UNIVERSITI PUTRA MALAYSIA

FLEXURAL RESPONSE OF REINFORCED CONCRETE BEAMS WITH EMBEDDED CFRP PLATES

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By

RACHAEL BUKOLA OHU

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,
in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

'TO JEHOVAH ALMIGHTY'

AND

TO MY PRECIOUS FAMILY

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment
of the requirement for the degree of Doctor of Philosophy

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November 2012

Chairman : Professor Mohd Saleh Jaafar, PhD

Faculty : Engineering

Fiber reinforced polymers (FRP) are used as either internal or as external reinforcements in structures. However, issues related to reduced ductility performance and large deflections have been observed by several other researchers which needs to be addressed in order for these reinforcements to be more widely adopted as alternative structural reinforcements in practice.

In this regard, an alternative method of using FRP plates as internal reinforcements in concrete beams is explored and presented in this thesis in terms of ductility/deformability performance as well as other structural responses under static loading with the aim of improving the ductility/deformability response as well as examining some aspects of structural behaviour. In addition, the bond behaviour of this reinforcement which is a key factor towards the improvement of structural performance especially with regards to the bond-slip behaviour at service and ultimate conditions was studied. Thus, different surface treatments have been experimentally investigated through pullout tests to identify the best bond effects. Based on the experimental bond-slip behaviour obtained, a concrete – CFRP plate bond interface model is proposed and incorporated into a finite element algorithm for the analysis of concrete beams reinforced with embedded CFRP plates taking into consideration differences in the surface textures of the embedded CFRP plate. A 2-D nonlinear finite element program was thus adopted for the analysis of the proposed reinforcement technique. The most suitable surface treatment obtained from the pullout tests was then adopted in the embedded carbon fiber reinforced polymer plates (CFRP) in concrete beams via experimental testing under flexural load.

The results showed that embedded CFRP plates in concrete beams is an effective alternative form of reinforcement with a 37% decrease in deflection response and a 54% improvement in deformation/ductility performance. In addition the bond behaviour is dependent on the type of surface treatment with an increase in bond strength ranging between 78% - 284%. While an increase in concrete strength led to a 58% increase in the bond strength of embedded CFRP plates in concrete. Similarly, the proposed bond model for the embedded CFRP plates successfully depicted the concrete-CFRP plate interface behaviour and the FE results were in agreement with the experimental results with a percentage difference of 12% exhibiting a realistic simulation of the experimental load-deflection response.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

TINDAKBALAS LENTURAN BAGI RASUK KONKRIT BERTETULANG DENGAN PLAT CFRP TERBENAM

Oleh

RACHAEL BUKOLA OHU

November 2012

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Fakulti : Kejuruteraan

Polimer Bertetulang Gentian (FRP) biasanya digunakan sebagai tetulang dalaman atau luaran di dalam struktur. Walaubagaimanapun, isu berkaitan dengan pengurangan sifat kemuluran dan jumlah lenturan yang besar perlu ditangani berdasarkan pemerhatian beberapa pengkaji bagi membolehkan gentian bertetulang ini digunakan dengan lebih meluas sebagai tetulang alternatif dalam struktur yang sebenar.

Sehubungan dengan ini, kaedah alternatif menggunakan plat FRP sebagai tetulangan dalaman bagi rasuk konkrit telah diterokai dan dipersembahkan dalam tesis ini dari segi keupayaan kemuluran/ubahbentuk dan juga lain-lain tindakbalas struktur apabila beban statik dikenakan dengan matlamat untuk meningkatkan tindakbalas kemuluran/ubahbentuk juga memeriksa beberapa aspek perlakuan struktur. Disamping itu, perlakuan ikatan bagi tetulang ini yang merupakan faktor utama kearah menambahbaik keupayaan struktur terutamanya berkaitan dengan perlakuan ikatan-gelinciran pada keadaan khidmat dan muktamat juga dikaji. Oleh sebab itu, penggunaan rawatan pemukaan yang berbeza telah dikaji secara ujikaji melalui ujian tarik keluar untuk mengenalpasti kesan ikatan yang terbaik. Berdasarkan perlakuan ikatan-gelinciran yang diperolehi dari ujikaji, model ikatan permukaan konkrit- plat CFRP dicadangkan dan digunapakai didalam algoritma unsur terhingga bagi analisis rasuk konkrit bertetulang plat CFRP terbenam dengan mengambilkira perbezaan tekstur permukaan plat CFRP terbenam. Progam 2D unsur terhingga tak lurus telah digunapakai untuk menganalisis teknik tetulang yang dicadangkan. Rawatan permukaan yang paling sesuai berdasarkan ujikaji tarik keluar telah diadaptasi dalam rasuk konkrit bertetulang plat CFRP terbenam melalui ujikaji beban lenturan.

Keputusan ujikaji menunjukan plat CFRP yang dibenamkan dalam rasuk konkrit adalah satu kaedah alternatif tetulang yang efektif dengan 37% pengurangan tindakbalas lenturan dan 54% penambahbaikan perlakuan kemuluran/keupayaan ubahbentuk. Disamping itu, perlakuan ikatan adalah bergantung kepada jenis rawatan permukaan yang menunjukan peningkatan kekuatan ikatan dari 78% - 284%. Juga, peningkatan kekuatan konkrit membolehkan 58% peningkatan kekutan ikatan plat CGRP terbenam dalam konkrit. Dalam masa yang sama, model ikatan yang dicadangkan bagi plat CFRP terbenam telah berjaya menggambarkan perlakuan permukaan antara konkrit- plat CFRP dan keputusan unsur terhingga adalah selari dengan keputusan ujikaji dengan peratsu perbezaan sebanyak 12% menggambarkan simulasi yang realistik bagi tindakbalas ujikaji beban- lenturan.

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I certify that a Thesis Examination Committee has met on the 7th of November 2012 to conduct the final examination of Rachael Bukola Ohu on her thesis entitled " Flexural Response of Reinforced Concrete Beams with Embedded CFRP plates " in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded Doctor of Philosophy.

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DECLARATION

I declare that the thesis is my original work, except for quotations and citations, which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institution.

RACHAEL BUKOLA OHU

Date: 7th November 2012

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a = depth of equivalent rectangular stress block

A_f = FRP reinforcement area

A_s = area of steel and embedded CFRP plates

b and d = concrete section width and depth to reinforcement from compression fibre

b = width of beam (mm)

β_1 = factor taken as 0.85 for concrete strength f'_c up to and including 28MPa

[B] = the strain-displacement matrix

$[B]_j$ = the strain displacement matrix of the interface element

d = diameter

D^2 = depth of beam (mm)

$[D]$ = global elasticity matrix of the element material

E_f = design or guaranteed modulus of elasticity of FRP

ε_{cu} = ultimate strain in concrete

f'_c = compressive strength of concrete

f_f = stress in FRP reinforcement in tension

f_s and f_f = the steel strength

f'_t = Split tensile strength (N/mm^2)

f_{fu} = design tensile strength of FRP, considering reductions for service environment

F_r = modulus of rupture (MPa)

$[J]$ = Jacobian matrix

$[K]$ = interface element stiffness matrix in the global direction

l = cylinder length

l_b = embedment/bond length

L = Span length

M_n = nominal moment capacity

M_u = maximum ultimate bending moment (kNm)

n = number of sampling points

p = constant material parameter

P_{max} = maximum load

ρ_f = FRP reinforcement ratio

ρ_{b} or ρ_{fb} = FRP reinforcement ratio producing balanced strain conditions

ρ_{max} = maximum allowable reinforcement ratio

ρ_{min} = minimum allowable reinforcement ratio

s_{s} = shear slip (mm)

t = thickness of the element in the direction normal to the plane

τ = maximum shear bond stress

τ_{o} = interface shear bond strength

τ_{u} = shear bond strength (MPa)

τ_{bmax} = interfacial bond strength

T = splitting tensile strength

μ = interface coefficient of friction

w_f and t_f = plate/strip width and thickness

w_i and w_j = weighting coefficients appropriate to the position i and j

w_{max} = maximum allowable reinforcement index

Δu_i and Δv_i = relative displacements of the nodal points at the middle surface (a, b and c)

ε, σ = instantaneous values of the stress and strain

ε_o, σ_o = the ultimate peak strain and stress

ε'_s ε'_n = tangential and normal strains at a point (shear slip and normal displacement)

σ_n is the normal stress (N/mm^2)

$\sigma_{t'}$ = tensile bond strength on the interface (N/mm^2)

$\{\delta\}$ = vector of the displacements (u, v)

BIODATA OF THE AUTHOR

Rachael Bukola Ohu was born on the 8th of September 1975 in Oyo State Nigeria. She obtained her Bachelors degree in Civil and Water Resources Engineering in December 1999 from the University of Maiduguri, in Borno State Nigeria.

