be made of metallic or other suitable materials. The matrix may contain discontinuous fibers. This definition ignores as important type of reinforcement currently in use in ferrocement i.e. the combination of steel rods and wire mesh.

India has been identified as a developing economy which tends to give rise to a lot of infrastructure developments especially the building projects. RCC is most widely used in all over world because of its high load carrying capacity but the cost of cement and steel is increasing day-by-day. So, we require a substitute to concrete which gives the strength as that of RCC with low cost. In ferrocement, hydraulic cement mortar with closely spaced small diameter wire meshes is used. To improve certain characteristics of ferrocement various materials such as admixtures, silica fumes, fly ash and fibres are used. Generally, the thickness of ferrocement ranges from 20 – 50 mm. Ferrocement is a wire mesh reinforcement impregnated with mortar to produce elements of small thickness, high durability and resilience and, when properly shaped, high strength and rigidity. To bypass these problems and directly determine the response of ferrocement in unconventional applications, numerical simulations exploiting the Finite Element Method (FEM) have yielded important results in recent years. To provide realistic outcomes that accurately reflect real-world scenarios, the constitutive model of ferrocement must be improved to reproduce even the most elementary phenomena. Developments in FEM such as improvements in material constitutive models and large increases in computer calculation speed have led to the possibility of reproducing complex real-world situations with good accuracy. It is also necessary to take into account both deflection and possible cracks in the flexural test during applied load, for which various modeling strategies have recently been proposed that consider flexural strength. One of the most important ways to enhance the concrete properties is use of Ferrocement. Ferrocement improves the resistance of the concrete slabs to fragmentation, and increases the ability of slabs to withstand flexural loads. To study the behavior of concrete under the effect of flexural strength, a lot of experiments should be conducted. In order to decrease the number of experiments required, numerical simulation plays a very important role in predicting the complex behavior of concrete during flexural loading.

2. LITURATURE SURVEY

The unique properties of ferrocement have been investigated extensively by many researchers. The following literature survey includes summery of research papers presented in popular journals on topics similar to current field of study. P. Saranya Banu, S. Dharmar, Dr. S. Nagan (June 2014) Researcher conducted an experimental investigation on flexural behavior of trough shaped ferrocement panels. author concluded that, the flexural strength of the trough shaped panel with single and double layer of wire mesh is 81% and 77.95% more than flat panel's resp. And the deflection of single and double layer in trough panels is reduced by 61.18% and 56.36% when compared with flat panel's resp. The flexural strength of the trough shaped panel with single and double layer of wire mesh is 50% and 53.81% lower than folded panel's resp. The testing results reveals the superiority of the trough panels to flat and folded panels in terms of 1st crack and ultimate strength [1]. Ezzat H. Fahmy, Mohamed N. Abou Zeid, Yousry B. Shaheen, Ahmed A. Abdelnaby (august 2014), expiremental program is performed for Permanent Ferrocement Forms: A Viable Alternative for Construction of Concrete Beams, All specimens were tested under 3-point flexural loadings. The effect of the test parameters on the strength, stiffness, cracking behaviour, and energy absorption properties of the tested beams was investigated. The results showed that high first crack, serviceability and ultimate loads, crack resistance control, and good energy absorption properties could be achieved by using the proposed permanent ferrocement forms compared with the conventional reinforced concrete beams. Great saving in the total reinforcing steel weight ranging from 27.4% to 37.7% could be achieved by employing permanent ferrocement forms depending on the type of steel mesh and number of steel layers [2]. K. Kesava, K. L. A. V. Harnadh, K. Nehemiya, "Experimental Investigation of Flexural Behaviour of Ferrocement Trough Type Folded Plate (February 2017), The casted specimens are tested for 28 days' strength in loading frame and the results are compared with theoretical analysis RCC folded plates for load vs deflection [3]. Resarchar Yousry B.I. Shaheen, Noha M. Soliman and Ashwaq M. Hafiz, studied the Structural Behaviour of Ferrocement channels Beams (septeber 2013), from the experimental results they come to an conclusion that The amount of HRWR was 1.0 % of the cement weight. Mild steel bars of 6 mm diameter were used for stirrups. Expanded metal mesh was used as reinforcement for ferrocement channels [4]. Indian scientist by the name Dr. T. Chandrasekhar Rao, Dr. T.D. gunneswara Rao and Dr. N.V. Ramana Rao, Ch. Rambabu done An Experimental Study On Ferrocement Box-Beams Under Flexural Loading (September 2012), and come with the following results As the volume of reinforcement increases an increase in the cracking and ultimate moment capacity is observed in solid and cored box-beams. Cores reduced the weight by about 11.8%; while ultimate load reduction is only 7.7% compared to solid box-beams with two layers of wire mesh. In the case of beams with four layers of wire mesh the reduction in the ultimate load is found to be 6.6% [5].

