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PII:S0958-9465(97)00068-1

*Cement and Concrete Composites* 20 (1998) 53–65
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Printed in Great Britain
0958-9465/98/$19.00

# Strengthening of RC Beams with Ferrocement Laminates

P. Paramasivam,* C. T. E. Lim & K. C. G. Ong

Department of Civil Engineering, National University of Singapore, 10 Kent Ridge Crescent, 119260 Singapore, Singapore

(Received 4 August 1997; accepted 18 September 1997)

*Abstract*

*In this paper methods of repair and strengthening of reinforced concrete beams using ferrocement laminates attached onto the surface of the beams are reviewed. Investigation into the transfer of forces across the concrete/ferrocement interface, the effects of the level of damage sustained by the original beams prior to repair, and the results of repeated loading on the performance of the strengthened beams are discussed. The results show that ferrocement is a viable alternative strengthening component for the rehabilitation of reinforced concrete structures. © 1998 Elsevier Science Ltd. All rights reserved.*

*Keywords:* Flexural strengthening, shear strengthening, interfacial shear strength, level of damage, cyclic loading.

## NOMENCLATURE

$A_f$ Cross-sectional area of the ferrocement laminates
$b$ Width of compression zone
$b_i$ Width of the beam at the concrete/ferrocement interface
$d_f$ Depth to ferrocement laminates
$E_m$, $E_r$ Elastic modulus of the ferrocement matrix and ferrocement reinforcement
$f_{cu}$ Compressive cube strengths of the concrete
$f_{ry}$ Yield strength of the reinforcement in the ferrocement laminate
$f_{fy}$ Yield strength of the ferrocement laminates
$H_f$ Thickness of the ferrocement laminate
$L_{shear}$ Shear span between load and support joints
$M_{ori}$, $M_{rep}$ Ultimate moment of resistance of the original and strengthened beams
$V_{ori}$ Shear capacity of the original beam
$x_{ori}$ Depth of neutral axis from the extreme compression fibre of the original beam
$\gamma_s$ Minimum design factor of safety against failure in shear
$\tau_{max}$ Maximum shear stress at the concrete/ferrocement interface in the beam
$\upsilon_s$ Modification factor to reconcile estimated interfacial shear strength in the beams tested to theoretical (or design) shear strength recommended by codes of practice or those obtained from pushout tests

## INTRODUCTION

Ferrocement is a type of thin composite material made of cement mortar reinforced with uniformly distributed layers of continuous, relatively small diameter, wire meshes. The design and construction of ferrocement are described in two state-of-the-art reports published by the ACI committee 549.[1,2] Ferrocement, being of the same cementitious material as reinforced concrete (RC), is ideally suited as an alternative strengthening compo-

*Correspondence to: P. Paramasivam

nent for the rehabilitation of RC structures. It possesses higher tensile strength to weight ratio and a degree of toughness, ductility, durability, and cracking resistance that is considerably greater than those found in other conventional cement based materials. Furthermore, all these properties are achieved within a thickness of about 40 mm, which can easily be cast into any shape to fit the contour of the elements being repaired.

**Background**

The incorporation of fine wire mesh beneath the surface of repair mortar has long been practised although these methods were not identified as ferrocement. Examples of these were reported by Dinardo and Ballingall.[3] The purpose of the fine mesh was simply for crack control and was not relied upon to contribute to the structural strength of the member. The use of ferrocement proper in repair was first introduced by Romualdi[4] and Iorns[5] in the early 1980s mainly as relining membranes for the repair of liquid retaining structures, such as pools, sewer lines, tunnels, etc. The ferrocement was utilised for its toughness, cracking resistance, and ease of application to fit the difficult contours of these structures. Initial investigation into the use of ferrocement as strengthening components for the repair and strengthening of reinforced concrete beams was carried out by Andrews and Sharma.[6] Damaged concrete and reinforcement of beams were removed and replaced with ferrocement, without any change in overall dimensions. Tested under static loading conditions, the strengthened beams were reported to exhibit improved cracking resistance, flexural stiffnesses, and ultimate loads as compared to the original beams when preloaded prior to repair. These improvements were, however, lower in beams where composite action between the ferrocement components and the original beams was lost.

The use of ferrocement laminates as strengthening components for the repair of beams was investigated by Lim,[7] Ong *et al.*,[8,9] Paramasivam *et al.*,[10,11] and Aurellado.[12] Thin ferrocement laminates, of thickness less than 40 mm, were cast onto the external surface(s) of the beams being repaired. This results in a slight enlargement of the beam's section. For flexural strengthening, the ferrocement laminates were cast onto the soffits (tension face) of the beams without any change in width of the beams, while in shear strengthening the ferrocement laminates were formed onto the three exposed faces of the beams, except for the top compression face. Shear transfer across the concrete/ferrocement interface, use of mechanical shear connectors, the effects of higher volume fraction of reinforcement in the ferrocement laminate, the level of damage of the original beams prior to repair and the behaviour under cyclic loading of the strengthened beams were examined.

## SHEAR STRENGTH ACROSS CONCRETE/ FERROCEMENT INTERFACE

The shear strength of the concrete/mortar interface, without aggregate–aggregate interaction, which is the case for ferrocement cast against concrete substrate, was investigated by Lim,[7] using double shear pushout specimens.

The specimens were designed and tested in accordance with BS5400: Part 5, 1979.[13] In all 14 specimens, with no less than three specimens per type of connections, were tested with the loads applied symmetrical, and parallel, to the concrete/ferrocement interfaces. The specimens were cast in plywood moulds. The effects of surface preparations, 'as-cast' and roughened, were examined in series PO1 and PO2, respectively. The average amplitude of surface roughness of the mechanically chipped surfaces in series PO2 was about 3 mm. The use of epoxy resin adhesive was investigated in series PO3 and PO4. In the former, the ferrocement mortar was cast onto the epoxy resin adhesive while it was still soft and in the latter the same epoxy resin adhesive was used to bond precast ferrocement legs onto the concrete plungers. In both cases, the thickness of the epoxy was about 2 mm. The epoxy resin adhesive used was a commercially available two-component bonding agent specially formulated for concrete/concrete interface with adhesion strength of 4 N/mm$^2$.