The author obtained her Master of Science degree in the Structural Engineering in 2007 and began her pursuit of a Doctor of Philosophy (PhD) in Structural Engineering in 2008 in the same institution. For the duration of her PhD the author was competently supervised by a team consisting of Prof. Ir. Mohd Saleh Jaafar, the late Prof. Jamaloddin Norzaie and Dr Farah Nora Aznieta from the structural engineering unit of the Department of Civil Engineering UPM. The author has worked as a research assistant in the Structural engineering unit of the Universiti Putra Malaysia on project proposals and executions and she has experience as a site engineer in Sani Mustapha and Associates a Structural Engineering Consultancy firm in Abuja, Nigeria specialising multi storey structures.

The author's main research interests include fiber reinforced composites, reinforced concrete design, prestressed concrete design, strengthening and repair of structures and ultra high performance concrete.

LIST OF PUBLICATIONS

1. Ohu, R.B., M.S. Jaafar, Aznieta, F.N., Al-wathaf, A.H. (2012). Effect of surface treatment on bond of embedded CFRP plates. Journal of Composite Materials. October 11, 2012 (IF=1.068).
2. Ohu, R.B., M.S. Jaafar, Aznieta, F.N., Al-wathaf, A.H. (2012). Performance of concrete beams reinforced with embedded CFRP plates. Indian Concrete Journal, Vol.86, No.7. Scopus Citation Index.
3. Ohu, R.B., Thanoon, W.A.M., Noorzaei, J., Abdul Kadir, M.R., Jaafar, M.S. (2009). Structural behaviour of Distressed and Strengthened Post-tensioned Box beams. Indian Concrete Journal, Vol.83, No.4. Scopus Citation Index.
4. Ohu, R.B., M.S. Jaafar, Aznieta, F.N., Al-wathaf, A.H. (2013). Deformability of Concrete beams Reinforced with Embedded CFRP plates. The Seventh International Structural Engineering and Construction Conference, (ISEC-7) Honolulu, June 18-23.
5. Ohu, R.B., M.S. Jaafar, Aznieta, F.N., Al-wathaf, A.H. (2011). The performance of concrete beams with embedded CFRP plates. International Building and Infrastructure Technology Conference,(BITECH) Penang, Malaysia. June 7-8.

CHAPTER 1

INTRODUCTION

1.1 General

For a long time, steel has been the dominant type of reinforcement for concrete structures. Its compatibility with concrete and strength has made it an efficient reinforcement. However, deterioration and even collapse of steel reinforced structures has shown the sensitivity of steel in terms of its corrosive activity. Corrosion affects several aspects of structural behaviour with the most fundamental being bond. The transfer of stresses between concrete and reinforcement at both serviceability and at the ultimate state are considered to rely strongly on the quality of bond while mechanisms that resist flexural bending, shear and torsion are connected to the development of adequate bond characteristics. When corrosion takes place, it results in a degradation of bond and the ultimate bond strength is reduced (Almusallam et al. 1996) or it could ultimately lead to structural failure (Johnson, 2010). A picture showing corrosion in reinforced concrete and its effect on bond is shown in Figure 1.1 where it can be seen that high levels of corrosion result in significant reductions in bond strength due to loses of confinement and adhesion strength as well as reductions in geometrical characteristics (Bhargava et al. 2007). Because corrosion can not be totally eliminated researchers looked for other types of materials that could be used as alternative reinforcements. This led to the introduction of composite materials. Apart from this detrimental factor, others such as high maintenance costs, durability concerns and limited service life of traditional structural materials can be made up for with the substitution of composites. Although composite materials have existed for a long time it took a while for it to be recognized as a type of reinforcement in civil engineering.

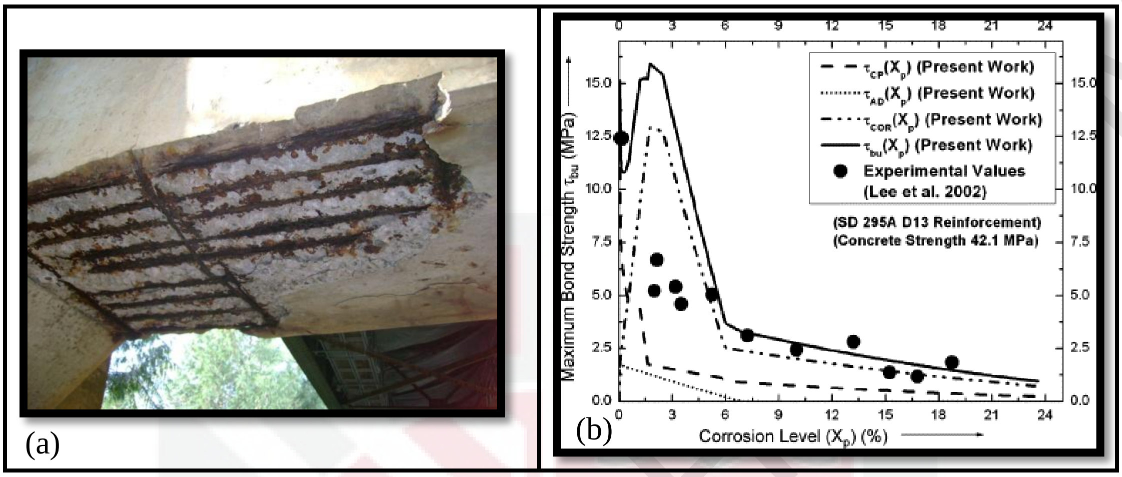

Figure 1.1 (a) Beam corrosion; (b) Bond strength as a function of corrosion (Lee et al., 2002 and Bhargava et al. 2007).

1.2 Versatility of Fiber reinforced polymers in construction

The use of composite materials in various aspects of civil engineering has grown steadily over the years. Just as material technology has evolved, so have structural techniques. Because of this evolution, several codes of practice have been modified to include and to cater for recent developments in research. To this end, fibre reinforced polymer composites have become one of the most versatile materials in use today. From being used for boat hulls, marine vessels, in the automotive industry and in aeronautics to being used as external or internal reinforcements of concrete structures. The versatility of FRPs stems from its' inherent properties some of which include its light weight, corrosion resistance and ease of use. Fiber reinforced polymers are currently manufactured in a variety of forms, shapes and textures. This variety also extends to its properties however these properties differ from those of steel. Depending on the structural requirement, engineers can chose what is best suitable for a particular structure and this has helped to increase the popularity of this composite material worldwide. As of today, FRP bars are used as either internal or external reinforcements in the construction industry for reinforced concrete structures while FRP plates or strips are traditionally used as external reinforcements. Some of the current applications of FRP bars used as internal reinforcements include bridge decks, multi-storey buildings, parking structures and industrial buildings to name a few. In order to further increase the popularity of using FRPs as well as its diversity of utilization in reinforced concrete structures certain aspects of FRP behaviour needs to be further understood and improved on which will instil more confidence in it's use as an innovative composite material by engineers.

1.2.1 FRP – reinforced concrete behaviour

Past research has shown that externally bonded FRP reinforcements (EBR) or near surface mounted FRP reinforced (NSM) structures which are the most widely used techniques show increased capacity resistance (Capozucca et al. 2002), improved cracking and stiffness (Li et al. 2006), significantly enhanced load carrying capacities in bending (Barros and Fortes, 2005) and an increase in the equivalent longitudinal reinforcement (laminates) resulted in improved overall structural performances (Barros et al. 2007 and Yost et al. 2007). Some characteristic behaviour of FRP bars in concrete have shown that larger deflections and crack widths occur in FRP reinforced structures than in steel reinforced structures (Bakis et al. 2002). In addition, the FRP beam reinforcement ratio did not affect the moment capacity

(Nawy and Neuwerth, 1971) and the development of its full strength when used as reinforcement could not be achieved. Apart from these characteristics another common feature of FRP reinforced concrete was that of debonding and reduced ductility (Liu et al. 2006, Kang et al. 2005 and Li et al. 2008). Serviceability concerns of FRP-concrete behaviour has also been highlighted by Arockiasamy, 2000; El-Salakway et al., 2004, Salib and Abdel-Sayed, 2004, Saika et al., 2007 where the general agreement is that the low elastic modulus of FRPs leads to a lower serviceability performance in comparison to its steel reinforced counterparts.