3. EXPIREMENTAL PROGRAM

3.1 Introduction

In spite of the large amount of work carried out on ferrocement, its flexural behaviour is far way from being clear. The literature review shows that the work on the flexural behaviour lacks two main aspects – first, the study of its basic options, particularly the cracking, deformation and strength in regard to one another, and second, identifying quantitatively the factors that have an effect on this behaviour. As the structural behaviour of the ferrocement section varies as per the type of the reinforcing mesh, it is necessary to study the flexural behaviour of ferrocement specimen reinforced with each type of mesh separately. In this study, we have considered only the welded and woven square steel wire mesh. The experimental program consists of casting and testing of ferrocement U-shape channel section under two-point loading. The variables in this study are the thickness of panels and the number of mesh layers.

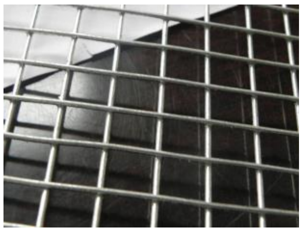
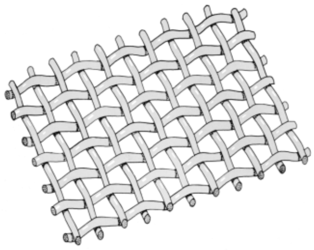



Figure-1. Steel Meshes Used

3.2 Moulds

For ferrocement channel section 200mm width 150mm height and 2000mm length are manufactured to cast channel section having varying thickness from 20-50mm. with different number of mesh layers.

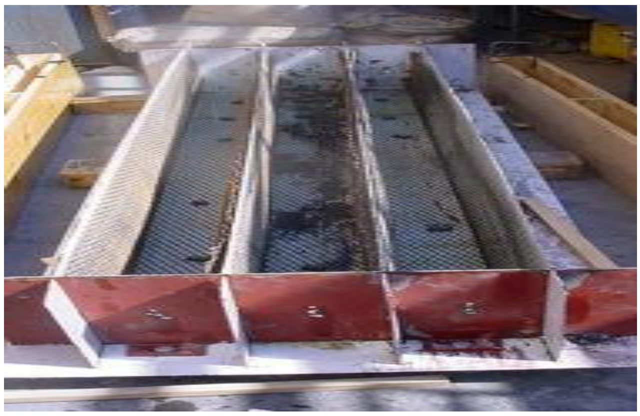


Figure-2. Mould for U-shape beam

3.3Experimental Setup

3.3.1 Universal Testing Machine

Universal Testing Machine also known as UTM for short is a multifunction testing machine for various tests for compression, Tension, Flexure etc. The load in UTM is applied by hydraulic action. The UTM in Applied Mechanics Department of MIT College, Pune was utilized for experimental work conducted. The capacity of UTM was 100 tonne.

3.3.2 Deflection Gauge

The deflection gauge used in the experimental work was readily available in Applied Mechanics Department of MIT College, Pune. It has a least count of .01mm or 10micron.

3.3.3 Four-Point Bending Test

At the time of testing, the specimen was painted with white paint to facilitate the visual crack detection during testing process. The specimen was laid on a universal testing machine of maximum capacity of 100 kN where the test was conducted under a four-point loads system with a span of 1800 mm. one dial gauges with an accuracy of 0.01 mm were placed under the test specimen at the centre to measure the deflection versus load. Load was applied at 100 N increments on the specimen exactly at the centre. Concurrently, the beam deflections were determined by recording the dial gauge reading at each load increment. Cracks were traced throughout the sides of the specimen and then marked with white chalk markers. The first crack-load of each specimen was recorded. The load was increased until complete failure of the specimen was reached.

