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STRENGTHENING OF RC BEAMS IN FLEXURE USING FERROCEMENT*

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Abstract– Assessment of the effectiveness of ferrocement strengthening techniques i.e., cast in situ Ferro-mesh layers and precast ferrocement Laminate is the aim of this experimental investigation. To accomplish this objective, ten (10) reinforced concrete beams including one control beam have been intentionally designed and detailed to fail in flexure. Prior to strengthening, beams have been tested under two-point loading till service limit. Beams have been strengthened in the flexural dominant region only and tested to failure under the same loading arrangement. It has been concluded that strengthening through cast in situ Ferro-mesh layer is the most efficient technique, whereas strengthening of the beams by using precast Ferrocement Laminate *B* is not only easy to implement at household level, but is also promising in terms of enhancing load carrying capacity, stiffness and ductility.

Keywords– Ferrocement, ferro-mesh, laminate, layers, flexural strengthening

1. INTRODUCTION

Structural members are usually designed to sustain required loading, however they may require upgrading or strengthening due to a variety of reasons including, human error, structural design and/or construction, amendments in practicing design standards/codes, structural deterioration due to ageing and environmental exposure, abusive use of buildings in the form of change in the utility of the structure resulting in an increase in the live load and stress concentration in structural members. The term "Strengthening" is, therefore, not only associated with existing structures but also newly built structures. Hence strengthening of structures is an essential domain for the researchers.

After its first use by Joseph Louis Lambot in 1948, ferrocement was utilised in a number of practical applications such as repair of shear damaged reinforced concrete beams, beams and slab with excessive deflection, joints, repair/strengthening of brick masonry columns [1] as well as plain concrete column [2,3]; it has been found that use of ferrocement is advantageous in terms of enhancement of load carrying capacity [4-6], better cracking behaviour, ductility, energy absorption properties [5, 6], stiffness [7, 8] and flexural capacity [7]. It may even lead to failure of RC section in a ductile manner, if a beam is designed for steel above the balanced reinforcement percentage [8]. To date, diverse experiments have been conducted using ferrocement to observe the effect of wire-mesh orientation, number of wire-mesh layers, type of wire-meshes and influence of cover thickness on the behaviour of ferrocement and it has been concluded that zero degree wire mesh orientation is the most efficient on the basis of lowest cost to strength ratio [4]. It has been found that number of wire-mesh does not significantly influence the performance [6]. Performance of chicken wire-mesh has been found to be better than any other type in terms of cracking resistance and bending moment [9], whereas cover thickness has a significant influence

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on the static moment capacity, flexural fatigue life, crack spacing and width, based on theoretical and experimental studies [10].

Computer based programming has also been utilized to design and determine the ultimate moment capacity and to calculate steel stress for a given section and ultimate moment [11, 12]. Recently, a new strengthening method based on High Performance Ferrocement Laminate (HPFL) comprised of grid rebar and ordinary cement mortar which contained polyethylene fibre, ettringite expansion agent, water reducer, and fly ash has been introduced and has been reported to be very useful in preventing the development of undesirable cracks [13]. Theoretical models of HPFL to evaluate the bending capacity, bending stiffness and the shear stiffness of the concrete members have also been proposed [13].

Although the strengthening of RC beams in flexure has been successfully practiced using tensile overlay [14], steel plate [15-17], external post tensioned prestressing [18-22], fibre composites [23-25], external unbonded reinforcement [26], carbon fibre reinforced polymer (CFRP) [27] and other newer techniques, strengthening with ferrocement is gaining respect as well. In the authors' view, tensile overlay, steel plate and ferrocement are most suited in rural areas. In tensile overlay, 97% of load carrying capacity of original beam has been achieved [14] and with steel plate 29% increase in load carrying capacity has been attained [16]. Steel plate bonding and tensile overlay are limited by the percentage of reinforcement already provided in the beam to be strengthened. Similar is the case of ferrocement, increase in the number of layers increases strengthening, however, the number of layers can also be increased up to a certain limit depending on the reinforcement already provided in the beam to be strengthened. Undoubtedly, all strengthening techniques do possess varying merits, however, the versatility of ferrocement technique is its low cost, readily available materials, simplicity in construction, reasonable quality control along with good strength and cracking resistance, which makes ferrocement especially suitable for rural areas of the developing world. Concrete is used frequently in rural areas nowadays and the cement and sand is easily accessible. Even the wire-meshes are also readily available due to its use in many other household works. Ferrocement is also known to be a forgiving material and can, therefore, sustain varying atmospheric conditions satisfactorily [28]. Ferrocement can also sustain abuses due to lesser skill of rural workers in comparison to other construction techniques.

The present investigation focuses mainly on flexural strengthening of under-reinforced RC beam in the constant moment region by varying the number of Ferro-mesh layers and its development length using three techniques: cast in situ Ferro-mesh layers, Precast Ferrocement Laminates in two forms identified as Ferrocement laminate *A* and Ferrocement Laminate *B*. As far as the knowledge of the author(s) of this paper is concerned, cast in situ Ferro-mesh layers is investigated only in this study, whereas ferrocement Laminates have been investigated earlier [7], in this study, however, a newer way of using laminates has been investigated.

