Fibre Reinforced Polymer Concrete Structures – Opportunities and Concerns

Noorsidi Aizuddin M.N[*1] & Hazren M.[*2]
Department of Property Management, Faculty of Geoinformation Science and Engineering,
Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor.[*1]
Department of Civil Engineering, Faculty of Engineering, University of Malaya,
50603 Kuala Lumpur. [*2]
noorsidi@utm.my

Abstract

In the civil engineering industry, deterioration of concrete structures is one of the major concerns in the construction field nowadays. Some of the earlier degradation of structures may caused by design or construction defects where in some cases a lower grade concrete has been supplied during constructions. Therefore, retrofitting of those defect reinforced concrete structures and also strengthening of insufficient capacity concrete structural elements has inevitably become an important activities in civil engineering. Instead of the old approach to demolish and reconstruct the buildings, structural repair and rehabilitation of reinforced concrete structures is becoming an ideal option for all deteriorated and damaged structures to restore, enhance the load bearing capacity and increase the life span of the structure. The strengthening of concrete structures with externally bonded reinforcement is generally done using either steel plates or Fibre reinforced polymer (FRP) composites system. However, the use of FRP composite materials for both new construction and strengthening of reinforced concrete structures has increased rapidly and gradually replace the steel plate method due to great advantages of FRP. The main objective of this research work is to evaluate and investigate the effectiveness of using Glass Fibre Reinforced Polymers (GFRP) to strengthen early age (green) concrete which is a very poor concrete grade. From the studies and analysis, high fatigue strength and high stiffness properties of the GFRP composites strengthening system give a high satisfaction results in improving the strength of all the concrete specimens tested.

Keywords: Fibre, Concrete, Structure, Sustainable, Construction.

1. Introduction

In the construction industry, design errors and construction defects are common issues that may interrupt the whole construction progress. Using poor grade concrete for construction by contractors was one of the examples that might happen in the real construction site. When the concrete grade does not meet the design requirement, demolition of the concrete structure and rebuild is the common repair method practiced by engineers. This certainly will slow down the construction progress and the repairing works will be very costly. Therefore, strengthening of the very poor grade concrete and also early age concrete, that is 1-2 weeks after de-mould of the formworks should be studied thoroughly. The defected structure parts are to be strengthened by externally bonded fibre reinforced polymer while the construction works are in progress.

Besides, throughout the world, hundred thousands of buildings and structures were constructed using reinforced or prestressed concrete materials. Now, at the beginning of the next century, many of these buildings have reached the end of their planned service life, and deterioration in the form of steel corrosion, concrete cracking, and spalling is observed frequently when exposed to harsh environments, de-icing salts, and other chemicals. In addition, many of these structures were built to carry loads that are significantly smaller than the current needs. Because of these factors, many

structural engineers are faced with the challenge of evaluating and implementing effective and economical repair and strengthening programs. (Tarek, 2006)
During the late 1970s and early 1980s, many applications of composite reinforcing products were demonstrated in Europe and Asia. In 1986, the world's first highway bridge using composite reinforcing tendons was built in Germany. The first all-composite bridge deck was demonstrated in China. The first all-composite pedestrian bridge was installed in 1992 in Aberfeldy, Scotland. In the U.S., the first FRP-reinforced concrete bridge deck was built in 1996 at McKinleyville, W.Va. followed by the first all-composite vehicular bridge deck (The No-Name Creek Bridge, 1996) in Russell, Kans. Numerous composite pedestrian bridges have been installed in U.S. state and national parks in remote locations not accessible by heavy construction equipment, or for spanning over roadways and railways (ACMA MDA 2006).

One of the most severe and widespread problems in concrete is the internal damage caused by the corrosive action of external chlorides on reinforcing or prestressing steel embedded in concrete. Corrosion problems are caused by a corrosion-process by-product (rust) that expands up to eight times its original volume. This expansion creates internal pressure, which causes the concrete to crack and spall, resulting in a reduction of the effective area of steel reinforcement and reduced structural capacity of the affected member. If not addressed at early stages, corrosion will continue to grow rapidly, ultimately creating a safety issue of falling concrete and loss of strength (Tarek, 2006). Structural strengthening describes the process of upgrading the concrete structural system of an existing building to improve performance under existing loads or to increase the strength of structural components to carry additional loads. For upgrade projects, design engineers must deal with structures in which every element carries a share of the existing load. The effects of strengthening or removing part or all of a structural element such as penetrations or deteriorated materials must be analyzed carefully to determine their influence on the global behaviour of the structure. Failure to do so may overstress the structural elements surrounding the affected area, which can lead to a bigger problem and even localized failure (Jay, 2006).