3.4 Calculation for Flexural Strength

The flexural strength formula is given by –

$$\frac{M}{I} = \frac{f}{y} \tag{1}$$

$$f = \frac{M}{Z} \times y \tag{2}$$

Where,

M = Bending Moment (N.mm) = PL/6

I = Moment of Inertia

$$y = \frac{A_1 y_1 + A_2 y_2 + A_3 y_3}{A_1 + A_2 + A_3}$$

I = Moment of Inertia

$$= \frac{b \times t^3}{12} \times b \times t \times \left(y - \frac{t}{2}\right)^2 + 2 \times \left(\frac{t \times D^3}{12} + D\left(\frac{D}{2} - y\right)^2\right)$$

Moment acting on channel section, M = $\frac{PL}{6}$

4. ANALYTICAL PROGRAM

The nonlinear response of ferrocement structures can be computed using the finite element method (FEM). This analytical method, gives the interaction of different nonlinear effects on ferrocement structures. The success of analytical simulation is in selecting suitable elements, proper material models and in selecting proper solution method. The FEM is well suited modelling composite material with material models. The various finite element software packages available are ATENA, ABAQUS, Hyper mesh, Nastran, ANSYS etc. Amongst the available finite element package for the non-linear analysis ANSYS (Analysis System), an efficient finite element package is used for of the present study. This chapter discusses the procedure for developing analysis model in ANSYS v17.0. This chapter discusses the models and elements used in the present analysis of ANSYS. The graphical user interface in ANSYS provides an efficient and powerful environment for solving many anchoring problems. ANSYS enables virtual testing of structures using computers, which is the present trend in the research and development world. Concrete is represented as solid brick elements; the reinforcement provided by structural steel simulated by bar elements. All the necessary steps to create these models are explained in detail and the steps taken to generate the analytical load-deformation response of the beam are discussed. The results from the finite element model are compared with the experimental results by load deformation plots and cracking patterns.

4.1 Design Details of ferrocement channel section

The channel designed for Finite Element Model (FEM) in ANSYS 17.0 took up the experimental study for the analytical study. The same beam is modelled in ANSYS using the following procedure. To create the finite element model in ANSYS there are multiple tasks that are to be completed for the model to run properly. Models can be created using command prompt line input or the Graphical User Interface (GUI). For this model, the GUI was utilized to create the model. This section describes the different tasks and entries into used to create the FE calibration model.

Three basic steps involved in ANSYS include:

1. Pre-processing:

- Building FEM model
- Geometry Construction
- Mesh Generation (right element type)
- Application of Boundary and load conditions

2. Solving:

- Submitting the model to ANSYS solver

3. Post processing:

- Checking and evaluating results
- Presentation of Results-Stress/Strain contour plot, Load deflection plots etc.

4.2 Element Type Used in the Model

Concrete generally exhibits large number of micro cracks, especially, at the interface between coarse aggregates and mortar, even before it is subjected to any load. The presence of these micro cracks has a great effect on the mechanical behaviour of concrete, since their propagation during loading contributes to the nonlinear behaviour at low stress levels and causes volume expansion near failure. Some micro cracks may develop during loading because of the difference in stiffness between aggregates and mortar. Since the aggregate-mortar interface has a significantly lower tensile strength than mortar, it constitutes the weakest link in the composite system. This is the primary reason for the low tensile strength of concrete. The response of a structure under load depends largely on the stress-strain relation of the constituent materials and the magnitude of stress. The stress-strain relation in compression is of primary interest because mostly for compression members are cast using concrete. The actual behaviour of concrete should be simulated using the chosen element type. For the present type of model "mortar" material was created. The mortar material was used to model the concrete. This element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. The element has eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The solid capability may be used to model the concrete while the rebar capability is available for modelling reinforcement behaviour. Material Properties Parameters needed to define the material models were obtained from experimental study. Some of the parameters were obtained from the literature.

4.3 Loading and Boundary conditions for channel section

Displacement boundary conditions are needed to constrain the model to get a unique solution. To ensure that the model acts the same way as the experimental beam, boundary conditions need to be applied at where the supports and loadings exist. Loading applied was applied at loading point. at one end of the beam support, U_y is restrained to ensure roller support conditions and other end is restrained against x direction ensuring the symmetry boundary conditions along the longitudinal section. Similarly, along the z direction all the nodes are constrained ensuring symmetry boundary condition along cross section. The loading was applied on the nodes at one-third point. The range of load applied for flexure was between 100 N to 200 N for various dosages of load. The loading was applied at a distance of 666.67 mm from the support for span to depth ratio 13.3 for flexure. The bottom nodes are restrained in the longitudinal direction.

