PLATE BONDED STRENGTHENED R.C. BEAMS WITH END AND INTERMEDIATE ANCHORS

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ABSTRACT

This paper presents a study on strengthening of reinforced concrete beams. Various strengthening materials and methods and problems associated with strengthening are reviewed. An experimental programme to evaluate the structural behaviour of steel plate and CFRP laminate flexurally strengthened reinforced concrete beams is also reported. A total of three beams, each 2300 mm long, 125 mm wide, and 250 mm deep, were fabricated and tested. One beam was left un-strengthened to act as the control beam, while the other two beams were strengthened with steel plate and CFRP laminate. L shape end anchorage of 200 mm anchoring length together with intermediate anchorage of 40 mm anchoring length were installed in both of the strengthened beams to avoid premature failure. The experimental results showed that the strengthened beams had higher failure load, good failure modes, less deflections and better cracking patterns over the control beam.

Keywords: *reinforced concrete, beam, strengthening, plate, debonding, anchors*

INTRODUCTION

Strengthening of reinforced concrete beam is an important task in the field of structural maintenance. The aim is to increase the capacity of an existing beam element. This work is very significant since many civil structures are no longer considered safe which can be due to increase load specifications in the design codes, overloading, under-design of existing structures or to the lack of quality control. In order to maintain efficient serviceability, older structures must be repaired or strengthened so that they can meet the same requirements demanded of structures built today and in the future. It is becoming both environmentally and economically preferable to repair or strengthen structures rather than to replace them totally, particularly if rapid, effective and simple strengthening methods are available.

Different types of strengthening materials are available in the market. Examples of these are ferrocement, sprayed concrete, steel plate and fibre reinforced polymer (FRP) laminate. Generally the use of steel plate and FRP are preferred in this field due to their advantages such as easy construction work, minimum change in the overall size of the structure after plate bonding and less disruption to traffic while strengthening is being carried out. With the development of structurally effective adhesives now a day, these has been a marked increases in strengthening using steel plates and FRP laminates.

Plate bonding method often however, has a serious premature failure problem due to separation of plates and concrete rip off along the tensile reinforcing bars before reaching the beam’s ultimate capacity. It is an extremely significant problem because invariably debonding of adhesive joints results in a brittle and catastrophic failure. Many research works had been conducted over the last two decades, to find a solution in minimizing these debonding problems. End anchorages have been shown to have some effect on preventing premature debonding failures. Additional intermediate anchorages in the shear span zone are sometimes required to prevent shear failure occurring before flexural failure.

The objective of this study is to,

i) review main methods of strengthening methods of reinforced concrete beams
ii) study the behaviour of steel plate and CFRP laminate flexurally strengthened reinforced concrete beams.

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STRENGTHENING MATERIALS AND METHODS

For the purpose of repair and strengthening of r.c. beams, several materials and methods are available such as sprayed concrete, ferrocement, steel plate and fibre reinforced polymer (FRP). Sprayed concrete is the oldest materials amongst the group and is the most common method of repairing and strengthening of reinforced concrete structures. Sprayed concrete has been used in strengthening concrete for almost 90 years. The technique of strengthening of reinforced concrete beam by using sprayed concrete as reported by Diab [1]. Ferrocement is another material which is used for strengthening of reinforced concrete structures. It has the same cementitious material as reinforced concrete. Dinardo and Ballingall [2] have reported that the incorporation of fine wire mesh beneath the surface of repair mortar has long been practiced although these methods were not identified as ferrocement. The use of the term ferrocement in repair was first introduced by Romuldi and Irons [3,4] in the early 1980s. Initial investigation into the use of ferrocement as strengthening components for the repair and strengthening of reinforced concrete beams was carried out by Andrew and Sharma [5]. The use of ferrocement laminates as strengthening components for the repair of beams was investigated by Paramasivam et al. [6]. However, among all of the strengthening materials, steel plate and FRP laminate are the most common and effective materials due to their several advantages which will be described in the next section.