Typical failure modes of specimens with 'as-cast' (series PO1) and roughened (series PO2) interfaces are shown in Figs 1 and 2. The shear strengths, calculated as the ratio of load at failure over the gross interface area, were about 0.91 N/mm$^2$ and 3.25 N/mm$^2$ for the 'as-cast' and roughened interfaces, respectively. The 'as-cast' surface therefore exhibited interfacial shear strength of just 28% of that achieved with

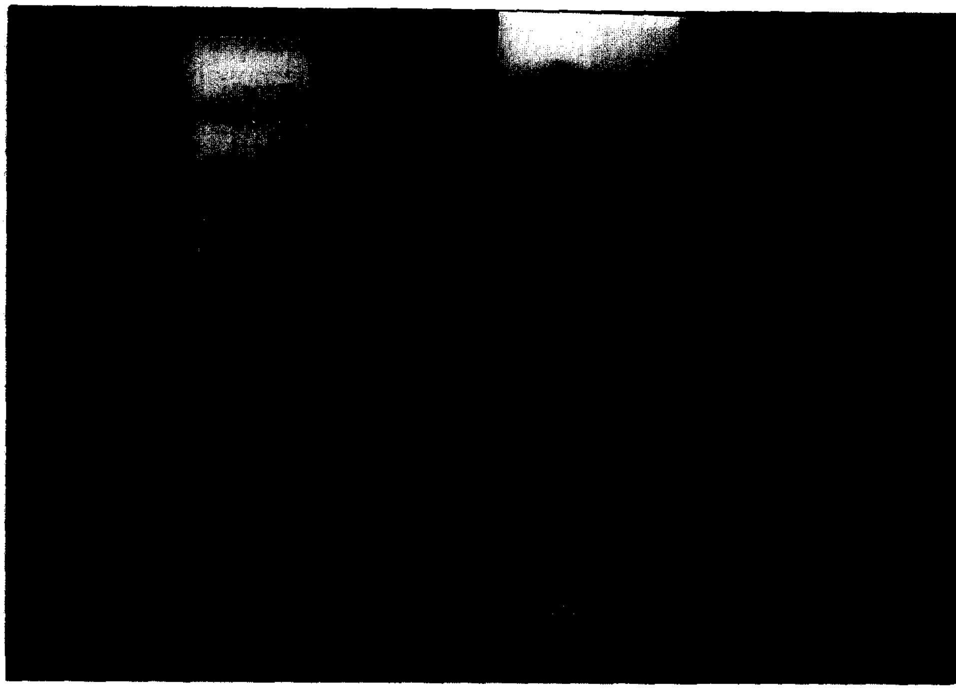

**Fig. 1.** Failure of pushout specimens cast with 'as-cast' interface.

the surface roughened. Surface preparation, hence, significantly increased the cohesion between the surfaces in contact. All the specimens in series PO3 (with epoxy resin and ferrocement cast *in situ*) failed asymmetrically with the failure planes occurring between the epoxy resin and ferrocement in either one of the legs. In contrast, the specimens with the precast ferrocement legs bonded onto the concrete plunger using the same epoxy resin adhesive (series PO4) exhibited the highest failure load. Failure was observed to have occurred within the concrete plunger away from the concrete/ferrocement interface, as shown in Fig. 3, thus indicating that the concrete plunger and epoxy bonded precast ferrocement legs behaved monolithically. Assuming that the shear force acted symmetrically across the

**Fig. 2.** Pushout specimen cast with roughened interface.

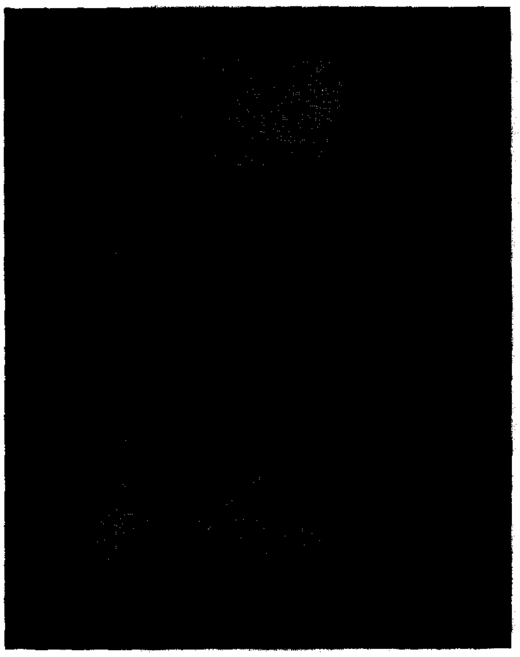

**Fig. 3.** Pushout specimen with epoxy bonded ferrocement laminates.

epoxy bonded interfaces, the shear strength of the concrete substrate is therefore greater than 4.32 N/mm$^2$.

## FLEXURAL STRENGTHENING OF BEAMS

For the strengthening of beams in flexure, prefabricated ferrocement reinforcements were attached onto the beams' soffit (tension face) before the ferrocement matrix was cast to complete the laminate. Shear connectors were introduced for the dual purpose of securing the ferrocement reinforcement during fabrication and to promote composite action between the concrete substrate and the ferrocement laminate during loading.