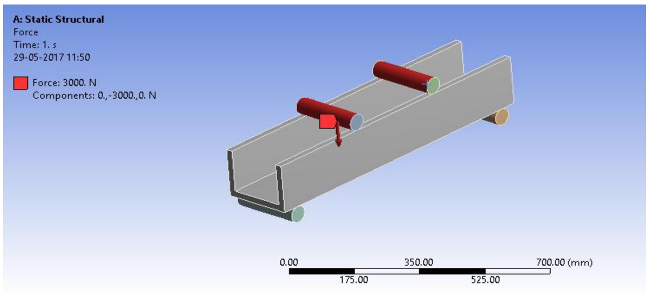


Figure-3. Support condition

The finite element model for this analysis is a simple beam under transverse loading. For the purposes of this model, the Static analysis type is utilized. The Solution Controls command dictates the use of a linear or non-linear solution for the finite element model. The analysis is small displacement and static type. The time at the end of the load step refers to the ending load per load step.

4.4 FE Analysis of ferrocement channel Beams

The ferrocement channel beam modelled in ANSYS 17.0 is compared with the experimental results. Typical ferrocement beam modelled in Ansys is shown in Figure 4-1. The loading applied was 100N to 200 N at a distance of 666.67 mm from the support.

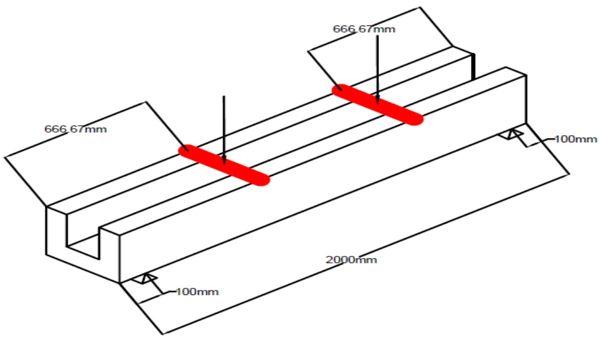


Figure-4. Loading Condition for U-Shape Channel Section.

5. RESULTS

Results of approximate analytical calculations are compared with the experimental values obtained are detailed in this chapter. The graphs obtained after testing different sections are also included. Also, comparative tables and comparative graphs are included in this section.

5.1 Flexural Strength Test Results

The test results of the samples at the age of 28 days from the day of casting are presented in following tables and graphs and compared with FEM results –

20mm Thickness (200mm X 150mm X 2000mm) 2 Layers welded channel section:

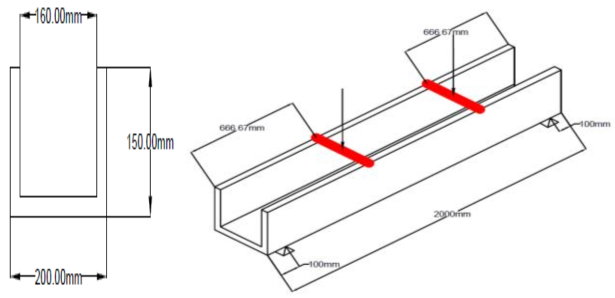
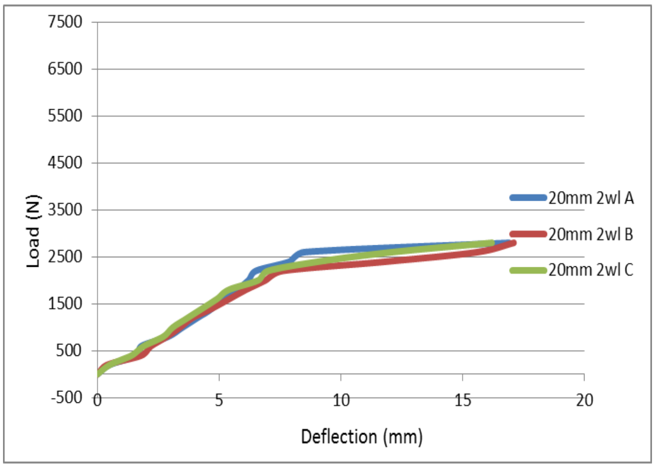
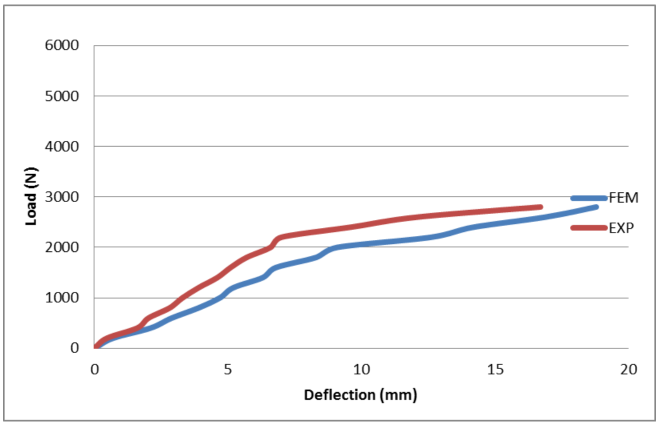


Figure 5.1. Loading condition for 20mm welded channel



Graph 1. Load-Deflection Curves using 2 Layer Welded mesh (20mm).