Materials and strengthening methods commonly applied on r.c. beams

Steel plate

Steel plate is one of the most common materials for strengthening of reinforced concrete beam. It is very effective for increasing the flexural and shear capacity of reinforced concrete beam. Strengthening by steel plate is a popular method due to its availability, cheapness, uniform materials properties (isotropic), easy to work, high ductility and high fatigue strength. Investigations into the performance of members strengthened by this technique were started in the 1960s. This method had been used to strengthen both buildings and bridges in countries such as Belgium, France, Japan, Poland, South Africa, Switzerland and United Kingdom [7].

The most common form of plating is to glue steel plates to the tension faces of beams. In this position, the plate is at its furthest extremity from the compression region and, as a result, the composite flexural action is at its maximum [8]. Furthermore, the composite action between the plate, glue, and concrete will be maintained until failure [9]. However the effectiveness of this method is depended on the surface preparation and bonding methods between existing beam and steel plates. Thus, the surface preparation of existing beam as well as steel plate has to be carried out effectively. Adhikary et al. [10] has described the roughening process of the beam surface before placing the plates. The roughening process is carried out using a mechanical grinding until the laitance was removed and the surfaces were then brushed and cleaned thoroughly with acetone. The bonding faces of the steel plates can also be sand-blasted and then cleaned with acetone. After surface preparation epoxy adhesive is placed on the roughened surface and then steel plate is positioned on top.

Fibre reinforced polymer (FRP)

Fibre reinforced polymer (FRP) for civil engineering structures are being increasingly studied in recent years. These materials are being used in the aerospace, automotive and shipbuilding industries for almost two decades [11]. In general, FRP offer excellent resistance to corrosion, good fatigue resistance (with the possible exception of some glass-based FRP), low density, high stiffness and strength, and a very low coefficient of thermal expansion in the fibre orientation. Garden and Hollaway [12] have described FRP materials as having superior mechanical and physical properties than steel, particularly with respect to tensile and fatigue strengths. Furthermore these qualities are maintained over a wide range of temperatures. However, its higher price, relatively low failure strains, and unknown long-term performance have for many years restricted the use of FRP for civil engineering structures [13]. Until recently some FRP can cost as much as 10 times by weight of traditional structural materials, such as structural steel. Notwithstanding the lack of practical knowledge of FRP, this fact alone probably would have kept FRP from becoming commonly used in the construction industry. Despite declining prices in composites as a result of improved manufacturing processes, FRP still remains relatively expensive when compared to traditional materials. Thus, FRP is usually considered only for special applications, such as in non-magnetic structures, or for use in aggressive corrosive environments. However, the usage of FRP can be more economical than using steel plates. This is because the material costs in a rehabilitation project rarely exceed 20 percent of the total cost of the repair. The remaining 80 percent is spent primarily on labour and implementation costs. It is in this 80 percent that FRP can significantly reduce the cost of rehabilitation [14]. The application process for the FRP can be carried out from a light scaffolding or a mobile platform, often during a 24 hour period, as compared to several days required to apply heavy steel plates using complex scaffolding systems.

Several FRP systems are now commercially available for the external strengthening of concrete structures. Grace et al. [15] described the fibre materials commonly used in these systems which include glass, aramid, and carbon. The fibres are available in many forms such as pultruded plates, uniaxial fabrics, woven fabrics and sheets. Amongst the material available, CFRP laminate is a popular choice of material due to its high strength. Although, FRP are more effective for flexural strengthening rather than shear strengthening due to its anisotropic properties, shear strengthening can be achieved if the fibre orientation is changed. For strengthening r.c. beams, the FRP application techniques on soffit of the beam are similar to steel plate application.