### Shear connectors

The use of mechanical shear connectors in flexural strengthening of beams was investigated by Ong *et al.*[8] Eight rectangular beams were cast in plywood moulds and strengthened in their virgin state (without damage). The surface to receive the laminate was left 'as-cast' and prefabricated ferrocement reinforcement fastened onto mechanical anchorages installed into the concrete substrate. Two types of anchorage systems were examined; namely, power driven nails of diameter 3.8 mm at spacings of 100 mm, 150 mm, or 200 mm; and anchor bolts of diameter 15 mm at the recommended spacing of 118 mm. The possible use of epoxy resin adhesive in place of the mechanical anchorages was also examined. Epoxy resin adhesive was first applied onto the beam soffit after which the ferrocement reinforcement was placed and the mortar cast onto the still soft epoxy. All the strengthened beams were then tested to failure under simply-supported conditions with loads quasi-statically applied.

It was found that composite action between the ferrocement laminates and the concrete substrate were sustained in the beams strengthened with the laminates attached via power driven nails at a spacing of 100 mm and that attached using epoxy resin adhesive. All other beams, despite the use of mechanical anchorages, exhibited localised horizontal cracks along the concrete/ferrocement interface at loads of about 60% of the theoretical load capacities, with localised delamination of the ferrocement laminates occurring near failure. Figure 4 shows a typical beam with the ferrocement delaminated. The interfacial shear strength between the 'as-cast' surface and the ferrocement laminate attached via power driven nails at spacings greater than 100 mm or anchor bolts at the recommended spacing of 118 mm, were therefore insufficient to sustain full composite action until failure.

All the strengthened beams exhibited higher initial flexural stiffness, by about 50%, compared to the unstrengthened control beams. This may be due to the increased depth arising from the addition of the ferrocement laminates onto the beams' soffits. The ultimate loads of the strengthened beams were also increased by about 20% compared to the control beams. Beams, where delamination of the ferrocement laminates occurred, exhibited larger mid-span deflection at service loads and lower percentage increase in ultimate loads.

In another study, Paramasivam *et al.*[10] tested 12 T-beams strengthened in flexure with ferrocement laminates attached onto the soffits of the beams using mild steel bars as shear connectors. Figure 5 shows the shear connectors and installation of the prefabricated ferrocement reinforcement. The beams were strengthened with and without surface roughening of the soffit to receive the ferrocement laminates and spacing of the bar shear connectors were varied at 200 mm, 300 mm, or 400 mm. Surface roughening was carried out

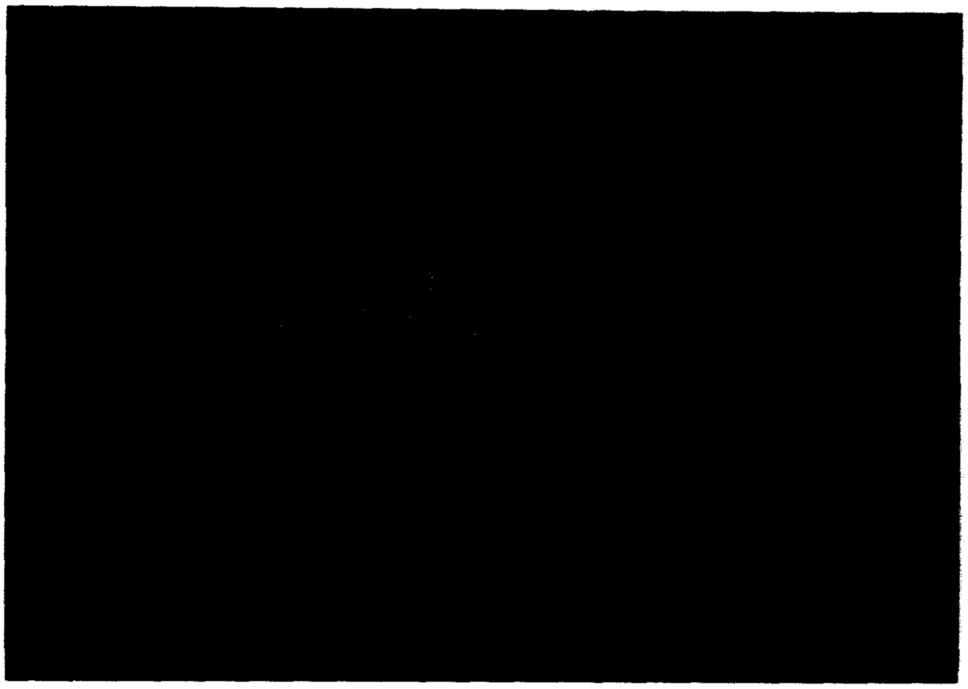

**Fig. 4.** Delamination of ferrocement laminate from 'as-cast' beam soffit.

mechanically to expose the aggregates, over the whole length of the beam soffit. The shear connectors consisted of 'L'-shaped round bars with one leg inserted into predrilled holes in the concrete substrate and fastened therein with epoxy resin adhesive while the other leg was bent along the span for embedment into the ferrocement laminates as shown in Fig. 6. All the beams were simply-supported and tested under concentrated load at mid-span.

The loads at first appearance of crack in the strengthened beams were increased by about 67% compared to the unstrengthened control beam. Cracks originated from the soffit of the laminate and propagated across the concrete/ferrocement interface into the original beams.