Graph 2. Comparing Experimental and FEM Results for 20 mm 2 Layer Welded Channel Section.

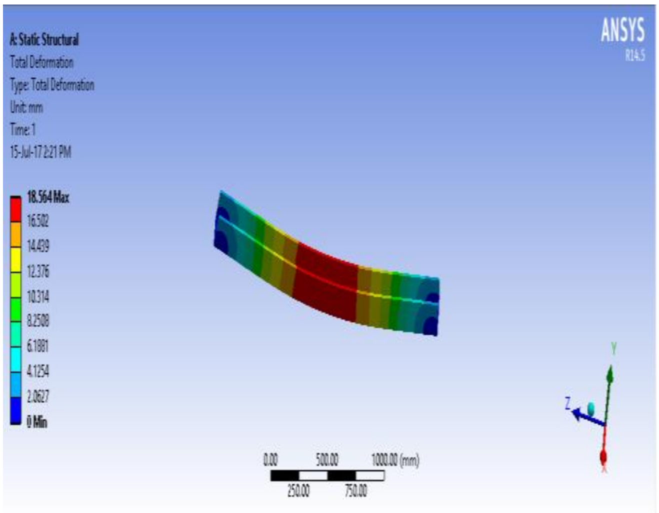


Figure 5.2. Maximum deflection using 2-layer welded mesh

Table 5.15. Experimental results and FEM results for deflection and flexural strength

No.	Description	Thickness (mm)	Ultimate load (N)	Deflection (mm)		Flexural Strength (MPa)	
				Experimental	FEM	Analytically	FEM
1.	20mm2-Wl	20	2800	16.7	18.56	2.81	2.24
2.	20mm2-Wo	20	2700	15.5	17.2	2.10	2.33
3.	30mm2-Wl	30	3700	17.4	16.2	2.22	2.39
4.	30mm2-Wo	30	3500	15.7	16.9	2.10	2.26
5.	30mm4-Wl	30	4550	15.8	17.5	2.73	2.94
6.	30mm4-Wo	30	4400	11.2	13.4	2.64	2.85
7.	40mm2-Wl	40	4300	15.2	16.5	2.58	2.40

8.	40mm2-Wo	40	4200	14.9	13.7	2.54	2.34
9.	40mm4-Wl	40	5225	12.7	14.6	2.07	2.92
10.	40mm4-Wo	40	5100	14.9	14.6	2.70	2.85
11.	50mm2-Wl	50	4900	14.5	16.3	2.38	2.50
12.	50mm2-Wo	50	4800	14.2	15.7	2.33	2.45
13.	50mm4-Wl	50	5900	11.8	13.1	2.87	3.01
14.	50mm4-Wo	50	5700	10.7	12.4	2.77	2.91