PROBLEMS ASSOCIATED WITH STRENGTHENING OF REINFORCED CONCRETE BEAMS

A number of failure modes for reinforced concrete beams bonded with soffit plates have been observed in numerous experimental studies to date. Smith and Teng [16] have identified some failure modes of plate bonded strengthened reinforced concrete beams. A schematic representation of the six main failure modes observed in tests is shown in Fig.1. These are namedly grouped under,

i. flexural failure by FRP rupture [Fig.1 (a)]
ii. flexural failure by crushing of compressive concrete [Fig.1 (b)]
iii. shear failure [Fig.1 (c)]
iv. concrete cover separation [Fig.1 (d)]
v. plate end interfacial debonding [Fig.1 (e)], and
vi. intermediate crack induced interfacial debonding [Fig.1 (f)]

It is also reported that, the three failure modes shown on Fig.1(d), Fig.1(e) and Fig.1(f) are not found in conventional r.c. beams and are instead modes unique to beams bonded with a soffit plate. These modes have often been referred to as premature debonding failures modes, as they occur before the flexural failure of the section in mode Fig.1(a) or Fig.1(b) or the shear failure in mode Fig.1(c) occurs. Besides these, EI-Mihilmy and Tedesco [17] and Dong [18] have reported another type of debonding failure at the interface level of plate and concrete. They reported that, debonding at the plate-concrete interface can occur in areas of concrete surface due to high interface shear stress (shear flow) or due to unevenness or due to faulty bonding.

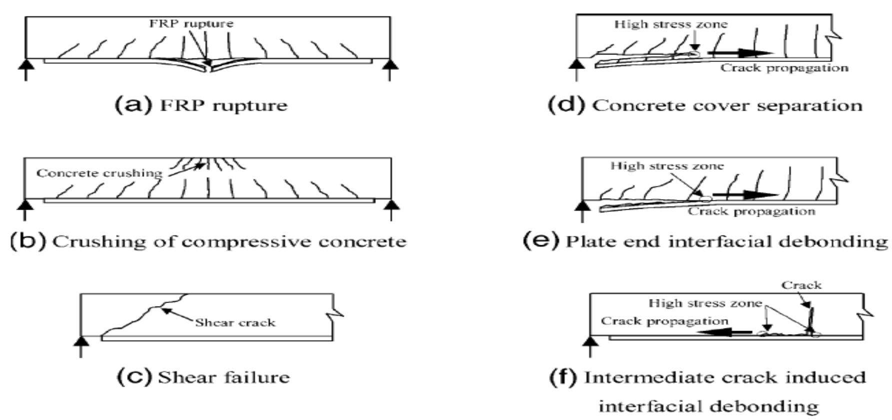

Figure 1: Failure modes of strengthened beams [16]

However, all of the modes of debonding can be broadly classified into three categories:
i. plate end debonding (those that initiate at or near one of the plate ends and then propagate away from the plate end)
ii. intermediate crack induced interfacial debonding or axial peeling (those that initiate at an intermediate flexural or flexural-shear crack and then propagate from such a crack towards the plate end), and
iii. debonding at interface level.
Out of these, debonding at the end of the plate is the main problem of plate bonded strengthened beams. This can be minimized by using appropriate end anchorages. Premature shear failure could also be minimized by using intermediate anchorages at shear span.

EXPERIMENTAL PROGRAMME

Description of specimens

Three rectangular beams were fabricated and tested in this study as shown in Table1. Beam A1 was left as the control beam. Beam B4 was strengthened by steel plate (2.76 mm x 73 mm x 1900 mm) and beam C4 was strengthened by CFRP laminate (1.2 mm x 80 mm x 1900 mm). Both of the strengthened beams (B4 and C4) were also end anchored by L shape anchoring plates of 200 mm anchorage length and were also anchored along the length of the beam with L shape anchoring plates of 40 mm anchorage length as the intermediate anchors. For all beams, the length of the strengthening plate is fixed at 1900 mm (see Fig. 2). The reason for the full span-length strengthening is to maximize the strengthening effects.

Table 1: Test variables

Serial No	Beam	Strengthening Materials			Anchorages	
		Type	Thickness (mm)	Width (mm)	End (200 mm)	Intermediate (40mm)
1	A1	-----	-------	------	---------	------------
2	B4	Steel Plate	2.73	73	L shape	L shape
3	C4	CFRP	1.2	80	L shape	L shape

Fabrication of specimens

All beam specimens were of 2,300 mm long, 125 mm wide, and 250 mm deep as shown in Fig. 2. These beams were reinforced with 12 mm diameter steel bars in the tension zone. Ten millimetre steel bars were used as hanger bars and 6 mm diameter bars were used for the shear reinforcement.