Another aspect of FRP to concrete behaviour that affects its usage in the construction industry is its ductility performance. Ductility is a concept which allows a dissipation of large amounts of energy in a system which in turn serves as a means of giving warning signals of impending failure and is thus a measure of safety. The non-yielding nature of FRPs resulting from its linear elastic response to failure makes the ductility of FRP systems quite small in contrast to steel reinforced systems however because FRP systems do undergo sufficient deformation with an associated dissipation of energy, some researchers prefer to adopt the term ‘deformability’ (Jaeger et al. 1995, Vijay et al. 1996 and Newhook et al. 2002) in place of ductility for FRP reinforced systems. Based on this concept several researchers found out that FRP reinforced member’s exhibit sufficient deformability (Vijay et al. 1996; Mufti et al. 1996; Shin et al. 2009 and Issa et al. 2011) and that the preferred concept of over-reinforced design adopted for FRP systems led to a more gradual failure with adequate warning.

Of all these aspects of behaviour, one of the most essential properties in an RC section for it to achieve an adequate level of performance is bond. Through bond a transfer of forces or stresses between the concrete and reinforcement occurs which allows a concrete section to develop strength and work as a single unit to resist external forces or loads. Three kinds of bond mechanisms typically occur; chemical adhesion, friction and mechanical interlock however, according to Cosenza et al. 1997; Wang et al. 1999; Benmokrane et al. 2002 and Firas et al. 2011, three (3) main factors control bond between FRP and concrete;

1. Chemical bond
2. Friction due to surface roughness of the bars
3. Mechanical interlock

Due to large differences in surface deformations, configurations or textures of FRP bars, differences in the bond strength achieved also differs. However the general consensus is that the bond strength of FRPs is lower than that of steel bars. Improving the bond strength can however be achieved by applying different surface treatments which could lead to bond strengths that are twice that of steel bars (Al-mahmoud et al. 2007; Makitani et al. 1993; Rosetti et al. 1995). Detailed investigations into the effects of elastic modulus (Achillides, 1997; Tepfers et al., 1997), effects of surface texture (Itoh et al., 1989; Makitani et al., 1993; Hattori et al., 1995; Jerrett and Ahmad, 1995), effects of cross sectional shape (Achillides et al., 1997) and effects of concrete strength on the bond of FRP bars has been carried out in several studies. Of these, the most popular effect considered is that of surface texture while others like Lee et al. (2008), Achillides (1998) and Okelo and Yuan (2005) studied the effect of concrete strength.

1.3 Problem Statement

Based on the above, the following problems have been identified;

A Reduced ductility performance of FRP reinforced concrete beams was observed in comparison to that of steel reinforced concrete beams mainly due to the linear elastic behaviour of FRPs up to failure. Secondly, larger deflections and crack widths at service were shown to occur largely due to the lower elastic modulus of FRPs. In addition, there was an inefficient utilization of the full tensile strength of FRP reinforcements which is necessary to gain the full benefits arising from the high tensile strength property of this composite material. Therefore as a means of providing solutions to these problems alternative techniques utilizing FRPs need to be examined.

1.4 Objectives

The main objective of this study is;

1. To determine the effectiveness of embedded fibre reinforced polymer plates as longitudinal reinforcements in concrete beams under bending.

In addition the following are sub-objectives of this study;

i. To evaluate the ductility performance and serviceability behaviour of concrete beams reinforced with longitudinal embedded fibre reinforced polymer plates.

ii. To ascertain the bond behaviour and characteristics of embedded fibre reinforced polymer strips in different concrete compressive strengths.

iii. To propose a bond model that represents the FRP-concrete interface behaviour using a 2D nonlinear finite element program.

1.5 Scope of the study

The scope of this study includes the experimental investigation on the effects of embedded CFRP plates of (tensile strength = 2800N/mm^2 and modulus of elasticity = 169,000N/mm^2). The bond behaviour involved the use of various types of surface treatments and concrete strengths (f_{cu} = 43.52MPa and 93.40MPa) in addition to the study of the structural response of this type of beams. The experimental bond tests were carried out via the use of standard sizes of 150Øx300mm cylinders while the experimental testing of 21 model scale beams of size 150x150x750 mm and 18 large scale beams of size 160x250x2500mm reinforced with steel bars or embedded CFRP plates and external/near surface mounted CFRP reinforcements was carried out. Although two (2) different concrete strengths were adopted for the bond tests, only one(1) concrete grade was employed for the beam tests.

Determination of the characteristics of bond behavior was made with respect to the effects of various surface treatments and different concrete strengths. In terms of the structural behavior of these beams, only some critical aspects of flexural behavior were examined which include; load-deflection response, deformation/ductility performance, cracking characteristics, ultimate loads and associated failure mechanisms. The numerical study was carried out using a 2D finite element program that was modified based on the experimental study. A bond model was proposed based on the experimental bond-slip relationship obtained which was then incorporated in the program for the simulation.

1.6 Research Significance

The possible application of fibre reinforced polymer plates as a replacement for longitudinal steel reinforcements or as an alternative to FRP bars would result in; (1) reducing the quantity of reinforcement used through an efficient maximization of the higher surface to cross sectional-area ratio; (2) an improved capacity performance due to larger ultimate strain capacity over that of FRP bars; (3) reduced long term maintenance or life cycle costs and (4) it could also be a useful alternative for section enlargement of structural elements without the need to significantly increase concrete member size.

The benefits mentioned in (1) and (2) in addition to increased flexural stiffness and high tensile strength rigidity of the CFRP plate would thus lead to a reduction in deflection and an increase in the ductility/deformability performance.

1.7 Limitations

Limitations of this study in terms of the issue of batching the concrete requires careful implementation. The process of batching these beams in practice needs to be carefully carried out and monitored to ensure that minimal or no voids are created or left at the soffit of the beam after casting due to the width of the plate. The use of properly sized concrete biscuits (casted in advance prior to casting) is essential to maintain the concrete cover throughout the beam length in addition, proper concrete vibration using a small vibrating nozzle to ensure it can be easily maneuvered at all the edges of the mould to allow the proper flow of fresh concrete under the embedded CFRP plate. In practice, careful monitoring of the casting process is essential and needs to be carried out in batches, however because of the relative thinness of the embedded CFRP plate and as long as the workability of the fresh concrete is ensured, a good outcome of the structural element can be achieved. In addition, aggregate sizes not exceeding (that is <) 10mm need to be adopted when casting concrete where embedded FRP plates are to be used. As long as these measures are adhered to, an acceptable concrete structure that meets required standard practices can be obtained.

Some variations in the F.E cracking results can also be minimized further by improvements in the solution algorithm procedure and finite element mesh which affect F.E nonlinear analyses.

1.8 Summary

This chapter gives a brief description about the advent and usage of fiber reinforced polymers (FRPs) in concrete. The general characteristic behaviours of FRPs when used as either external or internal reinforcements has been highlighted in addition to the associated problems observed when FRPs are used. As a means of solving these problems, objectives of this study have been chosen with the aim of finding possible answers to these problems and hence provide an alternative technique of reinforcing concrete that is structurally beneficial, while also investigating the characteristics of this alternative reinforcing technique.

REFERENCES

1. Abdalla, H.A. (2002). Evaluation of deflection in concrete members reinforced with fibre reinforced polymer bars. Composite Structures, Vol. 56, No. 1, pp.63-71.
2. Abdelrahman, A.A., Tadros, G., and Rizkalla, S.H. (1995). Test model for the First Canadian Smart Highway Bridge. ACI Structural Journal, V.92, No.4, pp. 451 - 458.
3. Achillides Z., Pilakoutas K., and Waldron P (1997). Bond behaviour of FRP bars to concrete. Proc. FRPRCS-3, Non-metallic (FRP) reinforcement for concrete structures, 3rd FRP International Symposium, Japan Concrete Institute, Sapporo, Japan, 2, pp. 341-348.
4. Achillides, Z. (1998). Bond behavior of FRP bars in concrete. PhD thesis, Universiti of Sheffield, Centre for Cement and Concrete, Department of Civil and Structural Engineering, Sheffield, UK.
5. Achillides, Z., and Pilakoutas K. (2004). Bond behavior of fiber reinforced polymer bars under direct pullout conditions. Journal of Composites for Construction, Vol.8, No.2, pp. 173-181.
6. ACI Committee 440. (2003). Guide for the Design and Construction of Concrete Reinforced with FRP Bars (ACI440.1R-03), American Concrete Institute, Farmington Hills, Michigan, pp. 41.
7. ACI Committee 440. (2006). Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures. ACI.1R-06, American Concrete Institute.