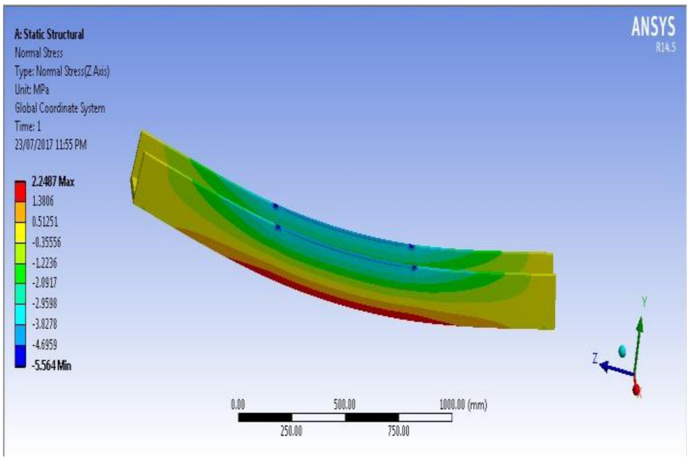
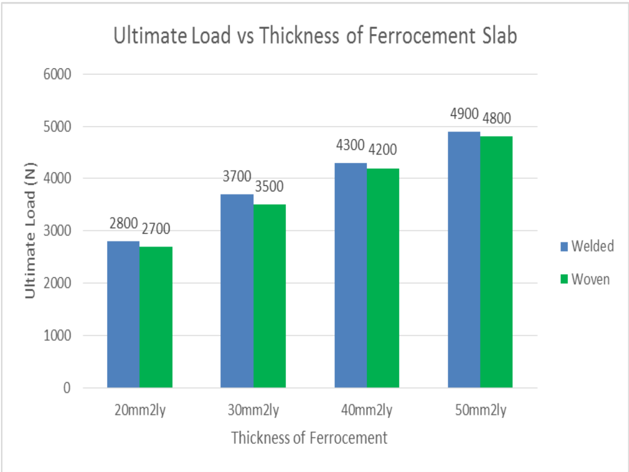
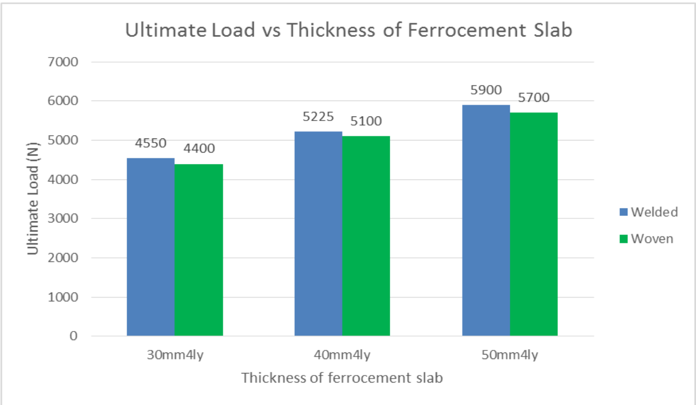


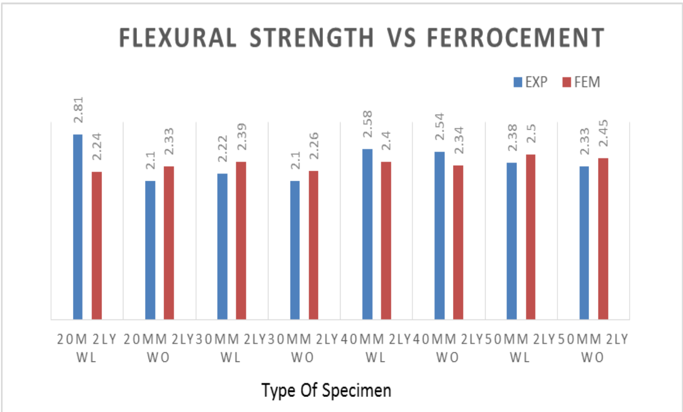
Figure 5.3. FE flexural strength for 20mm 2-layer welded channel section.



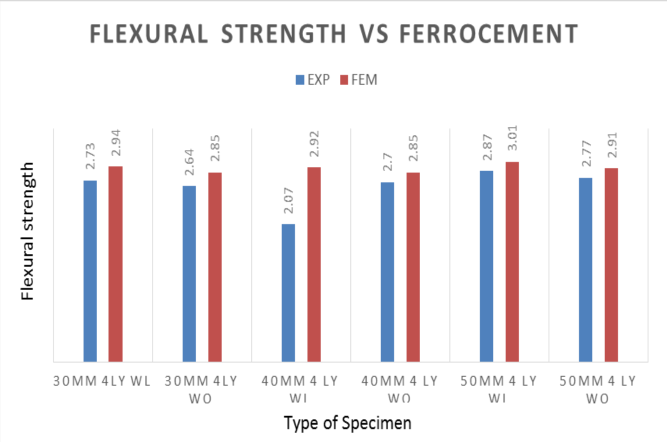
Graph 3.Ultimate load for 2-layer woven channel section.



Graph 4.Ultimate load for 4-layer woven channel section.



Graph 5. Flexural Strength of U-shape ferrocement channel 2-layer



Graph 6. Flexural Strength of U-shape ferrocement channel 4-layer

The test result of ferrocement U-shape channel section under four-point bending for experimental program and FE analysis using ANSYS software are presented in the above table. The load is applied to the ferrocement U-shape channel section until failure and the corresponding deflections were noted down. Total of three samples were tested for flexure for each specimen. The average value is taken as the experimental deflection value of the ferrocement channel. The value obtained from the experiment program is compared with that of the value obtained from FE analysis using ANSYS analysis software.