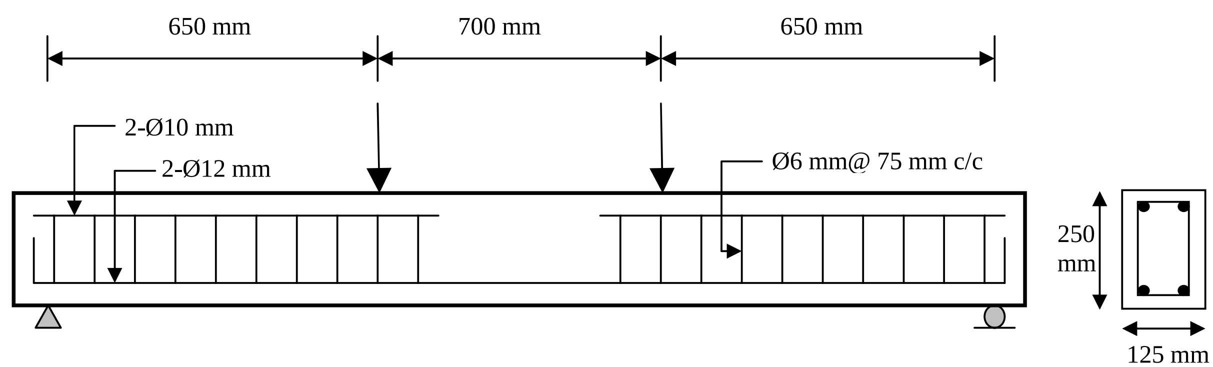

Figure 2: Beam details

Strengthening and anchoring

The concrete surface treatment prior to plating works was very important to guarantee a perfect bonding between concrete and strengthening plates. The concrete surface to be bonded was ground with a diamond cutter to expose the coarse aggregates. Dusts were then blown out by compressed air. The surface of the steel plate was also sand blasted to eliminate the rust. A special cleaner, Colma cleaner was used to remove carbon dusts form the bonding face of the CFRP laminate. The well mixed sikadur adhesive was then trawled on to the surface of the concrete specimens to form a thin layer. The same adhesive was also applied with a special "dome" shaped spatula onto the CFRP (Sika CarbaDur) laminates and steel plates. The plates were then positioned on the prepared concrete surfaces. Using a rubber roller, the plates were gently pressed into the adhesive until the material was forced out on both sides of the laminates. The surplus adhesive was then removed.

L shape end and intermediate anchorages were used at the end of both of the strengthened beams (B4 and C4) as shown in Fig. 3. All anchorages were made from steel plates.

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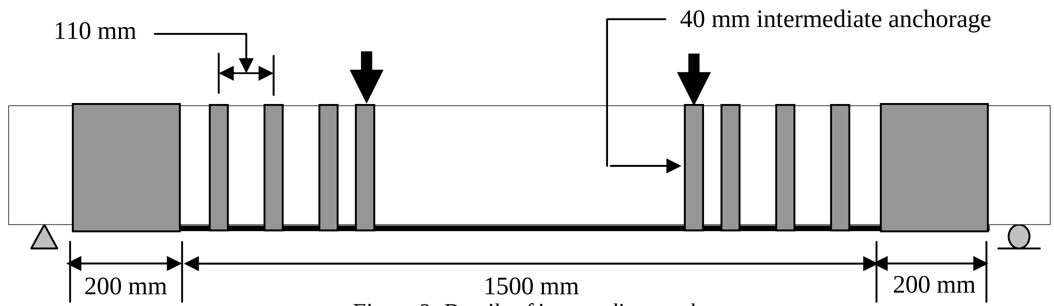

Figure 3: Details of intermediate anchorage

The thickness of the plate was 2 mm. The spacing of the intermediate anchor was chosen to be 110 mm, which was equal to half of effective depth (d/2). This is to ensure the every shear crack will have to cross the plate. The plate was sand blasted and the surface preparation and application methods were similar to that of plating method. An excessive amount of adhesive was applied to the edge of the structure to avoid any risk of gaps in the adhesive. The anchor-plates were fixed on to the beam and then pressed by a rubber roller. After fixing, it was clamped for 3 days for setting.

