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Applications of Fiber Reinforced Polymer (FRP) in Structural Strengthening: A Review

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Abstract - This paper summarizes the ongoing research on use of Fiber Reinforced Polymer (FRP) in structural strengthening. Strengthening is required when the structural members are damaged under excessive external loading or when there is change of Structural use of the Structure. Since Fiber Reinforced Polymer (FRP) have been the source of an increasing interest in the field of rehabilitation, the main focus of this paper is to study the work done by various researchers on the application of Fiber Reinforced Polymer (FRP) in rehabilitation of Structures. The main findings obtained in the previous studies are mentioned and the issues that are not yet well understood and require further investigations are pointed out.

Index Terms - Fiber Reinforced Polymer (FRP), Reinforced Concrete Members and Structural Strengthening

INTRODUCTION

In civil engineering applications the maintenance, rehabilitation and upgrading of structural members, is one of the most crucial problems. Furthermore, numerous systems designed using the previous design codes in different countries of the world are structurally unsafe according to present design codes. Thus, the restoration of civil engineering systems is therefore becoming more necessary because of the need to maintain and enhance the huge structural surroundings inherited from the past. Since replacing these defective elements of systems requires a tremendous amount of citizens money and time, rehabilitation has become an appropriate way to improve their capacity to carry load and prolong their service lives. Deterioration of infrastructure caused by premature decay of structures has led to the review of several systems for the purposes of repair or rehabilitation. One of the difficulties in Reinforced Concrete Structures is the selection of a retrofitting system that will improve the structure's strength, durability and life while resolving constraints such as constructability, building operations and budget.

In the past 20 years, Fiber Reinforced Polymers (FRP) material have appeared to be most promising material for construction activities. Originally the Fiber Reinforced Polymers (FRP) material originated for Aerospace industries and had applications in the automobile industries also. But over the period of time shifted to civil engineering applications because of its superior qualities over other materials.

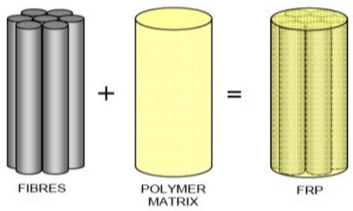

Fig.1

Materials combined to create an FRP composite.

LITERATURE REVIEW

Researchers over the years have carried out a various study on use of Fiber Reinforce Polymer (FRP) in construction industry for maintenance, rehabilitation, and up-gradation of structural members. These studies focused on different aspects of FRP such as applications systems, locations of application and different types of FRP (Glass Fiber, Carbon Fiber and Aramid Fiber). Some of the earlier studies and their findings are mentioned below.

Sangeeta Gadve et al. [1] studied the effect on concrete cylinders implanted with steel bars and submerged in salt water. Then an anodic current was passed through the embedded steel bars to instigate cracking in the concrete cylinders. This cracking was the result of accelerated corrosion of steel. This progression of steel corrosion in concrete was studied after adhesively bonding the cylinder with Glass and Carbon FRP sheets. The finding of this study revealed that the rate of corrosion was dramatically decreased after wrapping. Moreover, the decrease corrosion in samples wrapped with Glass FRP was more than that of Carbon

FRP. If should be noted that in the field application during the experimentation process the thickness of Glass FRP used was more than Carbon FRP.

A.H. Al-Saidy et al. [2] conducted an experimental program in which specimens of RC beams (rectangular) were subjected to accelerated corrosion. The rate of corrosion was varied from 5% to 15%. Due to which in the tension side of the beam the cross-sectional area of the steel reinforcement was reduced. To compensate the strength loss caused due to corrosion the tension side of the beam specimen that were corroded were repaired by CFRP bonding. It was found that, corrosion had an impactful effect on the bond between the reinforcement and the surrounding concrete. The ultimate strength of the repaired beams is increased with respect to the corroded beams. The structural integrity is maintained when CFRP sheets are used to strengthen the RC corroded beams.

Scott T et al. [3] conducted sequence of tests on concrete slabs which were simply supported and one way. These slabs were strengthened using FRP composites in flexure with tension face bonded and anchored with distinctive arrangements of FRP anchors. Behaviors of the specimens including the failure modes and selected strain results are investigated. Additionally, responses of the load deflection are plotted for all the slabs. The outcome of the study recommended that robustness can be build in to the member when anchored with Fiber Reinforced Polymer strengthening plate. The rate of de-bonding crack propagation was reduced when the anchors were closely spaced. Whereas, gains in deflection capacity but with limited gain in strength when the anchors spaced far apart.