Many buildings that originally were constructed for a specific use now are being renovated or upgraded for a different application that may require higher load-carrying capacity. As a result of these higher load demands, existing structures need to be reassessed and may require strengthening to meet heavier load requirements. In general, structural strengthening may become necessary because of code changes, seismic upgrade, deficiencies that develop because of environmental effects (such as corrosion), changes in use that increase service loads, or deficiencies within the structure caused by errors in design or construction (Tarek and Jay ,2004). The structural upgrade of concrete structures can be achieved using one of many different upgrading methods such as span shortening, external composites, externally bonded steel, external or internal post-tensioning systems, section enlargement, or a combination of these techniques. Similar to concrete repair, strengthening systems must perform in a composite manner with an existing structure to be effective and to share the applied loads.

2. Fibre Reinforced Polymer (FRP) Systems

Fibre reinforced polymer (FRP) systems are high-strength, lightweight reinforcement in the form of paper-thin fabric sheets, thin laminates, or bars that are bonded to concrete members with epoxy adhesive to increase their load carrying capacity. These systems have been used extensively in the aerospace, automotive, and sport-equipment industries, and now are becoming a mainstream technology for the structural upgrade of concrete structures. Important characteristics of FRPs for structural repair and strengthening applications include their non-corrosive properties, speed and ease of installation, lower cost, and aesthetic appeal.

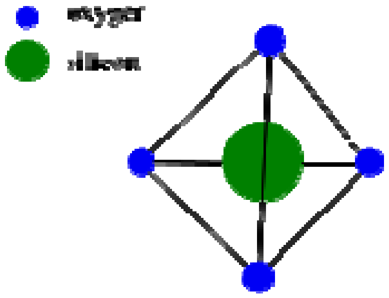
As with any other externally bonded system, the bond between the FRP system and the existing concrete is critical, and surface preparation is very important. Typically, installation is achieved by applying an epoxy adhesive to the prepared surface, installing the FRP reinforcement into the epoxy and, when required, applying a second layer of the epoxy adhesive. After curing, the FRP composite will add capacity to the element because it has a tensile strength up to 10 times that of steel. A structurally efficient, easy-to-install, and cost-effective strengthening option was achieved by using externally bonded FRP sheets.

3. Glass Fibre Reinforced Polymers (GFRP)

GFRP are made of high strength glass fibres encased within a tough matrix. Glass on its own is hard and strong but it is a very brittle material. Soft materials such as polymers are tough and ductile but usually have low yield strengths. By encasing the high strength fibres within a tough matrix we exploit the positive properties of the two materials.

Glass Fibre

Glass has been the predominant fibre for many civil engineering applications because of an economical balance of cost and specific strength properties. Glass fibres are commercially available in E-glass formulation (for electrical grade), the most widely used general-purpose form of composite reinforcement, and other formulations for high strength (S-2 glass), improved acid resistance (ECR glass), and alkali resistance (AR glass). The basis of textile-grade glass fibres is silica, SiO_2 (Figure 1). In its pure form, it exists as a polymer, $(SiO_2)n$. It has no true melting point but softens up to 2000°C, where it starts to degrade. At 1713°C, most of the molecules can move about freely. If the glass is then cooled quickly, they will be unable to form an ordered structure. (Gupta & Kothari, 1997). In the polymer it forms SiO_4 groups which are configured as a tetrahedron with the silicon atom at the center, and four oxygen atoms at the corners. These atoms then form a network bonded at the corners by sharing the oxygen atoms.