2. TEST PROGRAM

Test program has been designed keeping in mind the available laboratory resources, skills of the rural population and practical utility of the technique in rural areas of the developing world. The cross section and span length of all beams have been kept the same and beams have been detailed to ensure the flexural mode of failure. The parameters for structural behaviour have been limited to stiffness, load carrying capacity, failure mode and ductility of the beams by varying number of wire mesh layers, development length and technique of application, i.e. cast in situ Ferro-mesh layers, Ferrocement Laminate *A* and Ferrocement Laminate *B*.

a) Material and mechanical properties

Concrete: Ordinary Portland cement, sand (passing through 3.125 mm ASTM sieve), coarse aggregate (passing through 12.5 mm and retained on 4.75 mm ASTM sieves) were used for all specimens. The mix proportions and water cement ratio have been selected as per local rural practice with water cement ratio of 0.5 and 1:2:4, cement: fine aggregate: coarse aggregate proportion. The average compressive strength of concrete was found to be 23.3 MPa.

Steel: Locally available deformed steel bars of 12 mm diameter (f_y = 504 MPa) were used as flexural reinforcement and plain mild steel bars of 6 mm diameter (f_y = 330 MPa) were used for hanger and transverse shear reinforcement for all beams.

Mortar: Mortar with a mix proportion of 1:2 by weight with water cement ratio of 0.5 was used to prepare Ferro-mesh layers whether cast in situ or precast. Briquette specimens and cubes have been prepared to evaluate the tensile strength and compressive strength of mortar respectively. The average compressive strength of mortar has been found to be 20 MPa.

Ferro-Mesh: Locally available gauge 18 woven square Ferro-mesh (f_y = 383 MPa) with opening size of 6 mm, having the wire diameter of 1.1 mm was used. Sample of Ferro-mesh is shown in Fig. 1.

b) Preparation of specimens

A total of ten (10) RC beams having a concrete section of 150 mm × 200 mm and a total length of 1800 mm were cast. The test spans of all the beams were kept at 1650 mm with constant shear span to depth (a/d) ratio of 3.3. All beams had been identically designed and detailed as under-reinforced beam using steel percentage of 0.968 according to the provisions of ACI 318R-05 [29]. Typical reinforcement detail for all the beams is shown in Fig. 2. Each beam was cast along with three cylinders of 150mm x 300mm to evaluate the compressive strength ($f_c^{'}$) of concrete. After casting the beams, all beams were wet cured for 14 days, and then the faces of all the beams were white washed to increase the visibility of cracks during testing.

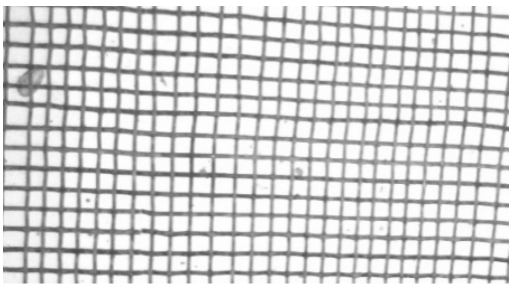
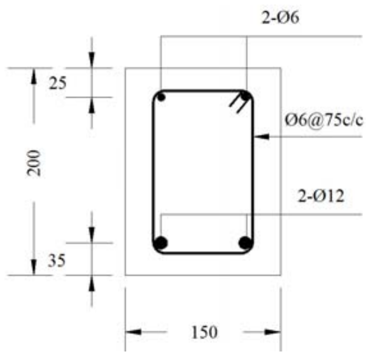


Fig. 1. Sample woven Ferro-mesh



(All dimensions are in mm)
Fig. 2. Typical beam reinforcement

b) Preparation of specimens

A total of ten (10) RC beams having a concrete section of 150 mm × 200 mm and a total length of 1800 mm were cast. The test spans of all the beams were kept at 1650 mm with constant shear span to depth (a/d) ratio of 3.3. All beams had been identically designed and detailed as under-reinforced beam using steel percentage of 0.968 according to the provisions of ACI 318R-05 [29]. Typical reinforcement detail for all the beams is shown in Fig. 2. Each beam was cast along with three cylinders of 150mm x 300mm to evaluate the compressive strength ($f_c^{'}$) of concrete. After casting the beams, all beams were wet cured for 14 days, and then the faces of all the beams were white washed to increase the visibility of cracks during testing.

c) Testing of beam specimens

Nine (09) beams were initially tested up to 45% of theoretical ultimate load carrying capacity, taken as service load based on working stress design approach, as shown in Fig. 3 and then unloaded. After unloading, beams were strengthened and then tested up to failure. The control beam, however, was tested up to failure under the same loading condition. The load increment has been kept as 5 kN.