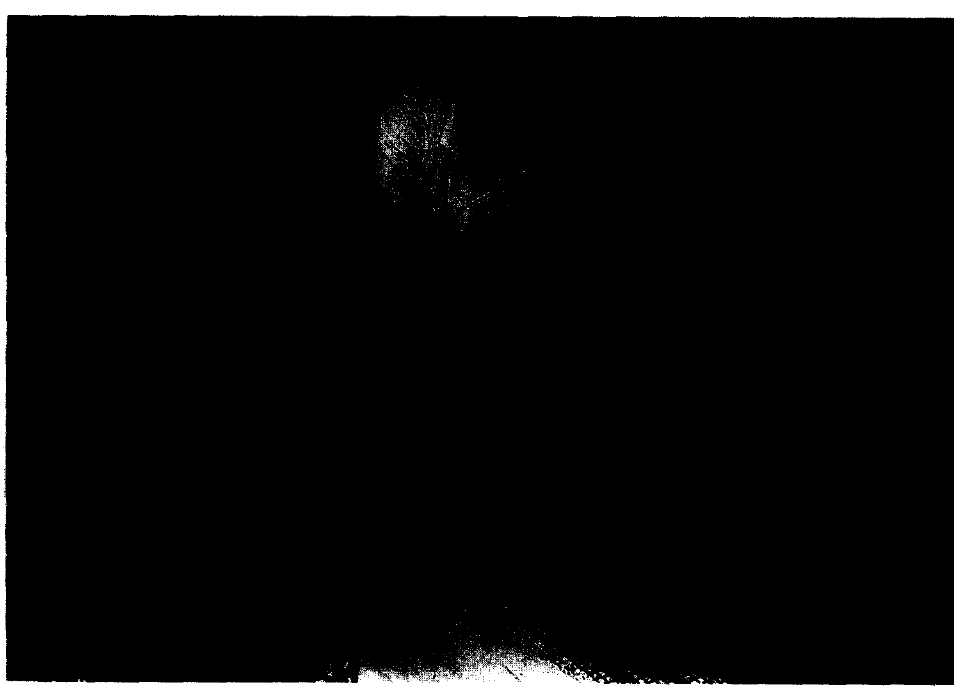

**Fig. 5.** Mild steel bars used as shear connectors.

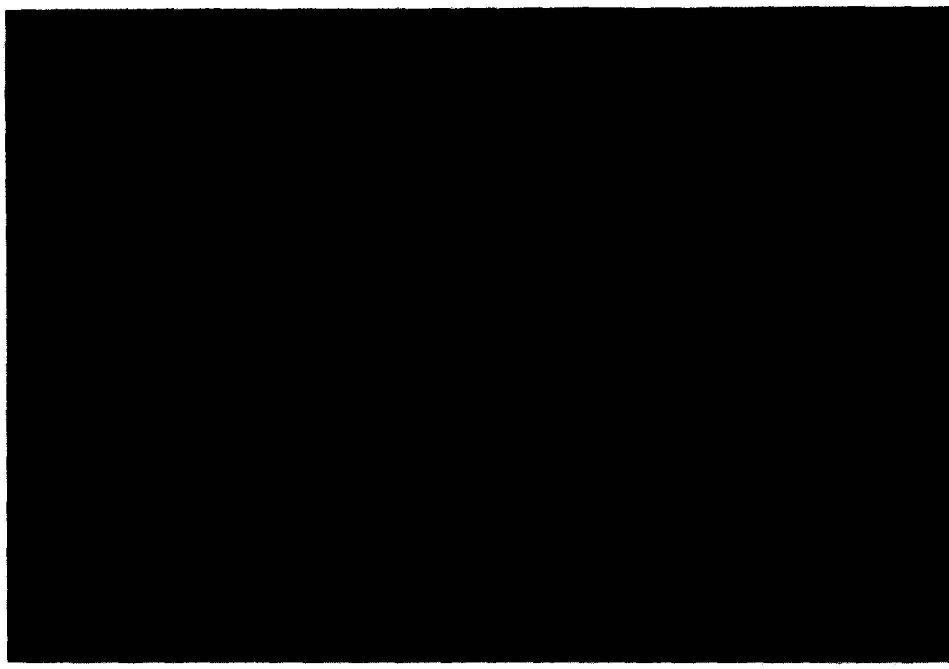

**Fig. 6.** Assembled ferrocement laminate reinforcement.

The stiffer ferrocement laminates, as shown in Figs 7 and 8, modified crack patterns at the soffit of the original beams. Closer crack spacings and smaller widths of the cracks were observed in the strengthened beams compared to the unstrengthened control beams. The crack spacings and crack widths at the soffit of the beams were reduced by about 50% and 25%, respectively. Composite actions were sustained in beams where the surface to receive the ferrocement laminates was roughened and ferrocement reinforcement attached via 'L'-shaped bar connectors at 200 mm spacings. The performance of these beams was substantially improved compared to the unstrengthened control beam. All the beams strengthened without surface roughening exhibited horizontal cracks at the concrete/ferrocement interface and