Φιγυρε 1. Μολεχυλαρ στρυχτυρε οφ γλασσ

Although E-glass has a lower strength and stiffness, but it is more widely used than S-2 glass and others glass types. Based on an alumina-lime-borosilicate composition, E-glass produced fibres are considered the predominant reinforcement for polymer matrix composites because of their high electrical insulating properties, low susceptibility to moisture, and high mechanical properties. The letter E is used because it was originally for electrical applications. S-glass is a high strength formulation for use when tensile strength is the most important property. GFRP's whose fibres are continuous and arranged parallel to each other are strong when stressed in tension in a direction parallel to line of the fibres. These are called unidirectional fibre composites.

However they are considerably weaker when stressed in other directions. When stressed in a direction transverse to the line of fibres the strength of the material can be as little as 5% of the maximum strength. The strength of a unidirectional GFRP is usually given as a specific strength in the fibre direction. GFRP becomes tougher when cracked. This is because when a crack in the matrix reaches a fibre it continues along the fibre rather than through it. This increases the area of the tip of the crack making the likelihood of the crack propagating much less, therefore the overall toughness of the material is greater. GFRP have a high strength to weight ratio, therefore they can be used to replace metals such as steel and aluminium in applications where a saving in weight is advantageous. They have relative high tensile and compressive strength if compared to steel. It means that GFRP are stronger than steel. Table 1 shows the general comparison of the strength properties between GFRP and steel.

Ταβλε 1. Γενεραλ χομπαρισον οφ τηε στρενγτη προπερτιεσ βετωεεν ΓΦΡΠ ανδ στεελ

Material	**Density (Mg/m^3)**	**Young's modulus E(Gpa)**	**Strength (Mpa)**
GFRP, 50% uni-axial glass in polyester	2.0	48	1240
High-strength steel	7.8	207	1000

Source : *Author (2008).*

Besides, GFRP possess a great number of advantageous and superior properties other than high strength. GFRP are highly resistant to corrosion and are also resistant to most hazard environments. GFRP has the ability to produce a wide range of shapes. It can be used to form more complex shapes than is possible in wood or sheet metal.

In addition, Glass fibres have a high modulus of elasticity and high tensile strength which means they provide a much higher level of reinforcement than any other reinforcement materials. Good thermal insulation properties are one of the excellent properties that make it superior to fire resistant when applied in building structures. They are dimensionally stable and can withstand temperatures of nearly 600°C.

Furthermore, Glass fibres are relatively inert and non-combustible, have good electrical resistance and will transmit light. Most importantly is Glass fibre can be processed easily and can develop a wide range of mechanical properties when laminated. In other words, GFRP offer greater design freedom.

4. Research Objective

The main objective of this research work is to evaluate and investigate the effectiveness of using Glass Fibre Reinforced Polymers (GFRP) to strengthen early age (green) concrete which is a very poor concrete grade. The project is aimed at showing that GFRP has the ability to strengthen small concrete specimens (compressive, flexural and tensile splitting) as well as structural reinforced concrete (beams) by just wrapping fabric externally on the concrete surface.

5. Measurement Instrument

The experiment conducted involved testing small concrete specimens of cylinders and prisms followed by fabrication of two small size beams and load tests. The variables in this research include age of concrete and numbers of GFRP layer. The important parameters interested were ultimate failure load of concrete and effectiveness of wrapping GFRP on concrete for increment in compression, flexural and tensile splitting. Also, 2 beam each with and without GFRP sheet was fabricated to verify the possibility of GFRP in strengthening concrete structurally. In addition, modes of failure for each properties test are to be evaluated.

6. Data Collection

The proper installation method and application of GFRP was done in accordance to the BASF MBrace Composite Strengthening System manual and demonstrated by the technician from BASF Company, the supplier of the materials used for strengthening concrete. The proper wrapping of fibres externally on concrete is crucial to give perfect results. The system is installed using wet lay-up techniques that is, the fibre materials are placed on the surface dry and then impregnated with epoxy resins to form the FRP laminate. The MBrace system can easily be installed on properly prepared, sound concrete surfaces in a series of steps.

