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Experimental and Cost Optimization of Prefabricated Elements Using Ferrocement

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Abstract - This study introduces a semi-fabricated system for the construction of floor slab. The slab panel consists of two layers joined together using truss type shear connectors. The first layer is a precast ferrocementlayer which acts initially as a formwork, while the second layer consists of bricks and mortar. Continuous truss shear connectors are used to connect the two layers. The paper experimentally investigates the structural response of ferrocement–brick composite panel under flexural load. Four full scale specimens were cast and tested under two-line loads. The study highlights the effect of shear connectors and brick layout on the overall structural response of the slab. The results in terms of load–deflection, crack pattern, strain distribution and failure loads indicate that the response of the composite slab to the flexural loading is satisfactory and can be used as a floor slab in construction sector.

Key words*:* Ferrocement, Pre fabrication.

I. INTRODUCTION

Prefabricated floor is used in the construction sector in many parts of the world. It is an alternative system used to overcome the formwork problems (cost and delay in construction) in addition to getting better quality control. It was found, however, that the prefabricated elements made of reinforced concrete are very heavy and difficult to transport and construct. In addition, concrete provides low thermal insulation quality, which is desired for living quarters and shelters. Jointing connectivity is another problem observed in precast construction, which leads to somehow, a less integrated structure. To reduce these deficiencies, a large number of precast systems have recently been developed. Pessiki et al. [1] summarized the use of 19 different precast structural floor systems that are suitable for office building construction in different parts of the world. Thin ferrocement panels were used in floor construction for low cost housing [2,3] due to its low cost and good structural performance. The introduction of insulating sandwich panels increased the attractiveness of this type of construction. The panels consist of thin layers of relatively higher strength material sandwiching a thick core, of normally much weaker and lower density material [4–6]. However, the high manufacturing and construction costs limit the use of precast sandwich panels in construction. The profiled sheeting–cement board composite is another recent development in the floor slab system [7,8]. The system consists of profiled sheeting attached to a top layer of dry board by simple mechanical connectors. Lightweight concrete with a density of 1000 kg/m3 was used as an infill material to act as a sound insulator for the floor. However, one of the limitations of this system is its low stiffness which results in a large deflection and development of cracks in the finishing elements connected to the slab. Half-slab construction technique is another development in the construction of floor slab [9,10]. The techniques employs reinforced precast floor panel that serve as permanent formwork which is composite with cast in situ concrete. Steel lattice trusses project from the top of the precast unit were used to connect the two layers and provides the unit with stiffness during erection. Again the heavy weight of the full slab and their low thermal efficiency are some of the disadvantages of the system. To develop a new floor slab system to overcome the shortcoming in the in situ concrete floor slab and existing precast floor systems is a challenging task for many researchers. As a summary, the main shortcomings in the existing systems could be one or more of the followings:

_ Long construction time.
_ Heavy weight.
_ Dependency on heavy equipment on job site.
_ Bad thermal and sound barrier.
_ Wastage of material
_ Dependency on formwork.
_ Does not ensure structural integrity.
_ Jointing problems.
_ High cost

This study introduces a semi-precast floor slab system; ferrocement– brick composite slab to address some of the above listed shortcomings in existing systems. The new system consists of a bottom ferrocement skin, brick masonry and in situ mortar ribs. The ferrocement layer is the precast part of the composite slab, which consists of a wire mesh and steel reinforcement, required to resist the tensile stresses. The thickness and reinforcement of this layer will depend mainly on the span of the slab. The brick layer and the in situ ribs provide the necessary resistance to the compressive forces developed due to bending. The two layers areinterconnected using truss type shear connectors.The advantages of this system, amongst others, are its relatively lighter weight

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compared to R.C which will reduce the load transferredto the beams/walls. The masonry bricks act as light (especially voided brick), natural, cheap effective insulation material and at the same time resisting partially the compression forces developed due to bending of the composite. On site, the construction of the composite slab does not require heavy equipments to handle the ferrocement layer. Furthermore, the construction does not need any formwork since the bottom layer of ferrocement is a precast unit that can be easily fixed in position, using simple crane, to provide a platform that acts as a formwork for the brick layer and the in situ concrete ribs. However, laying the brick might be labour intensive job especially in countries where the cost of labour is high. Alternatively, the masonry brick may be laid during casting the ferrocementlayer in the factory to reduce the need for intensive labour. The cold joint problem usually observed in precast constructioncould be eliminated in this system. The floor slab units togetherwith the supporting beams might be integrated during casting ofthe in situ mortar ribs.This experimental study is limited to investigate the structuralperformance of one way ferrocement–brick composite slab subjectedto two-lines loading. The study highlights the effects ofbricks layout and shear connectors layout on its overall structuralresponse in terms of load–deflection characteristic, ductility, straindistribution, composite action and failure load.