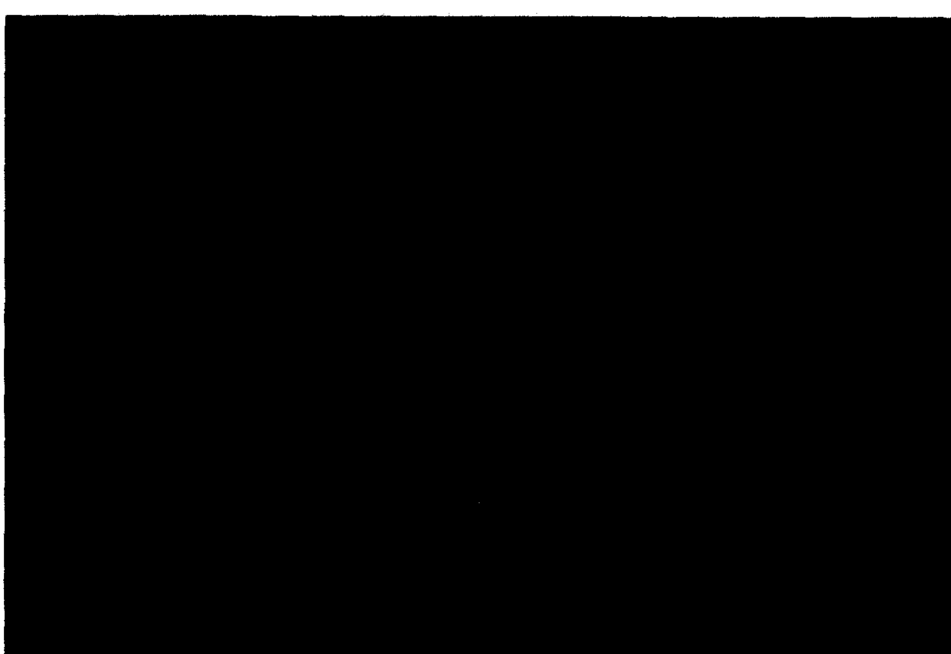

**Fig. 7.** Typical crack pattern at soffit of strengthened beams.

**Fig. 8.** Typical crack pattern at soffit of unstrengthened beams.

severe delamination of the ferrocement at failure. Ultimate loads of beams where severe delamination was observed were lower than the expected increase in strength with the addition of the ferrocement laminates.

### Effect of higher volume fraction of reinforcement in the ferrocement laminate

Paramasivam *et al.*[10] extended their investigation to examine the effects of higher degree of strengthening using ferrocement laminates with greater volume fraction of reinforcement. Four T-beams were strengthened in their virgin state (without damage) with increasing strengthening ratios (moment capacity of the strengthened beam over that of the original beam) from 15% to 35%. Surfaces to receive the ferrocement laminates were roughened and 'L'-shaped bar shear connectors installed at 200 mm spacing in all the beams.

The results showed that the load at first crack could be satisfactorily predicted using BS8110: Part 2, 1985[14] with material partial safety factors together with the tensile strength of ferrocement estimated as proposed by Nathan and Paramasivam.[15] The cracking strength, $\sigma_{cr}'$, of ferrocement is given by:

$$\sigma_{cr}' = \sigma_m' + \sigma_s'(V_{RL})^{1.1} \qquad (1)$$

where $V_{RL}$ is the volume fraction of reinforcement in the ferrocement, $\sigma_m'$ is 0.01% proof stress of matrix, and $\sigma_s'$ is 0.01% proof stress of the welded wire mesh. The initial flexural rigidity of the strengthened beams was higher than the unstrengthened control beams. This improvement however diminishes in cases where composite action is lost. Beams with higher volume fraction of reinforcement exhibited localised horizontal cracks at the concrete/ferrocement interface and delamination of the ferrocement from the concrete substrate. The increase in flexural capacity therefore depended on the preservation of composite action until failure to fully utilise the ferrocement laminates at the beam soffit.

Lim[7] analysed the shear transfer across the concrete/ferrocement interface based on conventional shear flow model. Twenty-two beams were compared and the shear flow corresponding to the first occurrence of horizontal crack at the concrete/ferrocement interface taken as the interfacial shear strength. These were correlated with the shear strength of the interface obtained from codes of practice and that obtained from pushout tests assuming a cohesion–friction relationship. The results show that the interfacial shear stress between the original beams and the ferrocement laminates was about 2.08 to 2.55 times higher than the estimated values calculated using the shear flow equation. This is perhaps due to the concentration of shear stress at locations of cracks in the ferrocement laminates. The theoretical shear strengths, $v_i$, of the concrete/ferrocement interface were estimated using the cohesion–friction equation:

$$v_i = c + \Phi f_{ly} \tan \phi \qquad (2)$$

where $f_{ly}$ is the yield strength of the shear connectors, $\Phi$ is the reinforcement ratio at the interface, $\phi$ is the angle of internal friction at the interface which is taken as 37°, and $c$ is the cohesion obtained from pushout test. Theoretical analysis was then extended by Lim[7] to relate strengthening ratio to the volume fraction of reinforcement in the ferrocement and the resulting interfacial shear stress at the concrete/ferrocement interface. The result is summarised in Fig. 9.

**Effects of the level of damage of original beams before strengthening**

The effect of damage prior to repair was investigated by Paramasivam *et al.*[11] Six T-beams with different levels of damage were repaired by epoxy resin injection and strengthened in flexure with thin ferrocement laminates