Glass Fibre Reinforced Polymer (GFRP)

A commercially available unidirectional GFRP system was used in this study. GFRP used was provided by BASF, the chemical company where they was developed their very own MBrace composite strengthening system The model of the GFRP is MBrace EG900, an E-Glass Fibre sheet which is the backbone of the MBrace system. MBrace glass fibres are manufactured by drawing molten glass through a die or a bushing. The resulting “E” type glass filaments are grouped into tows that are then assembled into a continuous unidirectional sheet. Mbrace EG900 has high strength to weight and stiffness to weight ratios. Tensile strength and elastic modulus are determined by testing cured samples of fibre and MBrace Saturant. The tensile strength and elastic modulus contribution of the saturant is neglected in computing the strength of the fibre. Therefore, stresses are calculated using the net area of the fibre only. The fibre sheets are supplied in a roll of 23m^2 where the width is 500mm to the length of 46m and cost RM985 per roll. The properties of the glass fibre supplied by the manufacturer are summarized in the table 2.

Ταβλε 2. Τψπιχαλ περφορμανχε δατα ανδ προπερτιεσ οφ ΜΒραχε ΕΓ900

Typical Properties	**MBrace EG900**
Density, g/m^2	910.74
Tensile Strength, N/mm^2	1,667
Tensile Modulus, N/mm^2	72,400
Thickness, mm	0.353
Ultimate Tensile Elongation, %	2.0
Width, mm	500 and 600
Generic Type	E-Glass
Colour	White

MBrace Composite Strengthening System using MBrace EG900	
Tensile Strength, N/mm^2	500
Tensile Elongation, %	2.0
Tensile modulus, N/mm^2	28,000
Thickness, mm	1.10
Shear Bond Strength (on G40 concrete), N/mm^2	2.5 or concrete substrate failure

Source : *Author (2008).*

7. Analysis and Discussion

From the experimental results of compression strength, an increase in strength and stiffness was seen in every specimen where GFRP was applied. All the results were shown in table 3. A very low grade concrete was used of where the compressive strength was just achieved 12.2N/mm^2 at the age of 9 days and 18.9N/mm^2 at 29 days. This is to simulate a very weak concrete in a structures caused by construction deficiency as well as aging process by environmental effect. Therefore, the deteriorated structures are required for restoring its strength and retrofitting.

For the specimen strengthened with the confinement wrapping of GFRP, the ultimate strength was increased dramatically where the values obtained were higher than expected. Although the curing period for the epoxy adhesion of GFRP was just 2 days when testing at early age, the glass fibre confinement still managed to provide a very high strength increment to concrete. According to the technician from BASF, epoxy saturant required 7 days to achieve a maximum performance. For 1 layer of fibre wrapping, the strength increased almost 4 times of the control strength while nearly 6 times higher for 2 layers of fibre strengthened.

Comparing with the previous research done by Li, Helms, and Pang (2003), the results obtained in my project were relatively more impressive. From his study, the compressive strength increased by glass fibre wrapping was just slightly higher than control strength. The strength gained in my study by using glass fibre even higher than carbon fibre reinforcement from S.S. Pang study. This shows that newly developed FRP nowadays are more advanced than the previous one. The epoxy resin play an important part in this strengthening system as it had contributed strength and stiffness to the concrete as well.

Besides, increment of strength by applying 1 layer and 2 layer of fibre are almost the same for both early age and 29 days concrete with different strength. This shows that glass fibre are only take into action when the concrete are failure to sustain any load again. The magnitude of strength increased was probably the capacity of the glass fibre as in table 4. An extra ply of fabric was very effective in confinement reinforced concrete. 2 layers of fibres wrapping almost double the strength of 1 layer fibre reinforcement. Failure mode for 1 layer and 2 layers of FRP wrapping in compression are much different from each others. For 1 layer of fibre specimen, delimitation of fibre was sudden just after some cracking sound heard and it lead to an explosive failure where concrete ruptured occurred too. In contrast, fibre ruptured was observed on 2 layers confinement and less explosive failure. The confining bonding of double layers was strong enough to hold the fibre and concrete together. Therefore, for strengthening the column like structure with FRP confinement, 2 layers of fibre are recommended.