8. Ahmed, O., Van Gemert, D., Vandewalle, L. (2000). Improved model for plate-end shear of CFRP strengthened RC beams. Cement and Concrete Composites, Vol. 23, pp.3-19.
9. Aiello, M. A., Leone, M., and Pecce, M. (2007). Bond performances of FRP rebars-Reinforced concrete. Journal of Materials in Civil Engineering, Vol. 19, No.3, pp. 205 – 213.
10. Arias, J.P.M., Vazquez, A., Escobar, M. (2012). Use of sand coating to improve bonding between GFRP bars and concrete. Journal of Composite Materials. 8th February, pp.1 – 8.
11. Ahmad, F.S., Gilles, F. and Robert L. (2011). Bond between carbon fibre-reinforced polymer (CFRP) bars and ultra high performance fibre reinforced concrete (UHPFRC): experimental study. Construction and Building Materials Journal. 25, pp. 479–485.
12. AL-mahmoud, F., Castel, A., Francois, R., and Tourneur, C. (2007). Effect of surface pre-conditioning on bond of carbon fibre reinforced polymer rods to concrete. Cement and Concrete Composites, Vol. 29, No. 9, pp. 677-689.
13. Almusallam, A.A., Al-Gahtani, A.S., Aziz, A.R. and Rasheeduzzafar. (1996). Effect of reinforcement corrosion on bond strength. Construction and Building Materials, Vol.10, No.2, pp. 123 -129.
14. Almusallam, T.H. (1997). Analytical prediction of Flexural Behavior of Concrete beams reinforced by FRP bars. Journal of Composite Materials, Vol.31, No.7, pp.640-657.
15. Almusallam, T.H. and Al-Salloum, Y. (2006). “Durability of GFRP Rebars in Concrete Beams under Sustained Loads at Severe Environments”. Journal of Composite Materials, Vol.40, No. 7, pp. 623-637.

16. Al-Salloum, Y., and Almusallam, T.H. (2007). “Creep effect on the behavior of concrete beams reinforced with GFRP bars subjected to different environments”. Construction and Building Materials Journal, Vol. 21, pp. 1510-1519.
17. Al-Salloum, Y. A., Al-Sayed, S.H., Almusallam, T.H., Amjad, M.A. (1996). Some Design Considerations for Concrete beams reinforced by FRP bars. Proceedings of the First International Conference on Composites in Infrastructure (ICCI' 96), Tuscon, Arizona, pp. 318-331.
18. Alsayed, S.H. and Alhozaimy, A.M. (1999). Ductility of Concrete Beams Reinforced with FRP Bars and Steel Fibers. Journal of Composites Materials, Vol. 33, No. 19.
19. Alunno Rosetti, V., Galeota, D., and Giammatteo, M.M. (1995). Local bond stress-slip relationships of glass fiber reinforced plastic bars embedded in concrete. Materials and Structures, Vol. 28, No. 180.
20. Al-wathaf, A.H. (2010). Non-linear finite element modelling of reinforced concrete beams. Journal of Structural Concrete, Vol. 11, No.2, pp. 63-72.
21. Al-wathaf, A.H. (2006). Development of finite element code for non-linear analysis of interlocking mortarless masonry system. PhD Dissertation, Department of Civil Engineering, Universiti Putra Malaysia, Malaysia.
22. Al-Zaharani, M. M. (1995). Bond behavior of fiber reinforced plastic (FRP) reinforcements with concrete. PhD thesis, Pennsylvania State University, University Park, Pa.
23. Al-Zahrani, M.M., A-Dulaijan, S.U., Nanni, A., Bakis, C.E., Boothby, T.E. (1999). Evaluation of bond using FRP rods with axisymmetric deformations. Construction and Building Materials, Vol.13, No.6, pp. 299-309.

24. Al-Zahrani, M.M., Nanni, A., Al-Dulaijan, S. U., and Bakis, C.E.(1996). Bond of FRP to concrete. Proceedings of the 51st annual conference of the composite institute. New York: Society of the Plastics Industry, pp. 3A1-8.

25. Aprile, A., Spacone, E., Limkatanyu, S. (2001). Role of Bond in RC beams strengthened with steel and FRP plates. Journal of Structural Engineering, ASCE. Vol. 127, pp.1445-1452.

26. Arockiasamy, M., Chidambaram, S., Amer, A. and Shahawy, M. (2000). "Time-dependent deformations of concrete beams reinforced with CFRP bars". Composites Part B: engineering, Vol.31, pp. 577-592.

27. Ashour, A.F. (2006). Flexural and Shear capacities of concrete beams reinforced with GFRP bars. Construction and Building Materials, Vol. 20, No. 10, pp.1005-1015.

28. ASTM Standard C470/C470M (2009). Standard specification of moulds for forming concrete test cylinders vertically.

29. Au, Francis T.K. and Du, J.S. (2008). Deformability of concrete beams with unbounded FRP tendons. Engineering Structures, Vol.30, pp. 3764-3770.

30. Azizinamini, A., Stark, M., Roller, J.J., and Ghosk, S. K. (1993). Bond performance of reinforcing bars embedded in high-strength concrete. ACI Structural Journal, Vol.90, No 5, pp.554 -561.

31. Baena, M., Torres, L., Turon, A. and Barris, C. (2009). Experimental study of bond behavior between concrete and FRP bars using a pull-out test. Composite Part B: Engineering, Vol. 40, No.8, pp.784-797.

32. Bakis, C.E., Bank, L.C., Brown, V.L., Cosenza, E., Davalos, J.F., Lesko, J.J., Machinda, A., Rizkalla, S.H, Triantfillou, T.C. (2002). Fiber – Reinforced Polymer Composites for Construction – State-of-the-Art

Review. Journal of Composites for Construction, Vol. 6, No. 2, pp. 73-87.

33. Bakis, C.E., Uppuluri, A., Nanni, A. and Boothby, T.E. (1998). Analysis of Bonding Mechanisms of smooth and lugged FRP rods embedded in concrete. Composites Science and Technology, Vol. 58, pp. 1307-1319.

34. Baky, H.A, Ebead, U.A., Neale, K.W. (2007). Flexural and Interfacial behavior of FRP strengthened reinforced concrete beams. Journal of Composites for Construction. Vol. 11, No. 6, pp.629-639.

35. Balendran, R.V., Tang, W.E., Leung, H.Y. and Nadeem, A. (2004). Flexural behavior of sand coated Glass fibre Reinforced Polymer (GFRP) bars in concrete. 29th Conference on “Our World in Concrete and Structures”: 25-26 August 2004, Singapore.

36. Barros, J.A.O. and Fortes A.S. (2005). Flexural strengthening of concrete beams with CFRP laminates bonded into slits. Cement and Concrete Composites; Vol. 27, pp. 471-480.

37. Barros, J.A.O., Dias, S.J.E., Lima, J.L.T. (2007). Efficacy of CFRP-based techniques for the flexural and shear strengthening of concrete beams. Cement and Concrete Composites; Vol. 29, pp. 203-217.

38. Barros, J.A.O., Ferreira, D., Fortes, A.S., Dias, S.J.E. (2006). Assesing the effectiveness of embedding CFRP laminates in the near surface for structural strengthening. Construction and Building Materials; Vol.20, pp. 478-491.

39. Bazant, Z.P and Novak, D. (2001). Proposal for Standard test of Modulus of Rupture of Concrete with its Size Dependence. ACI Materials Journal, Vol. 98, No.1, pg 79-87.

40. Bazant, Z. P., and Sener, S. *(*1988*)*. Size Effect in Pullout Tests. ACI

Materials Journal, Vol.85, No.5, pp. 347-351.

41. Belaid, F., Arliguie, G. and Francois, R. (2001). Effect of Bar Properties on Bond Strength of Galvanized Reinforcement. Journal of Materials in Civil Engineering, V.13, No.6, pp. 454 – 458.
42. Benmokrane, B., Chaallal, O., and Masmoudi, R. (1996). “Flexural Response of Concrete Beams Reinforced with FRP Reinforcing Bars”. ACI Structural Journal, Vol.93, No.1, pp. 46-55.
43. Benmokrane, B., Tighiouart, B. and Chaallal, O. (1996). Bond strength and load distribution of composite GFRP reinforcing bars in concrete. ACI Materials Journal, Vol.93, No.3, pp. 246-252.
44. Benmokrane, B., Zhang, B., Laoubi, K., Tighiouart, B., Lord, I. (2002). Mechanical and Bond properties of new generation of carbon fiber reinforced polymer reinforcing bars for concrete structures. Canadian Journal of Civil Engineering, Vol. 29, No.2, pp.338-343.
45. Bertero, V.V. (1988). State – of – the Art Report on Ductility based structural design. Proceedings of the Ninth World Conference on Earthquake Engineering, Tokyo – Kyoto Japan, Vol. VIII.
46. Bhargava, K., Ghosh, A.K., Mori, Y., and Ramanujam, S. (2007). Corrosion – induced bond strength degradation in reinforced concrete – Analytical and Empirical models. Nuclear Engineering and Design, Vol. 237, pp. 1140 – 1157.
47. Bizindavyi, L., and Neale, K.W. (1999). Transfer length and bond strengths for composites bonded to concrete. Journal of Composites for Construction, Vol. 3, No.4, pp.153-160.
48. Blaschko, M. (2003). Bond behavior of CFRP strips glued into slits. In:

Proceedings FRPRCS-6. Singapore: World Scientific, pp. 205-214.