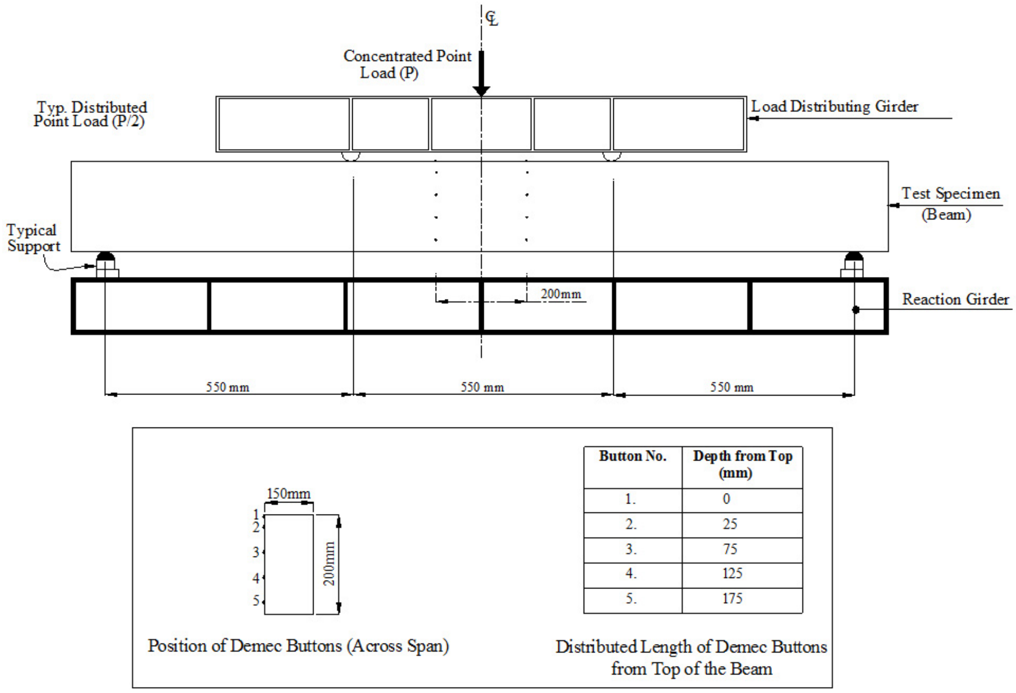


Fig. 3. Typical loading arrangement for the tested beams

d) Strengthening strategy

Nine (09) RC beams were divided into three groups labelled as ‘A’ ‘B’ and ‘C’ based on the respective strengthening technique. Group ‘A’ was comprised of four (04) beams which have been strengthened using cast in situ Ferro-mesh layers. Group ‘B’ was also comprised of four (04) beams strengthened using precast Ferrocement Laminates *A* prepared by using mortar and Ferro-mesh having the following size and number of layers:

- 125 mm x 18 mm cross section and 700 mm length with 2-layers of Ferro-mesh
- 125 mm x 18 mm cross section and 700 mm length with 3-layers of Ferro-mesh
- 125 mm x 18 mm cross section and 850 mm length with 2-layers of Ferro-mesh
- 125 mm x 18 mm cross section and 850 mm length with 3-layers of Ferro-mesh Group ‘C’ was comprised of one (01) beam strengthened using precast Ferrocement Laminate *B* having the same attributes as for Laminates *A* given above and is only the application of Laminate *A* and Laminate *B* on the beams that differ. The methodologies for all the groups have been described in the latter part of this paper. Group description and nomenclature of the beams are summarized in Table 1.

For strengthening, soffit of the beams of the groups ‘A’ and ‘B’ were chiselled in the constant moment region including development length (75 mm or 150 mm) as shown in Fig. 4 and Fig. 5, cleared of loose debris and cleaned with wire brush. A slightly larger development length as determined by using Eq. 12-1 of ACI 318-05 [29] was provided and kept as 75 mm or 150 mm as shown in Fig. 4.

The beam of group ‘C’ was used for application of strengthening technique without chiselling the beam and the Ferrocement Laminate *B* was glued at the soffit of the beam. Hairline cracks which appeared on the beam surface after testing up to 45% of theoretical ultimate load carrying capacity were not filled only to avoid additional application skills at rural level. Further details of strengthening are discussed as under:

Strengthening through cast in situ Ferro-mesh layers (Group 'A'): After chiselling soffit of the beam and preparing the surface, Ferro-mesh was anchored to beam through nails and then mortar applied to finish the soffit in such a manner that beam depth remained the same as shown in Fig. 4. After hardening of mortar, beams were wet cured for 14 days and were then tested up to failure.

Strengthening Through Precast Ferrocement Laminates A (Group 'B'): Soffit of all the beams of group 'B' were chiselled to a length shown in Fig. 5 to expose stirrups. After chiselling, connectors were placed over the exposed stirrups, and then mortar was applied to fix the connectors with stirrup. After hardening and curing of mortar, precast Ferrocement Laminates were fastened with connectors through nuts in such a manner that beam depth remained the same as shown in Fig. 5 (refer Detail "D") and Fig. 6. Finally, mortar was applied on the side of the beam to finish the work as shown in Fig. 6 (d). After hardening of mortar, beams were wet cured for 14 days and then tested up to failure. This method of application of Laminate has been named "Strengthening through precast Ferrocement Laminates *A*".

Strengthening Through Precast Ferrocement Laminate B (Group 'C'): Epoxy resin was applied on the surface of the beam soffit after cleaning the surface and then Laminate was attached to the epoxy coated surface of the beam as shown in Fig. 7 and Fig. 8. This method of application of Laminate has been named "Strengthening through precast Ferrocement Laminates *B*". One specimen has been tested only to observe its behaviour and effectiveness and if found satisfactory may be taken up in an extended study.