Ταβλε 3. Εφφεχτσ οφ ωραππινγ γλασσ φιβερσ ον χομπρεσσιωε στρενγτη οφ χψλινδερσ

Concrete Age	Average Compressive Strength (N/mm^2)			Increment to control (%)		Increment between 1 layer and 2 layers (%)
	Control	1 layer	2 layers	1 layer	2 layers	
9 days	12.2	47.0	72.4	287	496	54
29 days	18.9	51.0	78.3	170	315	54

Source : *Author (2008).*

Ταβλε 4. Μαγνιτυδε οφ χομπρεσσιϖε στρενγτη ινχρεασεδ αφτερ ωραππινγ ωιτη γλασσ φιβερσ

Concrete Age	Increment to control (N/mm^2)		Increment between 1 layer and 2 layers (N/mm^2)
	1 layer	2 layers	
9 days	34.9	60.0	25.1
29 days	32.1	59.4	27.3

Source : *Author (2008).*

Table 5 shows the experimental results of the testing of flexural strengthened prism, the results obtained were not less promising than compression strength tests as it gives a significant increased in flexural strength too. The control strength of the flexural tested prism are very low since concrete are well known for its weakness in tension, the flexural strength of the concrete normally was just 10-20% of the compressive strength. The Glass fibre used in this test was uni-directional fibre composite. To strengthening flexural strength of concrete effectively, orientation of the fibre should be placed 0° longitudinally on the bottom flange since fibre are the strongest when stressed in tension in a direction parallel to line of the fibres. This has been proved in the past researches indicated the most effective wrapping orientation in flexural strengthening.

The prisms wrapped with GFRP were obviously stiffer and can sustained higher loads before failure if compared with control prisms. For 1 layer wrapping of GFRP at early age, the ultimate strength increased from 3.5N/mm^2 up to 13.3N/mm2 which is approximately 4 times higher than before. It was noticed that the flexural strength of concrete are not much different between early age and 29 days and hence the strength improved after wrapping with GFRP are almost the same as well. The failure load of the control prism at 29days is 3.6N/mm^2 which it just 0.1N/mm^2 higher than early age and the ultimate strength obtained after wrapping GFRP was up to 14.2N/mm^2. Therefore, strengthening of concrete in flexural at early age by using GFRP can already achieve the strength as what we get in the later stage. In the real occasion, when there was any deficient in concrete detected in the construction at early age, we can immediately apply GFRP to gain the strength as desired and proceed the construction.

In the case of extra layer of glass fibre, it was clearly observed that the ultimate strength increased by wrapping 2 layer of fibre was not significant for both different concrete ages. Additional layer of glass fibre only increase the magnitude strength of 1.4N/mm^2 or just 10% from the strength of 1 layer at 9 days and 14% increment of strength between 1 layer and 2 layer of fibre reinforcement at 29 days as in table 6. This phenomenon can be explained by the failure mode of the specimens where the fibre sheets were split apart and separate from the concrete. The glass fibre sheet still can resist extra load, however the bonding between concrete and fibre was reached the limit. The failure of prisms attached with glass fibre was fail in shear crack from the loading point diagonally to the support. An abrupt and explosive failure occurred during the test and part of the specimens that cracked in shear even felt out from the flexural testing machine due to the impact. From the test results, we can conclude that by wrapping 2 or more layers of GFRP was not economic due to the small increase in flexural strength.

Furthermore, the magnitude of increment strength for 1 layer and 2 layers fibre wrapping are more or less the same for both different concrete strength. Here shows that the capacity of the GFRP composite system are constant regardless the strength or age of concrete.

Ταβλε 5. Εφφεχτσ οφ ωραππινγ γλασσ φιβερσ ον φλεξυραλ στρενγτη οφ πρισμσ

Concrete Age	Average Flexural Strength (N/mm^2)			Increment to control (%)		Increment between 1 layer and 2 layers (%)
	Control	1 layer	2 layers	1 layer	2 layers	
9 days	3.5	13.3	14.7	286	325	10
29 days	3.6	14.2	16.1	299	353	14

Source : *Author (2008).*

Ταβλε 6. Μαγνιτυδε οφ φλεξυραλ στρενγτη ινχρεασεδ αφτερ ωραππινγ ωιτη γλασσ φιβερσ

Concrete Age	Increment to control (N/mm^2)		Increment between 1 layer and 2 layers (N/mm^2)
	1 layer	2 layers	
9 days	9.9	11.2	1.3
29 days	10.7	12.6	1.9

Source : *Author (2008).*

2 small size beams, one non-strengthened beam for control and one strengthened beam with GFRP sheets attached to the bottom flange were tested under four point loadings condition. This beam tests aim to verify the possibility of strengthening concrete structurally by apply GFRP sheets externally. Both beam reinforcement detailing are identical and were tested on the same occasion so that the comparison of beams with and without GFRP wrapping could be done. Both beams were tested at the age of 41 days where the compressive strength of concrete cube gives average of $29.1N/mm^2$. From the tests, the ultimate load carrying capacity of the beams and load causing initial cracks were noted. A summary of the test results which include maximum mid-span deflection was given in table 7.