49. Blaschko, M., and Zilch, K. (1999). Rehabilitation of concrete structures with strips glued into slits. Proceedings of the Twelfth International Conference on Composite Materials, Paris.

50. Bordelon, Amanda (2008). Manual for Modulus of Rupture/Flexural Test (4-point bending) of 6x6inch (150x150mm) Fiber-Reinforced Concrete Beams. pp. 1 – 5.

51. Brosens, K. and Gemert, D. Van. (1997). Anchorage stresses between concrete and carbon fiber reinforced laminates. Non-metallic (FRP) Reinforcement for Concrete Structures, Proceedings of the 3rd International Symposium, Japan Concrete Institute, Japan, Vol.1, pp.271-278.

52. Brosens, K. and Gemert, D. Van. (1999). Anchorage design for externally bonded carbon fiber-reinforced polymer laminates, Proceedings of the FRPRCS-4, SP-188, American Concrete Institute, Farmington Hills, Michigan, pp.635-645.

53. Brown, V.L. and Barthlomew, C.L. (1993). FRP Reinforcing bars in reinforced concrete members. ACI Materials Journal, Vol.90, No.1, pp. 34-39.

54. Buyukozturk, O., Gunes, O., Karaca, E. (2004). Progress in understanding debonding problems in reinforced concrete and steel members strengthened using FRP composites. Journal of Construction and Building Materials, Vol.18, pp.9-19.

55. Capozucca, R., Cerri, M.N. (2002) Static and dynamic behavior of RC beam model strengthened by CFRP-sheets. Construction and Building Materials Journal; (16), pp. 91-99.

56. CEB-FIP Task Group 9.3. Externally bonded FRP reinforcement for RC structures. Comité Euro-International du Béton Bulletin 14, 2001.

57. Chaallal, O., and Benmokrane, B. (1993). Pullout and bond of glass-fiber rods embedded in concrete and cement grout. Materials and Structures, Vol.26, No.3, pp. 167-175.

58. Chajes, M.J., Finch, W.W., Januszka, T.F and Thomson, T.A. (1996). Bond and Force Transfer of Composite material plates bonded to concrete. ACI Structural Journal, Vol. 93, No.2, pp.208-217.

59. Chen, J.F., Yang, Z.J., Holt, G.D. (2001). FRP or steel plate-to-concrete bonded joints: effect of test methods on experimental bond strength. Steel Composite Structures, Vol. 1, No. 2, pp. 231-244.

60. Consenza, E., Manfredi, G., Realfonzo, R. (1997). Behaviour and modeling of bond of FRP rebars to concrete. Journal of Composites for Construction, ASCE, Vol.1, No.2, pp.40-51.

61. Cosenza, E., Manfredi, G. and Realfonzo, R. (1995). Analytical modeling of bond between FRP reinforcing bars and concrete. Proceedings of the 2nd International RILEM Symposium (FRPRCS-2), L. Taerwe ed.

62. CSA Canadian Standards Association. (2000). Canadian Highway Bridge Design Code, (CHBDC), CAN/CSA-S6-00, Rexdale, Ontario, Canada, 190 pgs.

63. Dai, J., Ueda, T., Sato, Y. (2005). Development of Nonlinear Bond Stress-Slip model of Fiber Reinforced Plastics sheet-Concrete Interfaces with a simple method. Journal of Composites for Construction, Vol. 9, No.1, pp. 52-62.

64. Daniali, S. (1992) Development Length for Fiber-Reinforced Plastic Bars.

Advanced Composite Materials in Bridges and Structures, K. W. Neale and P. Labossiere, eds., pp. 179-188.

65. Darwin, D. and Pecknold, D. (1977). Nonlinear biaxial stress-strain law for concrete. Journal of Engineering Mechanics Division, ASCE, Vol. 103, No.2, pp. 229-241.

66. Davalos, J. F., Chen, Yi., Ray, I. (2008). Effect of bar degradation on interface bond with high strength concrete. Cement and Concrete Composites, Vol.30, No.8, pp.722-730.

67. De larrad, F., Schaller, D. and Fuchs, J. (1993). Effect of bar diameter on the bond strength of passive reinforcement in high-performance concrete. ACI Materials Journal, Vol.90, No.4, pp. 333 -339.

68. De-Lorenzis, L. and Teng, J.G. (2007). Near-surface mounted FRP reinforcement: An emerging technique for strengthening structures. Composites: Part B, Vol. 38, pp. 119-143.

69. De-Lorenzis, L., Miller, B., Nanni, A. (2001). Bond of fiber reinforced polymer laminates to concrete. ACI Materials Journal, Vol.98, No.3, pp.256-264.

70. De-Lorenzis, L., Rizzo, A., La Tegola, A. (2002). A modified pull-out test for bond of near-surface mounted FRP rods in concrete. Composites: Part B, Vol. 33, No. 8, pp. 589-603.

71. Dias, S and Barros, J. (2005). Shear strengthening of RC beams with Near-Surface Mounted CFRP Laminates. ACI Special Publication; (230)47, 807-824.

72. Dolan, C.W. (1999). FRP prestressing in the USA. Concrete International, Vol.21, No.10, pp.21-24.

73. Ehsani, M. R.; Saadatmanesh, H.; and Tao, S. (1996). Design Recommendation for Bond of GFRP Rebars to Concrete, Journal of Structural Engineering, V. 122, No. 3, pp. 247-257.

74. El-Hacha, R., Rizkalla, S.H., Kotynia, R. (2005). Modelling of reinforced concrete flexural members strengthened with near-surface mounted FRP reinforcement. ACI Special Publication; (230)95, 1681-1700.

75. Elighehausen, R., Popov, E. P., Betero, V. (1983). Local bond stress-slip relationships of deformed bar under generalized excitations. 1983 Report No. UCB/EERC -83/23, Earthquake Engineering, Research Center, Berkeley, California, USA, p. 185.

76. El-Salakway, E., and Benmokrane, B. (2004). “Serviceability of Concrete Bridge Deck Slabs Reinforced with Fiber-Reinforced Polymer Composite Bars”. ACI Structural Journal, Vol. 101, No.5, pp. 727-736.

77. El-Sayed, A.K., El-Salakawy, E.F. and Benmokrane, B. (2006). Shear Capacity of High-Strength Concrete Beams Reinforced with FRP Bars. ACI Structural Journal, Vol. 103, No.3, pp. 383-389.

78. Faoro, M. (1992). Bearing and deformation behavior of structural components with reinforcements comprising resin bounded glass fibre bars and conventional ribbed steel bars. Proceedings of the International Conference on Bond in Concrete.

79. Faoro, R. (1996). The Influence of stiffness and bond of FRP bars and tendons on the structural behavior of reinforced concrete members. Proceedings 2nd International Conference on Advanced Composite Materials in Bridge Structures, M. El-Badry, ed., The Canadian Society of Civil Engineering, Montreal, Quebec, Canada, pp. 885-892.

80. Firas, S.A., Foret, G and Le Roy, R. (2011). Bond between carbon fibre-reinforced polymer (GFRP) bars and ultra high performance fibre reinforced concrete (UHPFRC): Experimental study. Construction and Building Materials Journal, Vol. 25, No. 2, pp. 479-485.

81. Focacci, F., Nanni, A. and Bakis, C. (2000). Local bond-slip relationship for FRP reinforcement in concrete. Journal of Composites for Construction, Vol. 4, No.1, pp. 24-31.

82. Fukuyama, H. (1999). FRP Composites in Japan. Concrete International, Vol.21, No.10, pp.29-32.

83. Fukuzawa, K., Numao, T., Wu,Z., Yoshizawa, H., and Mitsui, M. (1997). Critical strain energy release rate of interface debonding between carbon fiber sheet and mortar. Non-metallic (FRP) Reinforcement for Concrete Structures, Proceedings of the 3rd International Symposium, Japan Concrete Institute, Japan,Vol.1, pp.295-301.