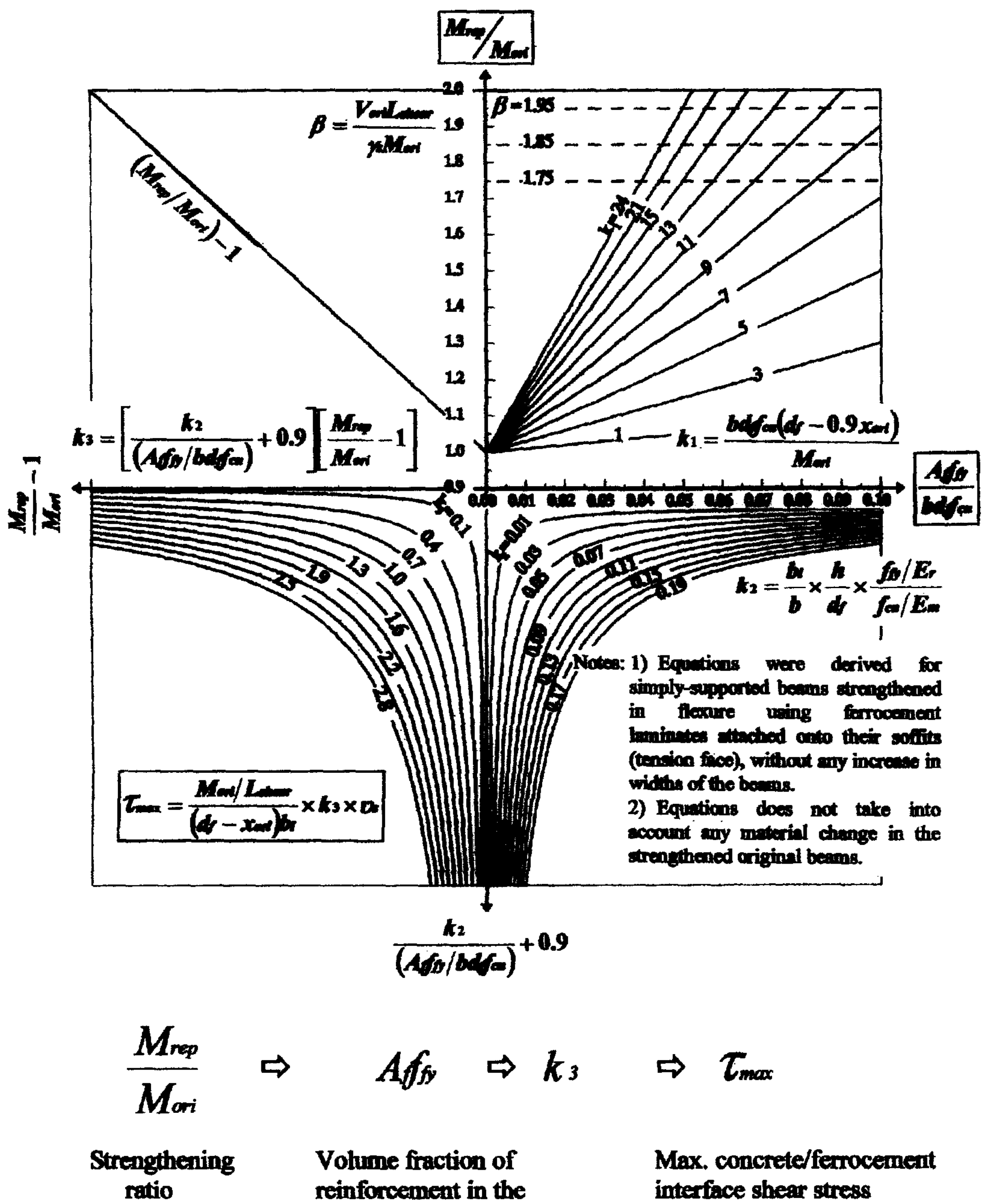


Fig. 9. Proposed design chart for the flexural strengthening of RC beams using ferrocement attached to the soffit (tension face) of the beam.

attached to the soffit (tension face). The level of damage was defined as preloading to collapse, 100%, and 90% of the beams' theoretical ultimate flexural capacity by applying short term static loads at mid-span with the beams simply supported. The loads were then removed and the beams repaired whilst under self-weight. Figure 10 shows the test beams after preloading. Epoxy resin injection was used to repair the cracks. In the beam RD1, where the original was completely failed, a 700 mm long portion of depth 100 mm of the crushed flange beneath the load-point was replaced with commercially available repair material. Only cracks in the severely damaged flexural zone of this beam were completely grouted, elsewhere cracks of width 0.1 mm and less remained ungrouted. In the original beams, RD2 and RD3, with 100% and 90% level of damage, cracks were observed to close upon unloading prior to repair. These cracks typically of width 0.08 mm to 0.1 mm left ungrouted in the repair. All the beams were similarly strengthened with the 'L'-shaped round bar shear connectors spaced at 200 mm.

Test after strengthening showed that the existing cracks reopened under load, initiating cracks in the ferrocement laminate at locations where the ungrouted cracks met the concrete/ferrocement interface. Fresh cracks were also observed to form at closer spacing compared to that of their respective original beams recorded during preloading. Crack patterns after failure are shown in Fig. 11. The widths of the cracks at the soffit of the ferrocement laminates were about 50% smaller than those found in the original beams during preloading for the same load level as a percentage of their theoretical moment capacity. These improvements were however marginally smaller than that obtained in the control beams, which were strengthened without prior damage, due to the lower stiffness of the repaired damaged beams caused by reopening of ungrouted cracks. The mid-span deflections of all the beams under service loads, defined as 2/3 of the theoretical strengthened capacities, were however less than the ratio of $L/250$, where $L$ is the span of the beams, recommended by BS8110: Part 2, 1985.[14] The results therefore showed that the presence of ferrocement laminates at the soffit of the strengthened damaged beams did not prevent the reopening of ungrouted cracks but acted to restrain the further widening of cracks under higher loads.

Beams strengthened after 100% and 90% levels of damage failed as under-reinforced sections by yielding of the tension bars and ferrocement laminates. Failure was preceded by the appearance of horizontal cracks at the concrete/ferrocement interface immediately below the load-point. Ultimate loads were, however, only marginally lower than the control beam, strengthened without damage. The variation in