Table 1. Beam Nomenclature and Description

Group	Strengthening technique	Nomenclature	Description
	-	Control beam	Beam designed as under reinforced and stirrups provided only in shear span.
Group 'A'	Cast in situ Ferro-mesh layers	Beam "Aii-3"	Beam strengthened in flexure with cast in situ Ferro-mesh layers comprising two layers of Ferro-mesh strengthened at constant moment region + development length of 75 mm (3")
		Beam "Aii-6"	Beam strengthened in flexure with cast in situ Ferro-mesh layers comprising two layers of Ferro-mesh strengthened at constant moment region + development length of 150 mm (6")
		Beam "Aiii-3"	Beam strengthened in flexure with cast in situ Ferro-mesh layers comprising three layers of Ferro-mesh strengthened at constant moment region + development length of 75 mm (3")
		Beam "Aiii-6"	Beam strengthened in flexure with cast in situ Ferro-mesh layers comprising three layers of Ferro-mesh strengthened at constant moment region + development length of 150 mm (6")
Group 'B'	Precast Ferrocement Laminate *A*	Beam "Bii-3"	Beam strengthened in flexure with precast Ferrocement Laminate *A* comprising two layers of Ferro-mesh strengthened at constant moment region after chiselling + development length of 75 mm (3")
		Beam "Bii-6"	Beam strengthened in flexure with precast Ferrocement Laminate *A* comprising two layers of Ferro-mesh strengthened at constant moment region after chiselling + development length of 150 mm (6")
		Beam "Biii-3"	Beam strengthened in flexure with precast Ferrocement Laminate *A* comprising three layers of Ferro-mesh strengthened at constant moment region after chiselling + development length of 75 mm (3")
		Beam "Biii-6"	Beam strengthened in flexure with precast Ferrocement Laminate *A* comprising three layers of Ferro-mesh strengthened at constant moment region after chiselling + development length of 150 mm (6")
Group 'C'	Precast Ferrocement Laminate *B*	Beam "Cii-6"	Beam strengthened in flexure with precast Ferrocement Laminate *B* comprising two layers of Ferro-mesh strengthened at constant moment region + development length of 150 mm (6")

Nomenclature Description: Aii-3

Development length (in)

Numbers of ferro-mesh layer(s)

Group based on strengthening technique

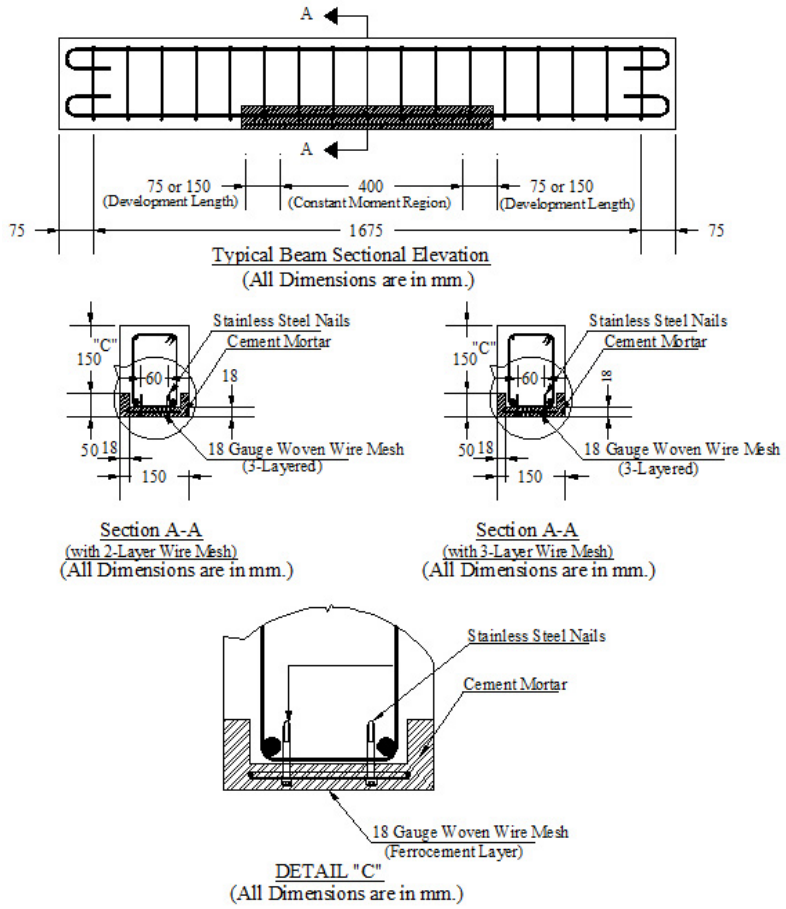


Fig. 4. Detail of beam with cast in situ Ferro-mesh layers (Group 'A')