First table is for the welded mesh ferrocement specimen and the second table is for woven mesh ferrocement specimen. It is observed that the change in type of mesh from welded to woven changes the characteristic of the ferrocement channel under flexure. It is seen that the welded mesh specimen has more load carrying capacity than that of the woven mesh ferrocement channel and the maximum deflection for failure is more for the welded mesh ferrocement U-section. While increasing thickness of section from 20mm to 30mm it is observed that the load carrying capacity of the U-shape ferrocement section also increases. But the ductility of the channel decreases. The deflection of the U-shape channel decreased from 16.7 mm to 16.4 mm for welded mesh and 15.5 to 15.7 mm for woven mesh. There is an 50% percentage increase in load carrying capacity when thickness of U-shape channel section increased from 20mm to 40mm in welded mesh channel and there is 60% percent increase in load carrying capacity for that of the woven mesh.

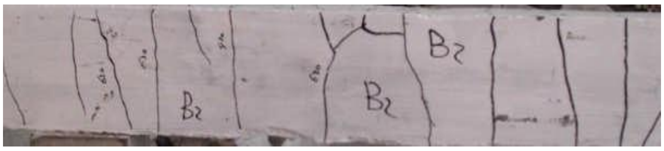
The summery of deflection of various panel having both woven and welded mesh is given Table 5.15. The name of the specimen is denoted in the order thickness of the section followed by the number of layer used in the specimen followed by the type of mesh used in the specimen. For example, in 20mm 2-Wl the "20mm" denote the thickness of the ferrocement slab is 20mm, "2" denotes two layers of mesh is used in the ferrocement and the "Wl" denotes welded mesh is used in the specimen. For woven mesh, the denotation "Wo" is used for naming. From the table, its observed that when the reinforcement used in the ferrocement section increases the ductility of the specimen also increases. It is seen that increase in thickness of specimen causes decrease in ultimate deflection of the specimen. Doubling the thickness of ferrocement panel from 20mm to 40mm while keeping same number of mesh the deflection is decrease from 16.7mm to 15.2mm for welded ferrocement panel. There is a 36 percent decrease in maximum deflection of welded ferrocement panel and 20 percent decrease in woven mesh ferrocement panel. While increase in number of layer from 2 to 4 layer it is noticed that the deflection of the section also increases as increase in the reinforcement causes increase in the ductility of the ferrocement slab. Both while increasing both the thickness of slab and number of layer of mesh it is noticed that the ductility of the material decreases. It is also noticed that the ductility of the welded mesh panel is more than that of the woven mesh panel.

In Table 5.15 the load carrying capacity of the two-layered welded and woven square mesh is given. From the graph, it is seen that the load carrying capacity of the welded mesh ferrocement U-section is more than that of the woven mesh ferrocement panel and it is also noted that while increasing the thickness of ferrocement panel in case of both welded and woven mesh there is an increase load carrying capacity. While increasing the sectional thickness from 20mm to 40mm load carrying capacity is increased to 35 percent for welded mesh ferrocement panel and 30 percentage increase for woven mesh panel. In the Table 5.15, maximum load carried by 30mm to 50mm four-layer mesh panel is given. When increasing the reinforcement used in the section for both welded mesh ferrocement panel and the woven mesh ferrocement panel the load carrying capacity also increases. When both thickness of panel and the reinforcement increased it is seen that the load carrying capacity also increased.

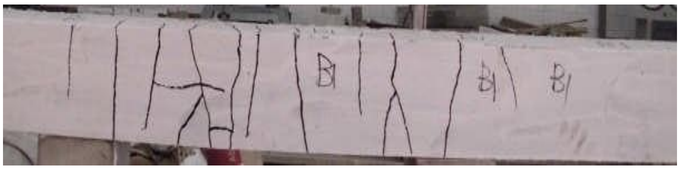
Flexural strength of ferrocement U-shape section is calculated using the equation.1 as given above. From the Table 5.16 and 5.17, it is observed that the flexural strength of ferrocement welded mesh U-shape section is more than that of the woven mesh ferrocement U-section channel section.it is also noticed that when the thickness of ferrocement section increases the flexural strength of the channel section decreases. When the thickness of the section increased from 20mm to 50mm and keeping the number of layers of mesh used same the flexural strength of the U-shape channel decreased to 25 percent for welded mesh ferrocement section and 20 for woven mesh ferrocement section. It is also seen that increasing the reinforcement used in the U-section causes an increase of the flexural strength of the panel.