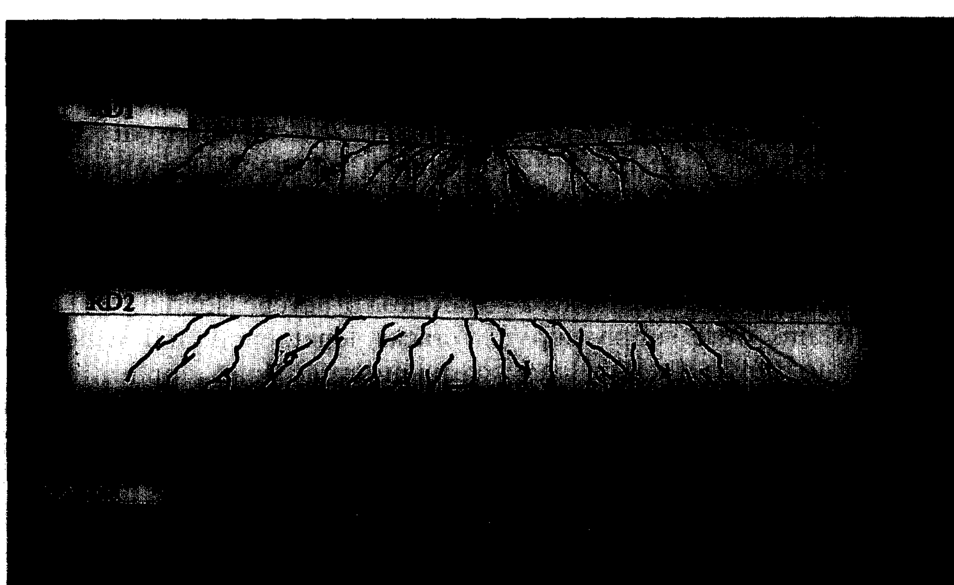

**Fig. 10.** Damaged beams before strengthening.

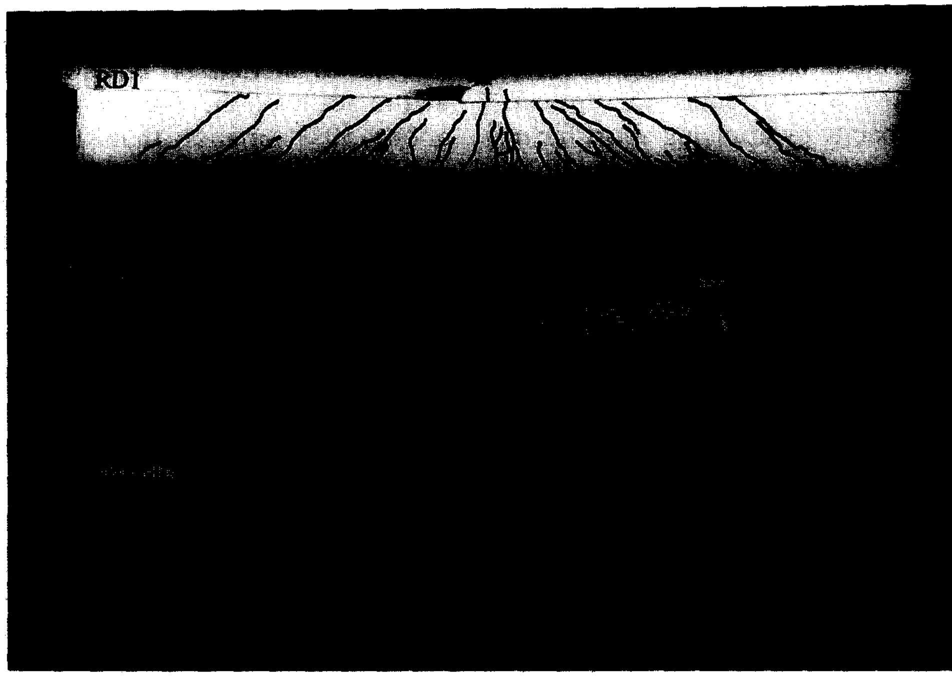


**Fig. 11.** Strengthened damaged beams after failure under static loading.

the level of damage sustained by the beams prior to repair thus does not significantly affect the ultimate strengths of the beams tested.

In the beam, where the original was completely failed, the recast flange under the load-point and the epoxy resin mortar repaired flexural zone resulted in predominant cracking of the shear span with diagonal cracks occurring at failure. The ultimate load of the beam was even higher than the maximum load recorded for the control beam. This improvement therefore shows that completely failed beams can be restored with improved performance and strength under short term static loading.

## Behaviour under cyclic loading

The effects of cyclic loading on the composite action of strengthened beams were investigated by Ong *et al.*[9] Three beams were simply supported and precracked to 90% of their load capacities and strengthened with cracks of widths less than 0.1 mm left ungrouted. All the beams were similarly strengthened with the 'L'-shaped round bar shear connectors spaced at 200 mm. The beams were then subjected to unidirectional cyclic sinusoidal loads alternating between a minimum load of 24% and a maximum load of either 50%, 70% or 90% of their respective theoretical static ultimate load capacities after strengthening. Beams that survived 150000 cycles were then tested statically to failure.

Figure 12 shows the beams after 150000 cycles of cyclic loading. Composite action between the original beam and ferrocement laminate was sustained in beam RD4, which was cycled under a maximum load of 50% of the theoretical static ultimate load capacity, throughout the 150000 cycles of load application. In beam RD5, with maximum applied load of 70% of the theoretical capacity, horizontal cracks at the concrete/ferrocement interface appeared after 80000 cycles of loading. Widespread delamination at the concrete/ferrocement interface was observed in beam RD6, which was cycled under a maximum load of 90% of the theoretical capacity. Horizontal cracks at the interface occurred after just 100 cycles of cyclic loading. These discontinuous cracks lengthened and widened under subsequent cyclic load applications. The width of these cracks exceeded 0.3 mm soon after approximately 80000 cycles. The horizontal cracks, at the concrete/ferrocement interface, in both beams RD5 and RD6 remained clearly visible even when the beams were unloaded after each predetermined number of cycles in order to measure residual flexural stiffness. The strengthened beams, RD5 and RD6, were thus considered to have failed under cyclic loadings of 70% and 90% of their theoretical static ulti-