Ταβλε 7. Συμμαρψ οφ βεαμ τεστσ ρεσυλτσ

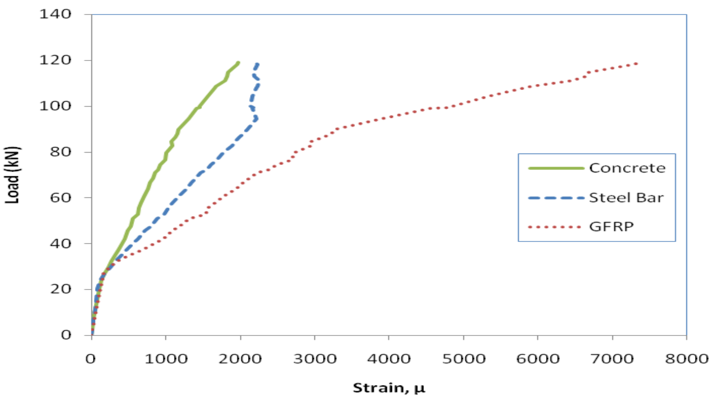
Beams	Ultimate Strength (kN)	Increment (%)	1st Crack Load (kN)	Increment (%)	Max mid-span deflection (mm)
Control	95	-	20	-	12.5
GFRP strengthened	120	26.3	45	125	9

Source : *Author (2008).*

Comparison of Strain for GFRP strengthened Beam

Figure 2 shows the load against recorded strain on the steel reinforcement, GFRP sheet and concrete top surface for strengthened beam. Concrete compressive strains are shown as positive for ease of presentation. From the figure, it was very obvious that all strain increasing rates of strengthened beam was linearly up to around 30kN with the same pace and immediately the strain rate was boosted after 30kN load due to the cracking of concrete. All the applied loads were then distributed among those 3 components while the increasing rate of strains was consistent and higher than before first crack load. The GFRP sheet strain was the highest followed by the steel bar strain and lastly the least strain was concrete compressive strain. It was interesting that all 3 strains maintain their respective strain increasing pace until the yielding point of steel reinforcement bar at load of 95kN. After yield load of 95kN, concrete strain increasing rate was slightly higher, however the well worth findings is the strain elongation rate of GFRP sheet are speed up drastically. This is because most of the applied load will be carried by GFRP laminate since the steel reinforcements were reach its limit strength and unable to sustain load anymore. All the strains measurement was stopped at the load of 120kN where it was the ultimate load of strengthened beam. From this analysis, GFRP prove that it has high ductility, higher yield load and higher strength over steel bars. In fact, the glass fibre still can withstand the load in this case, however the failure was due to de-bonding of fibre from concrete while the fibre still in fine condition.

Throughout these studies, the use of GFRP as externally strengthening material for reinforced concrete beam was very successful in all the aspects that have been assessed. Glass fibre wrapping on small concrete specimens did shows an increment of strength in all the mechanical properties tested while it also effective in strengthening concrete structurally. After concrete beam has been wrapped with GFRP, it gives greater failure load, higher cracking load, less deflection, less crack width and less strain in steel reinforcement as well as concrete compression. Brittle failure of the strengthened beam shows higher stiffness and strength in concrete. Comparison between control and strengthened beams was summarized in table 8.