Some photos showing failure that occur during testing of specimens as shown:

(a) web face-1



(b) bottom face



(c) web face-2

Figure 5.33. crack pattern for 20mm 2 layer welded

6. CONCLUSION

Based on the experimental and FEM results following conclusions are made.

1. The load carrying capacity and flexural strength of ferrocement channel section reinforced with welded square mesh is found to be more than that of ferrocement channel section reinforced with woven square mesh.
2. Flexural strength and load carrying capacity increases when the number of mesh layers increases from 2 to 4 numbers.
3. The proposed finite element model can be used efficiently in characterizing the behavior of ferrocement channel section under the flexural behavior.
4. The increase in the thickness of ferrocement channel section shows an enhancement in the load carrying capacity and decrease in the deflection.
5. The experimental results are in good agreement with the FEM results.

REFERENCES

[1] Alaa Abdel Tawab, Ezzat H. Fahmy, Yousry B. Shaheen, “Use of permanent ferrocement forms for concrete beam construction”, September 2012, Volume 45, Issue 9, pp 1319–1329

[2] Anisha G Krishnan, Allzi Abraham, “Experimental Study on the Effectiveness of Ferrocement as a Permanent Form Work for Beams”, Volume 5 Issue 9, September 2016

[3] Dr. C. Rama Chandrudu, Dr. V. Bhaskar Desai, “Influence of Fly ash on Flexural Strength of Ferrocement in Chemical Environment” UNIASCIT, Vol. 2 (4), (Page 324329) 2012.

[4] Dr.T.Chandrasekhar Rao, Dr.T.D.gunneswara Rao, Dr.N.V.Ramana Rao, Ch.Rambabu, “An Experimental Study On Ferrocement Box-Beams Under Flexural Loading”, ISSN 2250-2459, Volume 2, Issue 9, September 2012.

[5] Ezzat H. Fahmy, Mohamed N. Abou Zeid, Yousry B. Shaheen, Ahmed A. Abdelnaby, “Permanent Ferrocement Forms: A Viable Alternative for Construction Of Concrete Beams”, 30th conference on our world in concrete and structures: 23-24 august 2005, Singapore.

[6] Hassan M.H. Ibrahim (2011), “Shear capacity of ferrocement plates in flexure”, ElsevierEngineering Structures 33 (2011) 1680–168.

[7] K. Kesava, K. L. A. V. Harnadh, K. Nehemiya, “Experimental Investigation of Flexural Behaviour of Ferrocement Trough Type Folded Plate”, International Journal of Innovative Research and Advanced Studies (IJIRAS) Volume 4 Issue 2, February 2017.

[8] Laxmikant A Doddamaini, Vaijanath Hallali, “Generation of Strength Statistics for Concrete Beam with Alternative of Permanent Ferrocement form”, International Journal of Engineering Research & Technology, Vol. 3 - Issue 10 (October - 2014)

[9] Masood, M. Arif, S.Akhtar (2003), “Performance of ferrocement panels in different environments” Cement and Concrete Research 33 (2003) 555–562.

[10] P.SaranyaBanu, S.Dharmar, Dr.S.Nagan, “Flexural Behavior Of Trough Shape Ferrocement Panels” (IJIRST)Vol. 3, Issue 6, (Page 14010-14017) June 2014.

[11] S. Alnuaimi, A. Hago & K. S. Al-Jabri, “Flexural behaviour of ferrocement roof panels”, Department of Civil and Architectural Engineering, Sultan Qaboos University, Sultanate of Oman, WIT Transactions on The Built Environment, Vol 85, 2006

[12] T.M.Alhajri. M. M.Tahir, M.Azimi, J.Mirza, M.M.Lawan, K.K.Alenezi, M.B.Ragaee, “Behavior of pre-cast U-Shaped Composite Beam integrating cold-formed steel with ferro-cement slab”, Volume 102, May 2016, Pages 18-29.

[13] Yousry B.I. Shaheen, Noha M. Soliman, Ashwaq M. Hafiz, “Structural Behaviour of Ferrocement channels Beams”, Vol. 4 (3) –Sept. 2013.

[14] ACI Committee 549 “Guide for The Design, Construction and Repair of Ferrocement” (ACI.1R-93).

[15] ANSYS Help Manual (Version 17.0)