84. Godat, A., Neale, K.W., Labossiere, P. (2007). Numerical modeling of FRP shear strengthened reinforced concrete beams. Journal of Composites for Construction, Vol. 11, No. 6, pp.640-649.

85. Grace, N.F., Soliman, A.K., Abdel-Sayed, G., Saleh, K.R. (1998). Behavior and Ductility of Simple and Continuous FRP Reinforced Beams. Journal of Composites for Construction, Vol. 2, No. 4, ASCE.

86. Hamad, B.S. (1995). Comparative bond strength of coated and uncoated bars with different rib geometries. ACI Materials Journal, Vol. 92, No. 6, pp. 579-590.

87. Hao, Q-D., Wang, Y-L., Zhang, Z-C., Ou, J-P. (2007). Bond strength improvement of GFRP bars with different rib geometries. Journal of

Zhejiang University SCIENCE A, Vol. 8, No.9, pp.1356-1365.

88. Harajli, M.H. and Naaman, A.E. (1985). Static and Fatigue Tests on partially prestressed beams. Journal of Structural Engineering, ASCE, Vol. 111, No. 7, pp. 1602 – 1618.

89. Harries, K.A., Reeve, B., Zorn, A. (2007). Experimental evaluation of factors affecting monotonic and fatigue behavior of fiber reinforced polymer concrete bond in reinforced concrete beams. ACI Structural Journal, Vol.104, No.6, pp.667-674.

90. Hassan,T., and Rizkalla, S. (2003). Investigation of bond in concrete structures strengthened with NSM CFRP strips. Journal of Composites for Construction, Vol. 7, No.3, pp.248-257.

91. Hattori, A., Inoue, S., Miyagawa, T. and Fujii, M. (1995). A study on bond creep behavior of FRP bars embedded in concrete. Proceedings 2nd International RILEM Symposium (FRPRCS-2), L. Taerwe ed. pp. 172-179.

92. Hsu, T. T., and Zhang, L.X. (1996). Tension stiffening in reinforced concrete membrane elements. ACI Structural Journal, Vol. 93, No. 1, pp. 108-115.

93. Issa, M.S. and Elzeiny, S.M. (2011). Flexural Behavior of Cantilever Concrete Beams reinforced with Glass Fiber Reinforced Polymers (GFRP) bars. Journal of Civil Engineering and Construction Technology, Vol. 2, No. 2, pp.33-44.

94. Itoh, S., Maruyama, T., Nishiyama, H. (1989). Study of bond characteristics of deformed fiber reinforced plastic rods. Proceedings of the Japan Concrete Institute, Vol. 11, No.1, pp.777-782.

95. Jaeger LG, Tadros G, Mufti A. (1995). Balanced Section, Ductility and

Deformability in Concrete with FRP reinforcement. Research Report. No. 2, Industry Centre for Computer-Aided Engineering, Technical University of Nova Scotia, Halifax, Nova Scotia, Canada: pp. 1-29.

96. Jeong, S.M. 1994. Evaluation of ductility in prestressed concrete beams using fiber reinforced plastic tendons. PhD thesis, University of Michigan, Ann Arbor, Michigan.

97. Jerrett, C.V., Ahmad, S. H. (1995). Bond tests of Carbon Fibre Reinforced Plastic rods. Proceedings of the Second International RILEM Symposium. L. Taerwe, Ghent, E & SPON, London, pp.180-191.

98. Johnson, J.B. (2010). Bond strength of corrosion resistant steel reinforcement in concrete. MSc. Dissertation, Virginia Polytechnic Institute and State University.

99. Kanakubo, T., Yonemaru, K., Fukuyama, H., Fujisawa, M., Sonobe, Y. (1993). Bond performance of concrete members reinforced with FRP bars. Proceedings of the International Symposium on Fiber Reinforced Plastic Reinforcement for Concrete Structures. ACI SP-138, A. Nanni and C.W. Dolan eds.

100. Kang, J.-Y., Park, Y.-H., Park, J.-S., You, Y.-J and Jung, W.-T. (2005). Analytical Evaluation of RC beams strengthened with Near Surface Mounted CFRP Laminates. ACI Special Publication; (230)45, 779-794.

101. Karbhari, V.M. and Engineer, M. (1996). Investigation of bond between concrete and composites: Use of peeling test. Journal of Reinforced Plastic Composites, Vol.15, pp.208-227.

102. Keong, C. S. (2011). Bond Strength of Carbon Fiber Reinforced Polymer plates in Ultra High Performance Concrete. Bachelor’s Thesis, Department

of Civil Engineering, Universiti Putra Malaysia.

103. Kettil, P. (1995). Composite beams of fibre reinforced plastic profile and concrete. Thesis Division of Building Technology, Chalmers University of Technology, Work No.8, Goteborg, pp.80.

104. Larralde, J. and Silva-Rodriguez, R. (1993). Bond and Slip of FRP reinforcing bars in concrete. Journal of Materials in Civil Engineering, Vol.5, No.1, pp.30-40.

105. Lee, C., Jeong, S.M and Park, J.W. (2009). Use of fibre sheet strip stirrups for internal shear reinforcement of concrete beams. Magazine of Concrete Research, Vol. 61, No.9, pp.731 – 743.

106. Lee, C., Kim, J – Y., Heo, S – Y. (2010). Experimental observation on the effectiveness of fibre sheet stirrups in concrete beams. Journal of Composites for Construction, Vol. 14, No. 5, pp. 487 – 497.

107. Lee, H.S., Noguchi, T., Tomosawa, F. (2002). Evaluation of the bond properties between concrete and reinforcement as a function of the degree of reinforcement corrosion. Cement and Concrete Research, Vol. 32, No.8, pp. 1313–1318.

108. Lee, J.-Y, Kim, T.-Y., Yi, C.-K., Park, J.-S., You, Y.-C, Park, Y.-H. (2008). Interfacial bond strength of glass fibre reinforced polymer bars in high strength concrete. Composites Part B: Engineering, Vol. 39, No.2, pp.258-270.

109. Leone, M., Matthys, S., Aiello, M.A. (2009). Effect of elevated service temperature on bond between FRP EBR systems and concrete. Composites: Part B, Vol.40, No. 1, pp. 85 – 93.

110. Leung, C.K.Y. (2001). Delamination failure in concrete beams retrofitted

with a bonded plate. Journal of Materials in Civil Engineering, Vol.13, No.2, pp.106-113.

111. Li, L., Guo, Y., Liu, F. (2008). Test analysis for FRC beams strengthened with externally bonded FRP sheets. Construction and Building Materials Journal; (22), pp. 315-323.

112. Li, L.J., Guo, Y.C., Liu, F., Bungey, J.H. (2006). An experimental and numerical study of the effect of thickness and length of CFRP on performance of repaired reinforced concrete beams. Construction and Building Materials Journal; (20), pp. 901-909.

113. Liu, I., Oehlers, D.J., Seracino, R., Ju, G. (2006). Moment redistribution parametric study of CFRP, GFRP and steel surface plated RC beams and slabs. Construction and Building Materials Journal; (20), pp. 59-70.

114. Lu, F., and Ayoub, A. (2011). Evaluation of debonding failure of reinforced concrete girders strengthened in flexure with FRP laminates using finite element modeling. Construction and Building Materials, Vol. 25, N0. 4, pp. 1963-1979.

115. Lu, X.Z., Teng, J.G., Ye, L.P., Jiang, J.J. (2004). Bond –slip model for FRP sheet/plate-to-concrete interfaces. In: Proceedings of the second international conference advanced polymer composites for structural applications in construction. Guildford, UK: University of Surrey, pp.152-161.

116. Lu, X.Z., Teng, J.G.,Ye, L.P., Jiang, J.J. (2005). Bond-slip models for FRP sheet/plate-to-concrete interfaces. Engineering Structures, Vol. 27, pp. 938-950.

117. Makitani, E., Irisawa, I., Nishiura, N. (1993). Investigation of bond in

Concrete members with fiber reinforced plastic bars. Proceedings of the International Symposium on Fiber Reinforced Plastic Reinforcement for Concrete Structures. ACI SP-138, A. Nanni and C.W. Dolan eds.

118. Masmoudi, R., Theriault, M., and Benmokrane, B. (1998). “Flexural Behavior of Concrete Beams Reinforced with Deformed Fiber Reinforced Plastic Reinforcing Rods”. ACI Structural Journal, Vol.95, No.6, pp. 665-676.