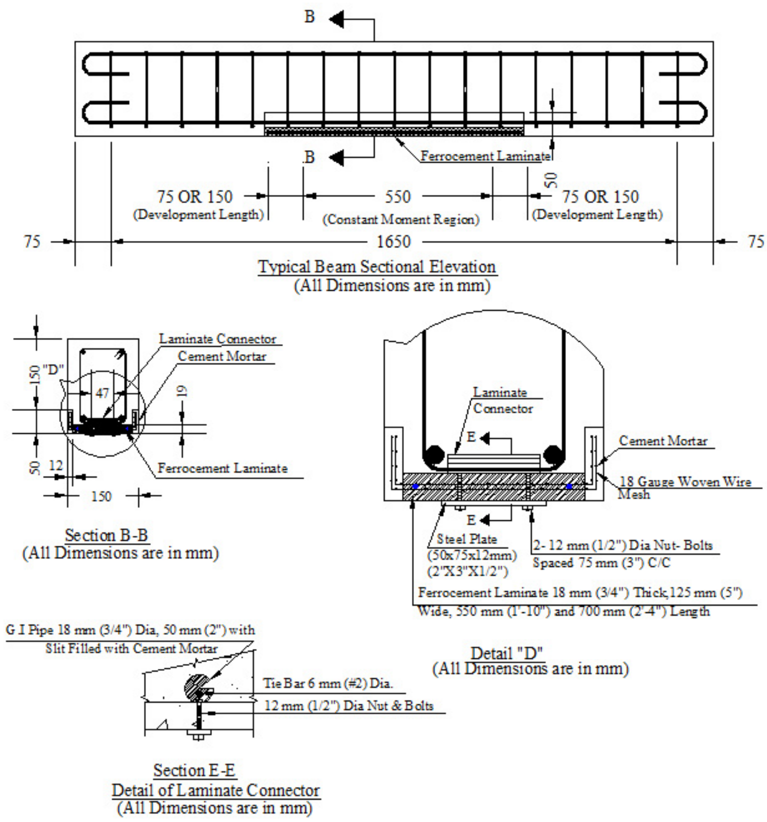
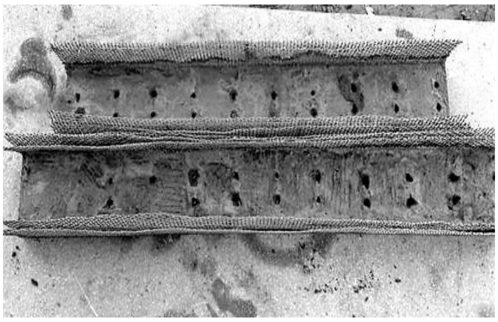


Fig. 5. Detail of beam with precast Ferrocement Laminate *A* (Group 'B')



(a) Ferrocement Laminates 700 mm and 850 mm long

(b) Placement of the connectors in the chiselled beam

(c) Finishing Surface of beam soffit after fastening Ferrocement Laminates with the connectors

(d) Beam soffit with Ferrocement Laminate *A* after white wash

Fig. 6. Method of attachment of precast Ferrocement Laminate *A* (Group 'B')

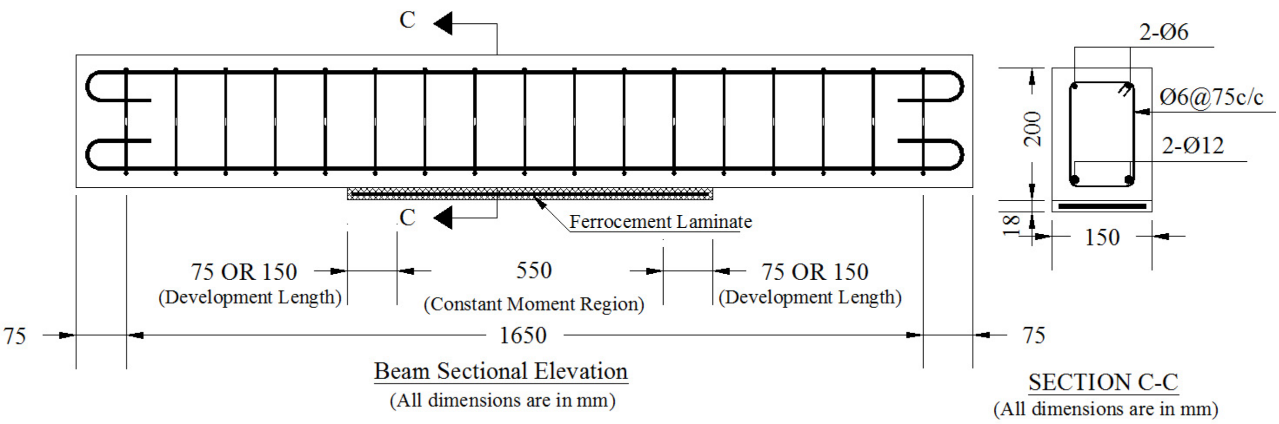
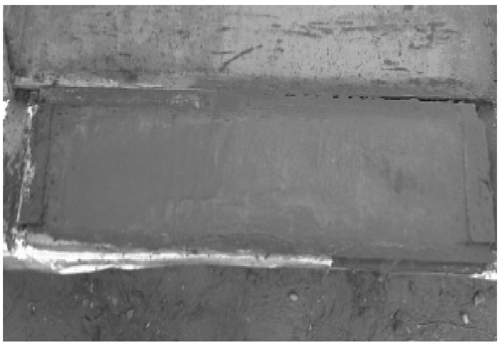


Fig. 7. Detail of beam with precast Ferrocement Laminate *B* (Group 'C')



Preparation of Ferrocement Laminate

Ferrocement Laminate placed to the inverted beam

Fig. 8. Inverted beam with precast Ferrocement Laminate *B* (Group 'C')

3. TEST RESULTS AND INFERENCES

Test results have been presented in Table 2 and Table 3. In this experimental study, performance of RC beams strengthened through different ferrocement strengthening techniques, has been analysed on the basis of two parameters i.e., number of Ferro-mesh layers and development length in order to identify the most effective strengthening techniques. Experimental results are primarily compared within and across each group with respect to load carrying capacity and failure mode, while other parameters have also been studied including stiffness, ductility and crack patterns.

a) Effect of ferro-mesh layers and development length on load carrying capacity

In Group ‘A’ and Group ‘B’, beams with two layers and three layers having development lengths of 75mm and 150 mm, showed increase in load carrying capacity with increase in number of layers, establishing that increase in Ferro-mesh layers favour the load carrying capacity. On the other hand, beams with the same number of Ferro-mesh layers having development length of 75mm and 150 mm showed decrease in load carrying capacity with increase in development length, establishing that increase in development length has an unfavourable effect on load carrying capacity.