Yasmeen Taleb Obaidat et al. [4] experimentally explored the performance of full-scale RC beams which were damaged structurally and later retrofitted in shear or in flexure using Carbon Fiber Reinforced Polymer laminates. The main variables observed were and the length of Carbon Fiber Reinforced Polymer, position of retrofitting and Internal reinforcement ratio. Findings of this study revealed that, when retrofitted in shear there was increase in maximum load and reached values about 23% for the retrofitted specimen. Similarly, when retrofitted in flexure there was increase in maximum load and reached values between 7% and 33%. Furthermore, it was observed that the mode of failure shifted to brittle. In flexural retrofitting when the CFRP plate length is increased it can make Carbon Fiber Reinforced Polymer more impactful for strengthening and concrete repair. To produce the intended strengthening effect the strengthening lengths should be sufficient enough.

Yousef A. Al-Salloum et al. [5] conducted experimentation on concrete cylinders subjected to high temperature and assessed the bond strength between concrete substrate and Fiber Reinforced Polymer. The experimentation was designed for both CFRP and GFRP wrapping. In all 42 standard concrete cylinder specimens of size 100mm x 200mm were casted. These 42 standard concrete cylinder specimens were distinguished into 3 groups of 14 unwrapped specimens,14 GFRP sheet wrapped specimens and 14 CFRP sheet wrapped specimens respectively. For both, GFRP and CFRP sheets wrapped specimens only single layer wrapping was adopted. It was found in this study, that peculiarly for CFRP wrapped specimens at a temperature of 200°C a notable deterioration occurred in the bond strength. Also, in FRP confines specimens rate of loss of compressive strength was observed at elevated temperature. Thus, attempts must be made to control the temperature within few hours to prevent very high loss of strength.

C.G. Bailey et al. [6] tested 8 circular columns which were shear critically reinforced, had a span to depth ration of 2.5 and were under a combined constant axial and cyclic lateral displacement history and simulating earthquake loading. These specimens were evaluated in 3 groups namely post-heated, post-heated plus restored with either CFRP or GFRP and unheated. A significant increase was observed in the energy dissipation, ductility and shear capacity of the post-heated damaged columns specimens jacketed with CFRP and GFRP. It was noticed that, the failure mechanism was shifted from column shear failure to flexural failure and there was a considerable degradation in the FRP properties at high temperature.

H.W. Zhang et al. [7] performed tests on 41 Fiber Reinforced Polymer to concrete joints which were anchored with single as well as multiple FRP anchors in addition to two unanchored control joints. Investigation is done on the location of the anchors and method of anchor installation. Results of the tests performed suggested that in comparison with unanchored control joints the multiple anchors increased the strain utilization of the Fiber Reinforced Polymer plate more efficiently. Moreover, when the anchors were optimally arranged it increases the strength of anchor joints 3 times more than the unanchored control joint average. It must be duly noted that joints anchored with rigid anchors were found to be stronger than joints anchored with flexible anchors.

Renata Kotynia [8] used externally bonded (EB) and near surface mounted (NSM) FRP strengthened RC beams to evaluate the bond behavior between concrete and Carbon Fiber Reinforced Polymer materials. Six parameters such as compressive concrete strength, CFRP bond length, beam's span and depth, type of the CFRP strips/ sheets and longitudinal steel reinforcement were considered to investigate the bond mechanism with the help of Modified RILEM beam bond test. It was found in this study that on the strengthened beams the concrete strength has an insignificant influence on the ultimate load when strengthened with both NSM and EB methods. Tests confirmed that internal steel bars play a crucial role in concrete to FRP bond and failure modes.

G. Promis et al. [9] suggested the usage of a performance index, based on a damage index, to evaluate the three experimental investigations and suggested effectiveness of external FRP reinforcement retrofitting with the help of 3 experimental investigations. Determination of the presence of FRP bars and FRP reinforcement on the performance index of the columns, the shape of the reinforced short column and the influence of axial compressive loading is done. The study concluded that for non-reinforced circular columns increases in the axial compressive load improves the performance. Under a heavy compressive load, the dissipated energy is lower for the same ultimate displacement. When the rectangular cross-section columns were analyzed, it suggested that anchoring FRP bars and using FRP jacketing for the strengthening of columns increases its performance. For the anchored FRP column and the FRP confined column the slope of the performance index is very high.

Rajeh Z. Al-Zaid et al. [10] studied reinforced concrete beams analytically which were strengthened for flexure with FRP reinforcement externally bonded. Development of numerical models was done considering the parameters such as equilibrium conditions, cross-sectional analysis and satisfying strain compatibility. These models also produced load– deflection relationship of the beam with respect to its preloading conditions, loading system and configuration. The comparison of the analytical results with the available experimental data suggested for the FRP strengthened beams the model which are developed can precisely produce the load – deflection response. In addition, for a Reinforced Concrete beam with the preload condition, specified dimensions, FRP cross-sectional area and internal steel reinforcement this model can be helpful in generating the moment–curvature relationship and subsequently the moment–deflection relationship. Moreover, the model developed in this study is very simple and easily implemented through a computer program.