119. Mavlar, L. J. (1994). Bond stress-slip characteristics of FRP rebars. Report TR-2013-SHR, Naval Fac. Engr. Service Ctr., Port Hueneme, California.

120. Menzel, C.A. (1939) “Some Factors Influencing Results of Pull-Out Bond Tests,” Journal of the American Concrete Institute, Vol.35, 516-543

121. Mo, Y. L., Chan, J. (1996). Bond and Slip of Plain Re-bars In Concrete. Journal of Materials in Civil Engineering. Vol.8, No.4, pp. 208-211.

122. Mufti, A. A., Newhook, J. P., and Tadros, G. 1996. Deformability versus ductility in concrete beams with FRP reinforcement. Proceedings 2nd International Conference Advanced Composite Materials in Bridges and Structures, El-Badry, ed., Canadian Society for Civil Engineering, Montreal, Canada, 189-199.

123. Mukherjee, A. and Arwikar, S.J. (2005). “Performance of Glass Fiber-Reinforced Polymer Reinforcing bars in Tropical Environments – Part 1: Structural Scale Tests”. ACI Structural Journal, Vol. 102, No.5, pp. 745 - 753.

124. Naaman A.E. (1981). A proposal to extend some code provisions on reinforcement to partial prestressing. PCI Journal, Vol. 26, No.2, pp.74-91.

125. Naaman, A.E. and Jeong, S.E. (1995). “Structural Ductility of Concrete

Beams Prestressed with FRP Tendons," Proceedings of the Second International RILEM Symposium (FRPRCS-2): Non-Metallic (FRP) for Concrete Structures, Ghent, Belgium, pp. 379-386.

126. Naaman, A.E., Harajli, M.H., Wight, J.K. (1986). Analysis of Ductility in Partially Prestressed Concrete Flexural Members. PCI Journal, May-June , 1986, Vol.31, No. 3, pp.64-87.

127. Nakaba, K., Kanakubo, T., Furuta, T., Yoshizawa H. (2001). Bond behavior between fiber reinforced polymer laminates and concrete. ACI Structural Journal, Vol. 89, No.3, pp.359-367.

128. Nanni A., Bakis C.E and Boothby T.E. (1995). Test methods for FRP-Concrete Systems Subjected to Mechanical Loads: State of the Art Review. Journal of Reinforced Plastics and Composites, 14(6): 524-558.

129. Nanni, A. (1993). Flexural behavior and Design of RC members using FRP reinforcement. Journal of Structural Engineering, Vol. 119, No.11, pp. 3344 – 3359.

130. Nanni, A., Al-Zaharani, M.M., Al-Dulaijan, S. U., Bakis, C.E., Boothby, T.E. (1995). Bond of FRP reinforcement to concrete-experimental results. Proceedings 2nd International RILEM Symposium (FRPRCS-2), L. Taerwe, ed.

131. Nanni, A., Bakis, C.E., Boothby, T.E. (1995). Test methods for FRP-concrete systems subjected mechanical loads: state of the art review. Reinforced Plastic Composites Journal, Vol.14, No.6, pp.524-558.

132. Nawy, E.G and Neuwerth, G.E. (1971). Behavior of Fiber Glass Reinforced Concrete Beams. Journal of Structural Division, ASCE, Vol.97, pp.2203-2215.

133. Newhook, J., Ghali, A., Tadros, G. (2002). Cracking and Deformability of Concrete Flexural Sections with Fiber Reinforced Polymer. Journal of Structural Engineering, Vol.128, No.9, pp. 20-28.

134. Newman, N., Ayoub, A. and Belarbi, A. (2010). Development length of Straight FRP Composite Bars embedded in Concrete. Journal of Reinforced Plastics and Composites, V.29, No.4, pp.571 – 589.

135. Nguyen, D.M., Chan, T.K., and Cheong, H.K. (2001). Brittle failure and Bond development length of CFRP-Concrete beams. Journal of Composites for Construction, ASCE, Vol. 5, No. 1, pp.12-17.

136. Noorzaei, J. (1991). Nonlinear Soil Structure-Interaction in Framed Structures. PhD Thesis, University of Roorkee, Roorkee, India.

137. Oehlers, D.J., Haskett, M., Wu, C., Seracino, R. (2008). Embedding NSM FRP plates for improved IC de-bonding resistance. Journal of Composites for Construction, ASCE; Vol. 12, No.6, pp. 635-642.

138. Okelo, R., and Yuan, R.L. (2005). Bond Strength of Fiber Reinforced Polymer Rebars in Normal Strength Concrete. Journal of Composites for Construction. Vol. 9, No. 3, pp. 203-213.

139. Orangun, C.O., Jirsa, J.O. and Breen, J.E. (1977). A Re-evaluation of Test data on Development length and Splices. ACI Journal, No. 74-11, pg. 114-122.

140. Pan, Jin Long, & Leung, Christopher K. Y. (2007). Effect of concrete composition on FRP/concrete bond capacity. Journal of Composites for Construction, Vol.11, No.6, pp. 611-618.

141. Pecce, M., Manfredi, G., Realfonzo, R., and Cosenza, E. (2001). Experimental and Analytical Evaluation of Bond Properties of GFRP bars.

Journal of Materials in Civil Engineering, Vol. 13, No. 4, pp.282 – 290.

142. Rafi, M.M., Nadjai, A., Ali, F. (2007). Analytical modeling of Concrete beams reinforced with carbon FRP bars. Journal of Composite Materials, Vol. 41, No.22, pp.2675-2690.

143. Rafi, M.M., Nadjai, A., Ali, F., Talamona, D. (2008). Aspects of behavior of CFRP reinforced concrete beams in bending. Construction and Building Materials. 22, pp. 277-285.

144. Rasheed, H.A., Pervaiz, S. (2002). Bond slip analysis of fiber-reinforced polymer strengthened beams. Journal of Engineering Mechanics, ASCE, Vol. 128, No. 1, pp.78-86.

145. Rashid MA, Mansur MA, Paramasivam P. (2005). Behavior of Aramid Fiber-Reinforced Polymer Reinforced High Strength Concrete Beams Under Bending. Journal of Composites for Construction, 9(2): 117-127.

146. Reported by ACI Committee, Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, July, 2008.

147. Rossetti, A.V., Galeota, D., Giammatteo, M.M. (1995). Local bond stress-slip relationships of glass fibre reinforced plastic bars embedded in concrete. Materials and Structures, Vol. 28, No. 180.

148. Saadatmanesh, H. and Ehsani, M.R. (1991). Fiber Composite Bar for Reinforced Concrete Construction. Journal of Composite Materials, Vol.25, No.188, pp.188-203.

149. Saika, B., Kumar, P., Thomas, J., Rao, K.S.N., Ramaswamy, A. (2007). “Strength and Serviceability performance of beams reinforced with GFRP bars in flexure”. Construction and Building Materials, Vol.21, No.2, pp.

1709-1719.

150. Salib, S.R. and Abdel-Sayed, G. (2004). “Prediction of Crack width for Fiber-Reinforced Polymer-Reinforced Concrete Beams”. ACI Structural Journal, Vol.101, No. 4, pp. 532-536.

151. Sato, Y., Asano, Y., and Ueda, T. (2000). Fundamental study on bond mechanism of carbon fiber sheet. Concrete Library International, JSCE, No. 37, pp. 97-115.

152. Sato, Y.,Kimura, K., and Kobatake, Y. (1997). Bond behaviors between CFRP sheet and concrete. Journal of Structures Construction Engineering, AIJ, No.500, pp.75-82 (in Japanese).

153. Saenz, L.P. (1964). Discussion of Equation for the stress-strain curve of concrete by Desayi and Krishnan. ACI Journal, Vol. 6, No. 9, pp. 1229-1235.

154. Sharma, S.K., Mohamed Ali, M.S., Goldar, D., Sikdar, P.K. (2006). Plate-concrete interfacial bond strength of FRP and metallic plated concrete specimens. Composites: Part B, Vol. 37, No.1, pp. 54-63.

155. Sika Kimia Sdn. Bhd. Malaysia. http://www.sika.com.my/

156. Shield, C., French, C., Hanus, J. (1999). Bond of GFRP rebars for consideration in bridge decks. Fourth International Symposium on Fiber Reinforced Polymer Reinforcement for Concrete Structures, SP-188, C.W. Dolan, S.H. Rizkalla and A. Nanni, eds., American Concrete Institute, Farmington Hills, Michigan, pp. 393-406.