II. TEST PROGRAM

Four full scale one way (termed as S1 through S4) simply supported (using steel roller at one end and a square steel rod at the other end of the specimen) slab ferrocement–brick composite specimens 3 m long and 1 m wide were cast and tested under two-line loading. The specimens differ in brick layout and number of shear connectors. The shear connector used is a continuous steel truss made of 5 mm diameter mild steel zigzagged at 45_ angles. For the slab S1, S2, S3 and S4, the numbers of bricks used in each slab are 60, 93, 88 and 108 respectively. The composite slab details and shear connector layout are shown in Fig. 2, while the arrangements of bricks for each slab are shown in Fig. 3. In all the specimens, the thickness of ferrocement layer is fixed to be 60 mm reinforced with two layers of 1.2 mm diameter wire mesh of 12.7 _ 12.7 mm square opening and 10 mm diameter steel reinforcement as shown in Fig. 2. The brick layer is 65 mm thick (brick size 215 _ 90 _ 65). All the specimens were designed considering full composite action between the ferrocement layer and the layer of brick–concrete ribs. The surface areas and volumes of the bricks with respect to total surface area and total volume of the specimen are presented in Table 1 along with the number of trusses used as shear connectors and rib details in both longitudinal and transverse directions.

For both ferrocement layer and in situ mortar ribs, Ordinary Portland Cement and natural sand were used in a ratio of 1:3 with water/cement ratio of 0.5. The 28-day average cube strength of this mix was 30 MPa. The tensile strength of the wire mesh and steel reinforcement tested using Universal Test Machine was found to be 300 MPa and 415 MPa respectively. Initially, the ferrocementlayer is cast after preparing the wire mesh, steel reinforcement and shear trusses. Next the bricks are laid on the top of ferrocementlayer according to a specified layout for each specimen as shown in Fig. 4.

Fig. 1.Ferrocement–brick composite slab

All specimens were tested as simply supported slabs over 3 m span with two-concentrated line load applied at the middle-third of the slab. Typical set-up of two-line load test is shown in Fig. 5. The loads were applied gradually using a hydraulic jack of 100 kN capacity. At every increment of the load, the reading of dial gauges and strain gauges were recorded until failure of the slab specimen. A number of demec points were fixed along the depth on the sides to measure the strain variation with load. Deflection under the middle-third was continuously monitored using both dial gauges and displacement transducers (LVDT). The locations of the cracks were marked with the progress of the applied load.

III. STRUCTURAL RESPONSE

1) *DEFORMATION AND DUCTILITY CHARACTERISTICS*

In general, the deformation responses of all the composite slabs are comparable. All the specimens behave in an elastic manner before cracking after which the stiffness of the specimen reduces and the slope of the load–deflection curves decrease. This gradual loss of stiffness with increasing load is dueto cracking of concrete inferrocement layer, cracking of the mortar in the connector embedment regions and yielding of steel reinforcement. The slab specimens S1 and S2 with two longitudinal ribs (dual shear connectors) show different deformation responses after cracking. The slab with discontinuous brick layout ‘‘S1” shows 70% higher maximum deflection compared to the slab with continuous brick layout ‘‘S2”. This high percentage increase in ultimate deflection is associated with 10% difference in ultimate load betweenboth specimens.

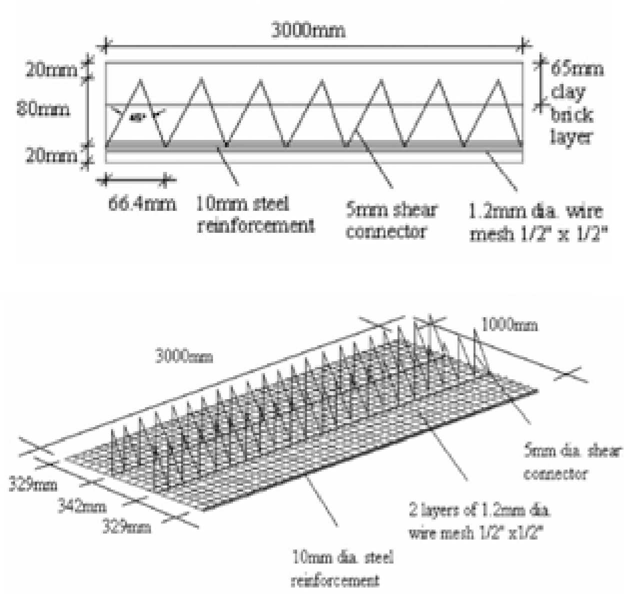


Fig. 2. Composite slab details and arrangements of shear trusses and steel reinforcement.