Φιγυρε 2. Γραπη οφ λοαδ αγαινστ στραιν φορ ΓΦΡΠ στρενγτηενεδ βεαμ

Features	Control	GFRP Strengthened
Ultimate load	95kN	120kN
First cracking load	20kN	45kN
Crack width at 60kN	0.5mm	0.16mm
Number of cracks	6	12
Max mid span deflection	12.5mm	9mm
Deflection at 60kN	6.5mm	3.5mm
Steel bar strain at 60kN	2243µ	1198µ
Yield load of steel bar	61kN	94kN
Concrete compressive strain at 60kN	1232µ	701µ
Failure mode	Flexural failure	Flexural failure and de-bonding of fibre

Source : *Author (2008).*

Ταβλε 8. Χομπαρισον οφ χοντρολ ανδ στρενγτηενεδ βεαμσ

8. Conclusion

In this paper, the following conclusions are made:

High fatigue strength and high stiffness properties of the GFRP composites strengthening system give a high satisfaction results in improving the strength of all the concrete specimens tested. All the strengthened concrete specimens with GFRP did show a considerable improved performance in compression, flexural and tensile splitting strength properties. Among the concrete properties tested, it was found that GFRP was very effective in enhancing the compressive and flexural strength of concrete whereas for tensile splitting strength was relatively less significant but still managed to increase up to nearly 2 times higher the strength. Compression and flexural strength was able to increase at least 4 times higher with 1 layer of GFRP wrapping. For extra ply of glass fibre, which is strengthening with 2 layers of GFRP did show an increment to 1 layer of fibre strengthened specimens in all the properties tested. Nevertheless, extra layer of GFRP in confinement strengthening of compression properties was the most effective among other properties tested. Increment of 54% between 1 layer and 2 layers of GFRP was achieved in compression test while for flexural and tensile splitting tests just show increment of 10% and 23% respectively at early age concrete. Strengthening of concrete at early age with GFRP sheets has proven that it could achieve a very high ultimate strength.

Regardless the concrete age or concrete strength, the magnitude of strength gained after applying GFRP sheets was almost equivalent. GFRP composites have verified its ability to strengthening and upgrade concrete structurally. From the two reinforced concrete beams test executed for comparison, the flexural strengthened beam with GFRP attached to the tension face did show a greater ultimate strength which is about 26.3% higher than the non-strengthened beam. The beam strengthened with GFRP possesses higher stiffness but lower ductility when compared with control beam. At the same load level exerted, the strengthened beam shows lower strain value in steel bar as well as concrete compression, the maximum mid span deflection was lesser, higher cracking load and lesser crack width were also examined. Yield load of steel rebar in strengthened beam was 94kN which is 54.1% greater than the control beam. Both beams tested were failed in flexural primarily due to fatigue of steel reinforcement and concrete failure in compression. Delimitation of GFRP composite sheet was the secondary failure mechanism in strengthened beam.

As a conclusion, the results of this study indicate that GFRP composite strengthening system is a highly effective technique in restoring and upgrading the various mechanical properties of the concrete structures regardless the concrete age.

9. Reference

[1] ACMA MDA, American Composites Manufacturers Association Market Development Alliance, Arlington, Virginia, U.S.A., http://www.mdacomposites.org (accessed August 2006)

[2] Alkhrdaji, T. & Thomas, J., “Upgrading Parking Structures: Techniques and Design Considerations”, Available online, http://www.structural.net/News/Media_coverage/media_csi.html , (download: February 2006)

[3] ASTM D 4541-02, “Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers,” ASTM International, West Conshohocken, PA, pp 13, 2002.

[4] G. Li, D. Davis, C. Stewart, J. Peck, and S.S. Pang, “Joining Composite Pipes Using Hybrid Prepreg Welding and Adhesive Bonding,” Polymer Composites, Vol. 24, No. 6, pp. 697-705, 2003.

[5] G. Li, J.E. Helms, and S.S. Pang, “Development of High-Pressure Composite Butt-Weld Joint,” Polymer Composites, Vol. 24, No. 1, pp.60-67, 2003.

[6] Gupta, V. B. and V. K. Kothari, Manufactured Fibre Technology. London: Chapman and Hall, 544-546. 1997.
[7] Tarek Alkhrdaji and Jay Thomas, Keys to Success: Structural Repair and Strengthening Techniques for Concrete Facilities. Structural Engineer, Available from Structural Group.2004.
[8] Thomas,J. et al,‘Field application of a carbon fibre sheet material for strengthening reinforced concrete structures’, Internal SAMPE symposium, Anaheim. 2006.