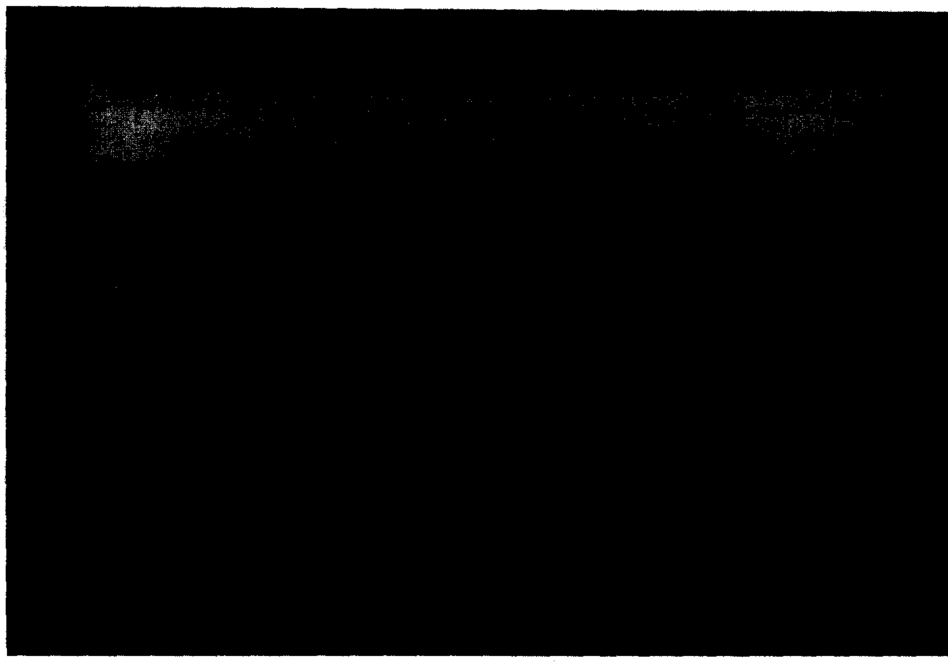

**Fig. 12.** Strengthened damaged beams after 150 000 cycles of cyclic loading.

mate load capacities after 80 000 cycles and 100 cycles of load application, respectively. The performance of the strengthened beams RD4 was not adversely affected by cyclic loading with a maximum applied load of 50% of the theoretical strengthened capacity.

## SHEAR STRENGTHENING OF BEAMS

The performance of reinforced concrete T-beams strengthened in shear under static and cyclic loads was investigated by Aurellado.[12] A total of six T-beams were tested inverted and simply-supported under a point load at mid-span. Except for the control beam, all beams were strengthened with ferrocement encased onto the faces of the web. Prefabricated ferrocement reinforcement with two methods of attachment was examined: with bar shear connectors installed through the web or through the flange of the beams. This was compared with conventional methods of strengthening where additional 'U'-shaped stirrups were inserted through predrilled holes in the flange before bending the ends in to form closed links. The beams were subjected to cyclic loading of two levels: 3.6% to 36% of their theoretical static ultimate load capacity for 100 000 cycles, followed by 4.8% to 48% of theoretical static ultimate load capacity for the next 100 000 cycles. The beams were thereafter statically tested to failure.

The results show that the beams were substantially strengthened and stiffened with the provision of additional stirrups and galvanised wire mesh in the thickened sections encasing the beams' web and soffit. Beams strengthened using prefabricated stirrup cages attached with mild steel dowel bars anchored either through the web or through the flange performed better than the conventional method of strengthening. Beams strengthened with prefabricated cages attached with mild steel dowel bars anchored through the web were able to sustain 200 000 cycles of cyclic loading with a maximum cyclic load applied of 48% of the theoretical static ultimate load capacity with negligible loss in flexural rigidity.

## CONCLUSIONS

In summary therefore, the above investigations into the use of ferrocement laminates as strengthening components showed the following.

(1) The addition of ferrocement laminates to the soffit (tension face) of the beams tested statically substantially delayed the first crack load, restrained cracks from

further widening, and increased the flexural stiffness and load capacities of the strengthened beams.

(2) The improvements in mid-span deflections and load capacities were lower in beams where composite action between the original beam and the strengthening ferrocement laminates was lost.

(3) To ensure full composite action, the surface to receive the ferrocement laminate may be roughened and provided with closely spaced shear connectors. This however is dependent on the strengthening ratio required and the volume fraction of reinforcement used in the ferrocement laminate.

(4) Mild steel bars of 8 mm diameter with anchorage length 240 mm may be used as mechanical anchorages for the ferrocement laminate reinforcement.

(5) The first crack strengths, widths of the cracks at the soffit of the beams, mid-span deflections and moment capacities of the strengthened beams may be estimated using equations as provided in BS8110: Part 2, 1985.

(6) The average maximum shear stress at the concrete/ferrocement interface in the strengthened beams may be estimated using the conventional shear flow equation with allowable interfacial shear strength as recommended by BS8110: Part 1, 1985 or as obtained from double shear pushout tests.

(7) The proposed non-dimensionalised design chart may be used to estimate the volume fraction of reinforcement for use as the ferrocement laminate, and the associated average maximum concrete/ferrocement interfacial shear stress for a given strengthening ratio.

(8) The different levels of damage of the original beams prior to repair did not affect the ultimate loads of the strengthened beams tested.

(9) Cyclic loading with a maximum load applied of 50% of the theoretical static ultimate load capacity did not seem to have any adverse effects on the performance of the strengthened beams after the 150000 cycles of load applications.

(10) Beams strengthened with prefabricated cages attached with the mild steel dowel bars anchored through the web performed better than the conventional method of shear strengthening and were able to sustain 200000 cycles of cyclic loading with maximum load applied of 48% of the theoretical static ultimate load capacity with negligible loss in flexural rigidity.

Based on the results of the above investigations, ferrocement is thus a viable alternative material for the repair and strengthening of reinforced concrete structures. It has been accepted by the local building authority in Singapore for use in upgrading and rehabilitation.

## ACKNOWLEDGEMENTS

The work upon which this paper is based was supported by the National University of Singapore, Research Grant No. 900616 for which the authors extend their thanks.

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