Table 1

Specimen	Cracking load (kN)	Yielding		Ultimate load		Ductility (du/dy)
		Load (kN)	Defl (mm)	Load (kN)	Defl. (mm)	
S1	9.5	19.6	15.3	30.6	39.4	2.6
S2	10.0	21.0	10.0	27.6	23.2	2.3
S3	8.2	17.5	14.0	34.7	47.7	3.4
S4	9.5	25.0	19.0	30.7	39.4	2.1

summarizes the cracking load of ferrocement, yielding load of main steel reinforcement, ultimate load at failure and deflection. In addition, the ductility of each specimen (defined here as the ratio of deflection at ultimate load to the deflection at yielding load) is calculated and presented in the same table. In general, all the tested specimens show ductility higher than 2.0, the specimens with continuous brick layout show less ductile behaviour compared with the specimens with discontinuous layout of bricks. This might be due to the gradual loss of bond between the bricks and surrounding mortar, which will take longer time in case of discontinues layout as the mortar surrounds all the sides of the bricks compared to two sides of the bricks in the continuous brick layout. The slab specimen S3 with discontinuous brick layout (longitudinal rib width of 65 mm and with 30% brick volume) and three shear connectors shows highest ductility compared to all other slab specimens. These ratios along with the large deflection observed and cracking might give sufficient warning before failure. The ductile behaviour is likely caused by cracking in the connections between the bent bar connector and the concrete that leads to a gradual loss of composite action and hence larger deflection. The maximum deflections at failure found in slab specimens with discontinuousbrick layout were 39.4 mm and 47.7 mm for slab specimen with dual and triple shear connectors respectively.

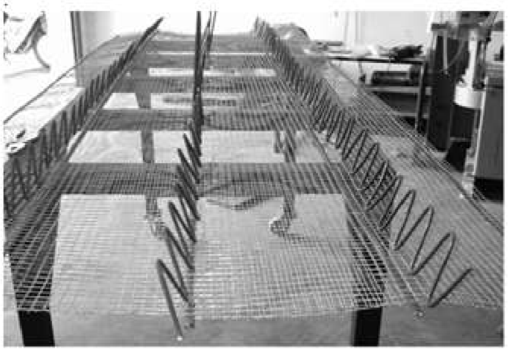


Fig. 4.Preparations of specimen.

(a) Line loads

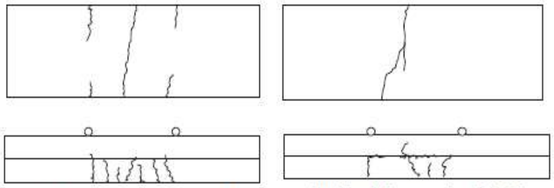
(b) Locations of displacement transducers.

Fig. 5. Test set-up.

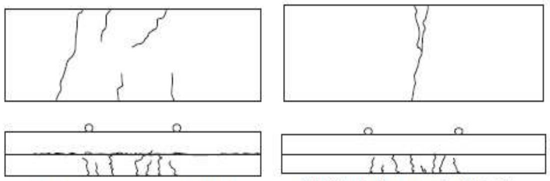
2) CRACKING CHARACTERISTIC

All specimens show similar cracking load ranges between 8.2 and 10 kN (about 30% of the ultimate load). The crack patterns observed are shown in Fig. 7. In general, these patterns are similar to those observed in reinforced concrete one way slab. All the cracks were located in the ferrocement layer. The majority of cracks are concentrated at the peak moment region. These cracks extended gradually upwards with the increase of the applied load. S3 slab specimen shows wider crack widths before failure compared to other slab specimens due to its higher ultimate load capacity. Cracking of the ferrocement layer results in a redistribution of the internal forces and increases the axial force in each layer.

Although the analytical calculation used to design the shear connectors was based on full composite section (see AppendixA), longitudinal cracks were observed at the intersection betweenthe two layers of the composite in all specimens in the advanced stage of loading. The separation was observed after yielding of steel and started at the mid span and gradually extended towards the ends. This might be due to the development of minor cracks nearby the steel reinforcement, which in turn causes slipping between the layers and steel trusses.