Materials

Ordinary Portland Cement (OPC) was used and the maximum size of coarse aggregate was kept at 20 mm. The mix proportion is as shown in **Table 2**. The compressive strengths of concrete were measured from three cubes after 28 days curing in accordance with the British Standard (BS 1881).

Table 2: Mix design

Slump	Water Cement ratio	Contents (kg/m^3)			
		Water	Cement	Coarse Aggregate	Fine Aggregate
60-180	0.65	208	320	740	1120

The average concrete compressive strength was found to be approximately 33 MPa. The measured yield and tensile strength of the tensile bars were found to be 551 MPa and 641 MPa respectively. Measured yield and tensile strength of the stirrup was found to be 520 MPa and 572 MPa respectively. The yield strength, tensile strength and modulus of elasticity of the steel plates were 320 MPa, 375 MPa and 200 GPa respectively. Whereas the tensile strength and modulus of elasticity of CFRP laminates were 2800 MPa and 165 GPa respectively. The design and ultimate strain of CFRP laminates were 0.0085 and 0.017 according to the manufacturer’s instruction.

Instrumentation and Test Procedure

Fig. 4 shows the test set-up. The beams were tested under 4 points loading using the Instron 8505 Universal Testing Machine. Electrical resistance strain gauge shows in the diagram was mounted on the bonding face of the beam’s reinforcement at mid-span to monitor the strains. They were also used to measure the strains in the steel plate, CFRP laminate and concrete at the mid-span. Demec gauges were also attached along the height of beam at the mid span for the purpose of plotting the strain distributions.

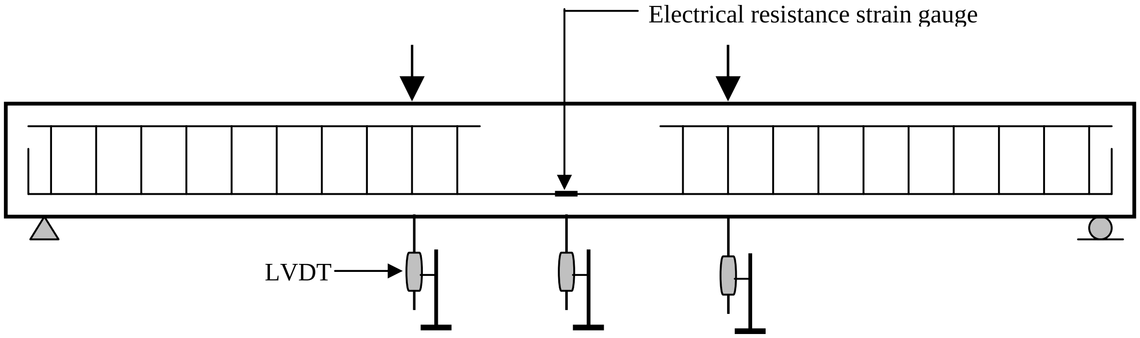

Figure 4: Beam instrumentations

Three linear variable displacement transducers (LVDTs) were used to measure vertical deflections of the beam at mid-span and under the two load points as shown in the diagram. The loads were applied incrementally under load control manner up to failure.

EXPERIMENTAL RESULTS AND DISCUSSION

Mode of failure

Plates 1, 2 and 3 show the failure modes for test beams of A1, B4 and C4 respectively. It was found from the test that beams A1 and B4 failed in flexure with a ductile failure mode whereas beam C4 failed with a concrete compression failure characteristic. It can be seen that all beams failed with a ductile mode of failure. Beam A1 failed in the natural manner expected of an under-reinforced concrete beam i.e. crack widening crashing of concrete. Beams B4 and C4 failed by concrete in the compression zone crushing but due to strengthening plate the concrete in the tensile zone remained intact.

Failure load

The experimental failure loads for all the beams are shown in Table 3. The results show that, the strengthened beams B4 and C4 had higher first crack loads and failure load than the control beam. Beam C4 gave the highest failure load whereas B4 gave the highest first cracks load.