An increase of 16% has been observed in load carrying capacity in one beam of Group ‘C’. This rise in load carrying capacity may contribute to modest level increase in live load needed in rural applications. An increase of 16% in load carrying capacity is also significant in comparison to the conventional strengthening method by tensile overlay and steel plate. Although, Group ‘C’ gave promising results, only one specimen was available. Therefore, this may be considered as a shortcoming of the present study, however, it opens a new area for further investigation. As discussed above, the development length may not matter, however, number of Ferro-mesh layers and other parameters may influence the performance of Group ‘C’ which needs further investigation.

Table 2. Theoretical and experimental failure loads

Group	Nomenclature	Compressive Strength at 28 days (MPa)	Experimental Failure Load (kN)	Theoretical Failure Load (kN) as per ACI 318-05[29]/ ACI 549.1R-93 [30]	% Increase in experimental loads as per CB	% Deviation in theoretical and experimental loads	Remarks
Control Beam	CB	24.2 (3.5 ksi)	62.4	66.82	-	-	1. Failure mode of all beams is Flexure. 2. Experimental results are validating theoretical results as per ACI 318-05[29]/ ACI 549.1R-93 [30]
Group ‘A’	Beam “Aii-3”	22 (3.1 ksi)	73.06	70	+15%	+ 4.2%	
	Beam “Aii-6”	22 (3.1 ksi)	72.32	70	+13.9%	+ 3.2%	
	Beam “Aiii-3”	22 (3.1 ksi)	75.4	72.8	+18.7%	+ 3.4%	
	Beam “Aiii-6”	25 (3.6 ksi)	73.06	72.8	+13%	+ 0.4%	
Group ‘B’	Beam “Bii-3”	24 (3.4 ksi)	65.14	70	+2.2%	- 7.4%	
	Beam “Bii-6”	24 (3.4 ksi)	66	70	+3.4%	- 6%	
	Beam “Biii-3”	23 (3.3 ksi)	74.84	72.8	+15.5%	+2.7%	
	Beam “Biii-6”	23.6 (3.4 ksi)	68	72.8	+6.15%	- 7.1%	
Group ‘C’	Beam “Cii-6”	23 (3.3 ksi)	75.32	75	+16.1%	+ 0.4%	Failure mode of beam is flexure.

b) Effect of ferro-mesh layers and development length on failure modes

All beams failed in flexural mode. Delamination in all beams of Group ‘A’ and ‘B’ has been observed to be minimal as 90^{o} bend length of Ferro-mesh was provided on the side faces of the beam, that helped to a great extent in preventing delamination of the ferrocement.

c) Other results

Mid-span deflection measured in all beams at a fixed interval of 5 kN has been presented in graphical form in Fig. 9. Parameters evaluated from the load-deflection diagram have been described and discussed in the succeeding section.

Effect of ferro-mesh layers and development length on initial stiffness: The initial stiffness of beams of Group 'A' increases with the increase in development length whereas stiffness of beams of Group 'B' reduces with increase in development length. In Group 'A' and 'B', beams with two layers showed lesser stiffness than the beams with three layers due to the lesser volume fraction of mesh reinforcement. Average stiffness of beams of Group 'A' and 'C' has been found to be the same while beams of Group 'B' showed lesser stiffness than the Group 'A' and 'C'.

Effect of ferro-mesh layers and development length on ductility: Ductility measured in terms of ductility ratio is defined in Table 3. There is no increase in ductility ratio in beams of Group 'A' and 'B' strengthened with two layers of Ferro-mesh with development length of 75mm and 150 mm. On the other hand, the ductility of the beams of Group 'A' and 'B' strengthened with three layers of Ferro-mesh with development length of 75mm and 150 mm increases as shown in Table 3.
The average ductility ratio of the beams of Group 'A' is 2.805 which is slightly higher than the beams of Group 'B'.

Effect of ferro-mesh layers and development length on cracks pattern: Beams of Group 'A' have shown the least number of vertical cracks, whereas the bond related horizontal crack propagated along the interface of ferrocement and beam, suggesting weaker composite action. Beams of Group 'B' showed better composite action as cracks showed propagation from ferrocement Laminate to beam. Beam of Group 'C' has also shown better crack pattern. No sign of significant delamination of ferrocement was observed, as shown in Fig. 10.