157. Shield, C., French, C., Retika, A. (1997). Thermal and Mechanical Fatigue effects on GFRP rebar- concrete bond. Proceedings of the Third International Symposium on Non-metallic (FRP) reinforcement for Concrete

Structures, (FRPRCS-3), Vol. 2, Japan Concrete Institute, Tokyo, Japan, pp. 381-388.

158. Shin, S., Seo, D. and Han, B. (2009). Performance of Concrete Beams Reinforced with GFRP bars. Journal of Asian Architecture and Building Engineering. Vol. 8, No.1, pp.197-204.
159. Soong, W.H., Raghavan, J., Rizkalla, S.H. (2011). Fundamental mechanisms of bonding glass fiber reinforced polymer reinforcement to concrete. Construction and Building Materials, Vol.25, pp. 2813-2821.
160. Song, P.S. and Hwang, S. (2004). Mechanical properties of high strength steel fiber-reinforced concrete. Construction and Building Materials, Vol. 18, No.9, pp. 669-673.
161. Spadea, G., Bencardino, F and Swamy, R.N. (1997). Strengthening and Upgrading Structures with Bonded CFRP sheets design, Aspects for structural integrity. Proceedings of the Third International RILEM Symposium (FRPRCS-3): Non-metallic (FRP) for concrete structures, Sapporo Japan, Vol. 1, pp. 379-386.
162. Supaviriyakit, T., Pornpongsaroj, P., Pimanmas, A. (2004). A finite element analysis of FRP strengthened beams. Songklanakarin Journal of Science and Technology. Vol. 26, pp. 497-507.
163. Taerwe, L.R and Matthys, S. (1999). FRP for concrete construction. Concrete International, Vol.21, No.10, pp.33-36.
164. Tann, D.B., Delpak, R., Davies, P. (2004). Ductility and deformability of fibre-reinforced polymer-strengthened reinforced concrete beams. Proceedings Institute of Civil Engineering: Structural Buildings, Vol. 157, No.1, pp.19-30.

165. Thanoon, W.A., Alwathaf, A.H., Noorzaei, J., Jaafar, M.S., Abdulkadir, M.R. (2008). Nonlinear finite element analysis of grouted and ungrouted hollow interlocking mortarless block masonry system. Engineering Structures, 30, pp.1560-1572.

166. Tepfers, R., and Karlsson, M. (1997). Pull-out and tensile reinforcement splice tests using FRP C-BARs. FRPRCS-3 Third International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures in Sapporo 14-16 October 1997, pp. 357-364.

167. Tepfers, R., Hedlund, G., and Rosinski, B. (1998). Pullout and tensile reinforcement splice tests with GFRP bars. Proceedings 2nd International Conference on Composites in Infrastructure (ICCI' 98), H. Saadatmanesh and M.R. Ehsani, ed., Tuscon, Arizona, Vol.II, 37 – 51.

168. Theriault, M., and Benmokrane, B. (1998). Effects of FRP Reinforcement Ratio and Concrete Strength on Flexural Behavior of Concrete Beams. Journal of Composites for Construction, ASCE, Vol.2, No.1, pp 46-56.

169. Tighiouart, B. Benmokrane, B. and Mukhopadhyaya, P. (1999). Bond Strength of Glass FRP Rebar Splices in Beams Under Static Loading. Construction and Building Materials, V. 13, No. 7, pp. 383-392.

170. Tighiouart, B., Benmokrane, B. and Gao, D. (1998). Investigation of bond in concrete members with fibre reinforced polymer (FRP) bars. Construction and Building Materials, Vol.12, No.8, pp. 453-462.

171. Toutanji H, Saafi M. (2000). Flexural Behavior of Concrete Beams Reinforced with Glass Fiber-Reinforced (GFRP) Bars. ACI Str. J. 97(5): 712-719.

172. Toutanji, H. and Deng, Y. (2003). Deflection and Crack width prediction of

concrete beams reinforced with glass FRP rods. Construction and Building Materials, Vol.17, pp.69-74.

173. Turk, K and Yildirim, M.S. (2003) Bond Strength of reinforcement in splices in beams. Structural Engineering and Mechanics, Vol. 16, No. 4, pp. 1-10.

174. Ueda, T. and Dai, J.G. (2005). Proceedings of the International Symposium on Bond Behavior of FRP in Structures (BBFS 2005), International Instiute for FRP in Construction, Chen and Teng.

175. Ueda,T., Sato, Y., and Asano, Y. (1999). Experimental study on bondstrength of continuous carbon fiber sheets. Proceedings of the FRPRCS-4, SP-188, American Concrete Institute, Farmington Hills, Michigan, pp.407-416.

176. Vecchio, F. (1992). Finite element modeling of concrete expansions and confinement. Journal of Structural Engineering, ASCE, Vol. 118, No.9, pp. 2390-2405.

177. Vijay, P.V., Kumar, S.V., and GangaRao, H.V.S. 1996. Shear and ductility behavior of concrete beams reinforced with GFRP rebars. Proceedings 2nd International Conference Advanced Composite Materials in Bridges and Structures, El-Badry, ed., Canadian Society for Civil Engineering, Montreal, Canada, 217-226.

178. Viladkar, M.N., Godbole, P.N., Noorzaei, J. (1994). Modeling of Interface for soil structure interaction studies. Computers and Structures, Vol. 52, No. 4, pp. 765-779.

179. Wambeke, B.W. and Shield, C.K. (2006). Development length of Glass Fiber-Reinforced Polymer bars in Concrete. ACI Structural Journal, V.103,

No.1, pp. 11 – 17.

180. Wang, H. and Belarbi, A. (2010). Static and Fatigue Bond Characteristics of FRP Rebars Embedded in Fiber-reinforced concrete. Journal of Composite Materials, Vol.44, No.13, pp.1605-1622.

181. Wang, H. and Belarbi, A. (2005). Flexural behavior of Fiber-Reinforced concrete beams reinforced with FRP Rebars. ACI Special Publication, Vol. 230, pp.895-914.

182. Wang, Z., Goto, Y, Joh, O. (1999). Bond strength of various types of fiber reinforced plastic rods. In: Proceedings of 4th International symposium on fiber reinforced polymer reinforcement for reinforced concrete structures, FRPRCS-4, ACI-SP-188, Baltimore, USA, pp.1117-1130.

183. Wang, T and Hsu, T.C. (2001). Nonlinear finite element analysis of concrete structures using new constitutive models. Computers and Structures, Vol. 79, No. 32, pp.2781-2791.

184. Weathersby, John Henry. (2003). “Investigation of bond slip between concrete and steel reinforcement under dynamic loading conditions” PhD Dissertation. Louisiana State University.

185. Williams, A. (1999). Design of Rienforced Concrete Structures, 2nd Edition. Austin, Texas: Dearborn Trade Publishing, Engineering Press. pp. 66 – 68.

186. Won, J-P., Park, C-G., Kim, H-H., Lee, S-W., Jang,C-I. (2008). Effect of fibers on the bond between FRP reinforcing bars and high strength concrete. Composites: Part B, Vol.39, pp.747-755.

187. Wong, R.S.Y., Vecchio, F.J. (2003). Towards modeling of reinforced concrete memberswith externally bonded fiber reinforced polymer composites. ACI Structural Journal, Vol. 100, No.1, pp. 47-55.

188. Xiao, J., Li, J., Zha, Q. (2004). Experimental study on bond behavior between FRP and concrete. Construction and Building Materials, Vol. 18, pp.745-752.

189. Yoshizawa, H., Myojo, T., Okoshi, M., Mizukoshi, M., Kliger, H.S. (1996). Effect of sheet bonding condition on concrete members having externally bonded carbon fiber sheet. *Fourth Materials Engineering Conference*, ASCE Annual Convention, Washington D.C.

190. Yoshizawa, H., Wu, Z., Yuan, H., and Kanakubo, T. (2000). Study on FRP-concrete interface bond performance. Trans. Society of Civil Engineering, Vol. 662, No. 49, pp.105-119.

191. Yost, J.R., Gross, S.P., Dinehart, D.W., Mildenberg, J.J. (2007). Flexural Behavior of Concrete Beams Strengthened with Near-Surface-Mounted CFRP Strips. ACI Structural Journal; Vol. 104, No. 4, pp. 430-437.

192. Zienkiewicz, O.C. (1977). The finite element method. McGraw-Hill Book Company, London, UK.

193. http://faculty.delhi.edu/hultendc/AECT480Lecture%2011.pdf(Factors affecting development length) 1.25pm; 8th March, 2012.

194. http://www.acmanet.org/fgmc/abc_frp.htm, 11.31pm; 23rd May, 2012.