Deflection

Fig 5 shows the load-mid span deflection plots for beams A1, B4 and C4. All beams showed a linear relationship before the yield points. Strengthened beams (B4 and C4) gave less deflections compared to the control beam due to their higher stiffnesses. The curves in deflections for beams B4 and C4 were found to be somewhat similar.

Cracking patterns

Crack spacing

The total number of cracks in beams A1, B4 and C4 were found to be 11, 18 and 18 respectively. The average crack spacings were found to be 182 mm, 111 mm and 111 mm respectively.

Table 3: Test results

Specimen	1st Crack Load in kN	Failure Load in kN	Theoretical Ultimate load in kN	Failure load / Theoretical Ultimate load
A1	14	80.59	76	1.06
B4	35	125.4	122.3	1.03
C4	25	157.8	119	1.33

Plate 1. Failure mode of beam A1 (Control beam)

Plate 2. Failure mode of beam B4 (steel plate strengthened beam with L shape end and intermediate anchorages)

Plate 3. Failure mode of beam C4 (CFRP laminate strengthened beam with L shape end and intermediate anchorages)

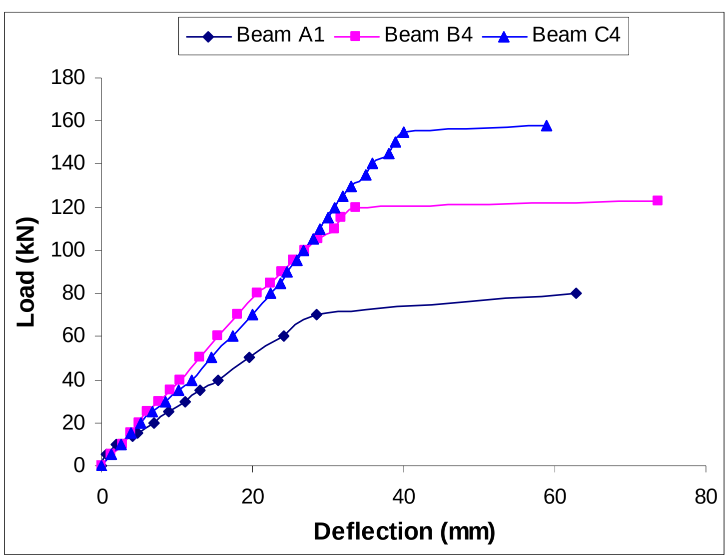

Figure 5: Behaviour of mid-span deflection of intermediate anchored strengthened beams

Crack width

Fig 6 shows the load versus crack width curves for A1, B4 and C4. The strengthened beams B4 and C4 showed smaller crack widths compared to the control beam.