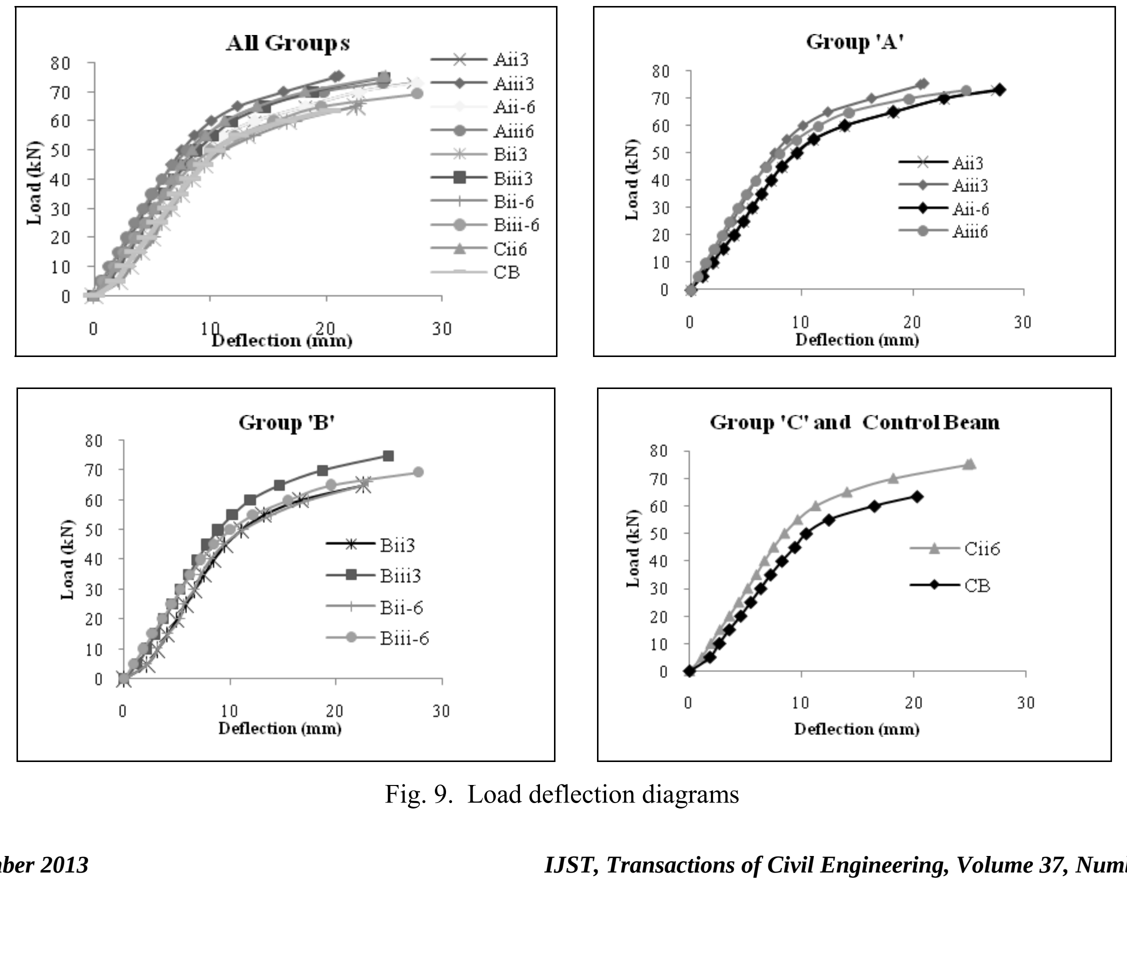
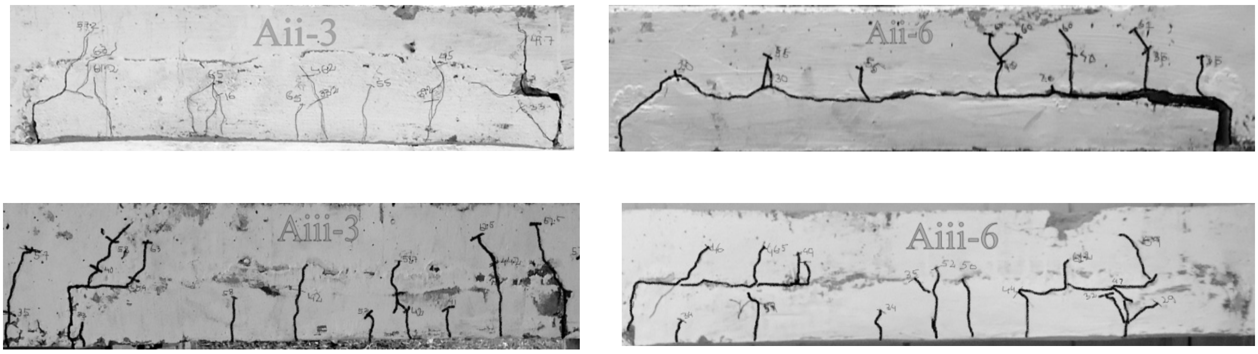