(a) Crack Patterns for Slab S1 (b) Crack Patterns for Slab S2



(c) Crack Patterns for Slab S3 (d) Crack Patterns for Slab S4

Fig. 7. Crack patterns for different specimens.

Furthermore, the small area of steel truss members (5 mm) might result in buckling of the diagonals which are in compression. This in turn will leads to only one half of the truss diagonals effectively resisting the horizontal shear force. The ultimate strengths of these panels were however found to be comparable with the analytical moment capacity.

The ultimate failure loads found were 30.6, 27.6, 34.7 and 30.7 kN for S1, S2, S3 and S4 respectively. The ultimate moment which can be resisted by the slab specimens ranges between 14 and 17 kN m/m width of the slab. Again, the specimens with discontinuous brick layout for both layouts of shear connectors show higher ultimate load compared to those with continuous brick layout. This was observed in both types of specimens i.e. those with two and three shear connectors. This is due to the presence of transverse ribs which stiffens the longitudinal main ribs. However, this effect is not significant as the maximum difference in the ultimate load of the slab specimen with discontinuous and continuous brick layouts is found to be only 13%.

Based on the analytical calculation using BS8110 [11] presented in the Appendix A, the estimated ultimate load for the slab specimens with dual and triple shear connectors are respectively equal to 26.7 and 25.1 kN if the material safety factors are used and equal to 31.5 kN and 30.0 kN when the material safety factors are ignored. The analytical calculation estimates lower ultimate load in the slab specimens with three shear connector compared to slab with two shear connectors due to the smaller total width of the longitudinal ribs. The experimental failure loads were found to be 14.6%, 3.4%, 38% and 22% higher than those estimated analytically for slab specimens S1, S2, S3 and S4 respectively (in case of ignoring the material safety factors these ratios become _2.8%, _12.4%, 15.6% and 2.3%). Moreover, after yield of steel reinforcement, nonlinear strain distribution was observed due to loss of compositeaction at the edges of the slab specimens. The specimens with triple shear connectors exhibit higher experimental capacity compared to dual shear connectors specimens although the total width of the ribs in triple shear connectors (of 277 mm) is smaller than that in dual shear connectors (of 354 mm). This contradicts with the analytical calculation where it is anticipatedthat the higher the rib width, the higher moment capacity willbe. This might be due to more uniform distribution of load betweenthe ribs, especially in the advanced stage of loading after yielding of the steel reinforcement.

3) STRAIN DISTRIBUTION

The distributions indicate that the two layers act in composite manner at lower applied load and before yielding of steel. A horizontal slip between the two layers started after the steel yielded, thus reflecting a semi composite behaviour as indicated in the strain distribution. This complies well with the occurrence of horizontal crack between the two layers after yielding of steel reinforcement in the ferrocement layers. Furthermore, it can be seen from Fig. 8 that there is very limited change in the neutral axis position after cracking. This might be due to the large width/depth ratio. After yielding of steel reinforcement there is a slight upward shift in the neutral axis position and the variation of strains become nonlinear due to the loss of composite action between the two layers at the slab edges.

IV. CONCLUSION

This paper introduces a semi-fabricated composite slab and investigates its structural behaviour under flexural load. The composite slab consists of two layers joined together using truss type shear connectors. The first layer is a precast ferrocement which acts initially as a formwork, while the second layer consisting of bricks and mortar.

The test results indicated that the slab can resist an average bending moment of 15 kN m/m. The ductility ratios observed are more than 2 and this is associated with large deformation and cracks. The cracking load observed is about 30% of the ultimate failure load and their patterns are similar to those observed in a typical reinforced concrete one way slab. The specimens with discontinuous brick layout and three trusses type shear connector layout show better structural performance in terms of ductility compared to the specimens with continuous brick layout and two shear connectors. The transverse ribs (in discontinuous brick layout) only enhance the ductility of the slab compared with the specimen without transverse ribs (continuous brick layout). The experimental failure loads especially for the slab specimens with triple shear connectors were found to be higher than those estimated analytically.

From the distribution of strain across the depth of the slab, the two layers are acting initially in full composite manner and the shear connecter used is capable of integrating both layers. However, before failure, the two layers start to separate at the mid span by forming a horizontal longitudinal crack. For better response, the shear connection needs to be modified to ensure the full integrity at high flexural load.

The predicted ultimate load using BS8110 were found to be compatible with those obtained experimentally. However when considering the material safety factor in the design; BS 8110 may provide a conservative design for the composite slab.

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