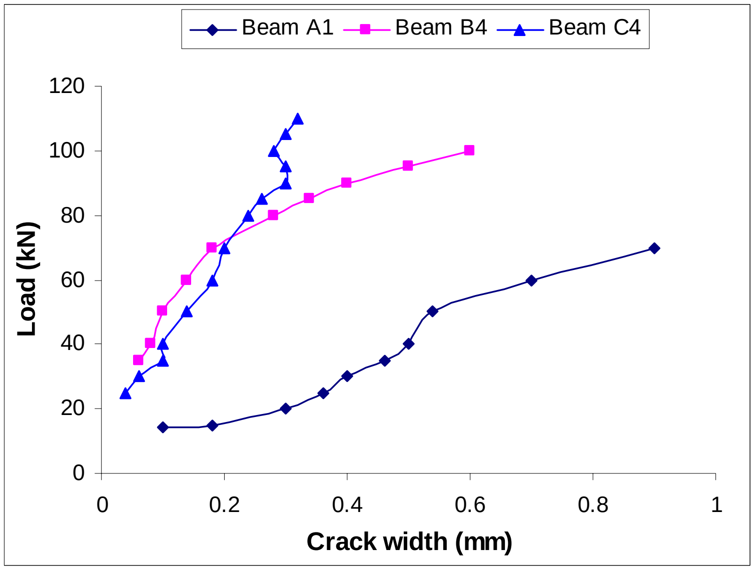

Figure 6: Behaviour of crack width of intermediate anchored strengthened beams

CONCLUSIONS

The conclusions that can be drawn from the study are as follows,

1. The steel plate and CFRP laminate flexurally strengthened beams gave higher failure loads than the control beam. All beams exhibited ductile failure modes. The strengthened beams even, though failing by concrete compression did not fail suddenly due to the inherent strength of the steel and CFRP laminate.
2. All strengthened beams showed lesser deflections than the control beam.
3. All strengthened beams were found to be superior compared to the control beam in terms of cracking characteristics.

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REFERENCES

[1] Diab, Y. G. (1998) Strengthening of RC beams by using sprayed concrete: experimental approach. Engineering Structures **20**(7): 631-643.
[2] Dinardo, C. & Ballingall, J. R. (1988) Major concrete repairs and restoration of factory structures – Uniroyal Ltd., Dunfries, Scotland. The Structural Engineer **6.6**(10): 151-160.
[3] Romualdi, J. P. (1987) Ferrocement for infrastructurerehabilitation. Concrete International:Design and Construction **9**(9): 24-28.
[4] Iorns, M. (1987) Laminated ferrocement for better repair. Concrete International: Design and Construction **9**(9): 34-38.
[5] Andrews, G. and Sharma, A. K. (1988) Repaired reinforced concrete beams. Concrete International: Design and Construction **4**: 47-57.
125
[6] Paramasivam, P., Lim, C.T.E. and Ong, K.C.G. (1998) Strengthening of RC beams with ferrocement laminates. Cement and Concrete Composites **20**: 53-65.
[7] Jones, R., Swamy, R. N. and Charif, A. (1998) Plate separation and anchorage of reinforced concrete beams strengthened by epoxy-bonded steel plates. The Structural Engineering **66**(5): 85-94.

[8] Oehlers D. J. and Mohamed Ali, M. S. (1997) Debonding of steel plates glued to reinforced concrete flexural members. Due to published in the progress in Structural Engineering and Materials.

[9] Swamy R. N., Jones R. and Bloxham J.W. (1987) Structural behaviour of reinforced concrete beams strengthened by epoxy-bonded steel plates. The Structural Engineer **65A**(2): 59-68.

[10] Adhikary, B.B., Mutsuyosh, H. and Sano, M. (2000) Shear strengthening of reinforced concrete beams using steel plates bonded on beam web: experiments and analysis. Construction and Building materials **14**: 237-244.

[11] Heffernan C. P. J. (1997) Fatigue behaviour of reinforced concrete beams strengthened with CFRP laminates. PhD thesis, UMI Dissertation services.

[12] Garden H. N. and Hollaway L. C. (1998) An experimental study of the influence of plate end anchorage of carbon fibre composite plates used to strengthen reinforced concrete beams. *Composite Structures* **42**: 175-188.

[13] Neale K. W. and Labossiere P. (1991) Advanced composite materials with applications to bridges. Mufti A. A. Erki, M. A., and Jaeger L. G., Editors. State-of-the-art report, CSCE, pp. 21-69.

[14] Meier U. (1992) Carbon fibre-reinforced polymers: Modern materials in bridge engineering. Structural Engineering International **2**(1): 7-12.

[15] Grace, N. F., Ragheb, W. F. and Abdel-Sayed G. (2004) Development and application of innovative triaxially braided ductile FRP fabric for strengthening concrete beams. Composite Structures **64**: 521-530.

[16] Smith S. T. and Teng J. G. (2002) FRP-strengthened RC beams. I: review of debonding strength models. Engineering Structures **24**: 385-395

[17] El-Mihilmy M. T. and Tedesco J. W.(2001) Prediction of anchorage failure for reinforced concrete beams strengthened with fiber-reinforced polymer plates. ACI Structural Journal **98**(3): 301-314.

[18] Dong, Y. (2003) Static and fatigue performance of reinforced concrete beams retrofitted with external CFRP composites. PhD thesis, UMI Dissertation Services.