Fig. 9. Load deflection diagrams

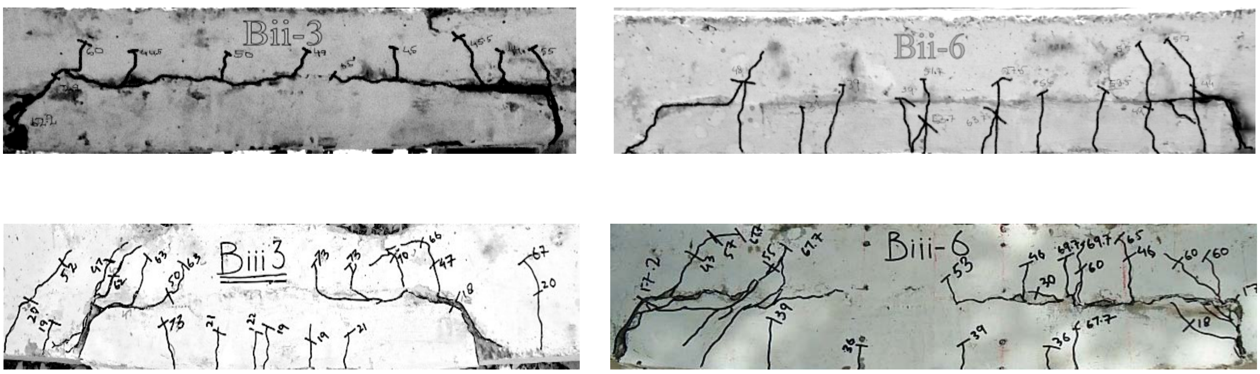
Table 3. Stiffness and Ductility

Group	Nomenclature	Stiffness before yielding P/Δ N/m	Δ_y mm.	Δ_u mm.	Ductility ratio = Δ_u/Δ_y
Control Beam	CB	4.72	9.4	20.32	2.16
Group ‘A’	Beam “Aii-3”	5.30	9.42	27.49	2.91
	Beam “Aii-6”	5.41	9.568	27.85	2.91
	Beam “Aiii-3”	5.84	9.063	21.02	2.32
	Beam “Aiii-6”	6.33	8.056	24.84	3.08
Group ‘B’	Beam “Bii-3”	4.81	9.548	22.62	2.37
	Beam “Bii-6”	4.71	9.8	23	2.34
	Beam “Biii-3”	5.07	10.24	25	2.44
	Beam “Biii-6”	4.89	10.00	27.83	2.78
Group ‘C’	Beam “Cii-6”	6.03	8.79	25.11	2.85

* Δ_u = deflection of beams at failure (refer Fig. 9)
*Δ_y = deflection of beams at Yielding of steel (70% of failure load) (refer Fig. 9)



Beams of Group ‘A’



Beams of Group ‘B’

Beam of Group ‘C’ Control Beam

Fig. 10. Cracks pattern of beams after failure

From the results it may be inferred that the cast in situ Ferro-mesh layer (Group 'A')shows more promise and that ferrocement is suitable for small span beams, however, Ferrocement Laminates (Group 'C') is also promising due to ease in application, especially for rural workers with lesser skill.

From the above mentioned results, it seems that though cast in situ Ferro-mesh layer (Group 'A') possess greater promise for strengthening of modest level beams, more skill is needed due to overhead application. Strengthening through Ferrocement Laminate *B* (Group 'C'), on the other hand, may prove to be more promising in terms of enhancing load carrying capacity, stiffness and ductility due to the lesser needed skill, simplicity in casting and application on the beam, except when a judicious selection of epoxy is done.

The technique may be mastered by local rural folks related to casting and application, however, it needs further evidence of its potential. Moreover, the precast Ferrocement laminate *B* which may increase the depth slightly and leave an uneven soffit may be levelled by applying mortar on the rest of the soffit of the beam. To reduce cracking between laminate and mortar, part of wire-mesh may be exposed from the edges of the precast laminates to be concealed later on with mortar containing 12.7 mm to 19 mm (½" to ¾") long steel fibres obtained from the leftover mesh.

In current investigation, as only one beam in Group 'C' has been strengthened, before recommending this method as a promising method for rural areas, further investigation is recommended to evaluate its potential with varying influencing parameters. In the opinion of the author(s), however, precast Ferrocement laminate *B* (Group 'C') should establish its promise as one of the viable method of strengthening of modest span beams for rural application.

4. CONCLUSION

The following conclusions and recommendations may be drawn from this study:

1. Cast in situ Ferro-mesh layer has been found to be the most suitable strengthening technique among all strengthening techniques investigated in this study.
2. Three layers of Ferro-mesh performed better in terms of load carrying capacity and stiffness; however, the ductility did not show proportionate increase in comparison to the two layers.
3. Increase in development length has shown unfavourable effect on load carrying capacity but has shown positive influence in increasing the initial stiffness.
4. Increase in development length has no apparent effect on ductility.
5. ACI 549.1R-93 [30] can be used effectively to predict the load carrying capacity for all the mentioned ferrocement strengthening techniques.
6. As far as practical utility in rural areas is concerned, Ferrocement laminate *B* (Group 'C') may be the preferred technique as it is convenient to apply; however, the performance of Ferrocement laminate *B* shall heavily depend on the bond between laminate and beam.

The following recommendation may be proposed for further study:

1. As only square woven wire mesh having a specific opening has been used in this study, the use of other types of wire meshes e.g. hexagonal, welded wire mesh etc. with varying openings may also be investigated.
2. To minimise the delamination in Ferrocement Laminate *B*, better surface preparation should be emphasized before the application of epoxy resin.
3. Application of the strengthening techniques used in this study may be applied on beams under service load for practical application eliminating propping.

4. Ferrocement Laminate *B* (Group ‘C’) needs further study to determine the optimum number of layers and influence of other parameters.
5. In this study Ferro-mesh has been applied in tension region as all beams have been designed as under reinforced, behaviour of over reinforced beams with the application of Ferro-mesh in the compression region may also be investigated.

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