Davood Mostofinejad et al. [11] experimentally tested 16 square reinforced concrete columns with cross section 133x133 mm cross section and 500 mm height under uni-axial compression. In this study a new method was developed by using FRP battens at sides and FRP strips at corners for the confinement of square concrete columns. The number of confining layers, the volume of fibers used and continuity or discontinuity of corner strips along height of column were the test parameters focused on. This research discovered that confining battens is the new technique of corner strip–batten which are uniformly stretched under the tension stresses of confinement. Hence, more uniform distribution of confining pressure on section occurs and the stress concentration at corners is eliminated. As compared to confinement using conventional FRP wraps a better performance was observed and the compressive behavior of the strengthened column was significantly improved by this proposed method.

J.H. Gonzalez-Libreros et al.'s [12] studied two different composites viz. Fiber Reinforced Polymer (FRP) and Fiber Reinforced Cementitious Matrix (FRCM) composites by experimentally investigating the behavior of reinforced concrete beams strengthened in shear with externally bonded composites. The parameters investigated included the variables such as the use of anchors, type of fiber and internal shear reinforcement ratio. This study revealed that with the increase axial stiffness of the composite the shear strength of strengthened beams increases. The anchors used changes the failure mode, the concrete crack pattern and mid-span displacement but did not affect the shear strength of the beams.

Jikai Zhou et al. [13] experimentally investigated concrete circular specimens of different sizes which were Carbon Fiber Reinforced Polymer confined. This investigation included studying the size effect on mechanical properties of Carbon Fiber Reinforced Polymer confined concrete circular specimens. The different sizes of CFRP confined concrete cylinders tested under uniaxial compressive were 70 mm, 100 mm, 150 mm, 190 mm and 310 mm. Further, different confinements layers CFRP were used namely, one layer, two layers and three layers. The four parameters obtained were peak strain, interception strength, strain of turning point and interception strength. The study revealed that mechanical properties of concrete have significant size effect and the uniaxial compressive strength of unconfined concrete cylinders has apparent size effect. Thus, size effect on large scale specimens confined with FRP should be investigated.

Anh Duc Mai et al. [14] studied 12 specimens of reenforced concrete columns of size 150 mm x 150 mm cross-section and 800 mm height which were tested under four-point bending, eccentric axial loads and concentric axial load. This study was carried out to explore the behavior fully and partially wrapped square reinforced concrete (RC) columns. It was learned that in both fully and partially wrapped RC column specimens the strength and ductility increased. The strength and ductility of fully wrapped square RC columns specimens was higher than partially wrapped square RC column specimens for all the loading conditions. Better performance of fully and partially CFRP wrapped square RC specimens as compared to non-wrapped square RC specimens revealed by axial load-bending moment interaction diagrams

Haytham F. Isleem et al. [15] developed a stress-strain model for CFRP confined rectangular RC columns and and subjected to cyclic axial compression. This model is based upon the experimentation carried out on 24 large-size CFRP-confined rectangular reinforced and unreinforced concrete columns under cyclic and monotonic axial compression. It was discovered that available strength and strain models peculiarly based on results of small size FRP-confined plain concrete specimens were inaccurate when assessed for FRP-confined large-size rectangular RC columns. As the cross-sectional size increases effectiveness of the confinement provided by FRP is decreased.

Alireza Rahai et al. [16] performed an experimental study on 8 large-scale rectangular RC columns under biaxial bending moment and axial load which were retrofitted with CFRP composites. These columns which had a regular cross section were casted and examined under bi-eccentric compressive loading up to failure. The various parameters taken into consideration were eccentricities, fiber orientation and CFRP thickness. The outcomes of these experiments and numerical research showed great development on the strength and ductility of RC column confined with CFRP.

J.J. Zeng et al. [17] experimented on 9 large-scale rectangular RC columns. Out of these 9 nine large-scale rectangular RC columns 1 was a controlled specimen without FRP jacketing and 8 were RC columns jacketed with FRP. The key test variables of this experimental program were the sectional corner radius and the FRP jacket thickness. The tests revealed that in the large-scale FRP-confined rectangular RC columns the stress-strain curves of FRP-confined concrete have a typical bilinear shape. The compressive strength of concrete of a standard concrete cylinder was more than that of concrete in a large-scale unconfined concrete column. The ratio between the two was found to be 0.94 for the columns tested.

Tara Sen et al. [18] performed experimentation on 14 beams specimens, in this experimental study the efficiency of jute textile reinforced polymer composite (JFRP) as compared to GFRP and CFRP for the flexural strengthening of reinforced concrete beams was investigated. This evaluation was done dividing the 14 beams specimens into 3 groups and by performing bending test on these beams. Observations were noted based on load deflection behavior, flexural strengthening effect on ultimate load, failure modes and s the deflection ductility study. It was seen that JFRP strengthening increased the flexural strength of the RC beams by 62.5%, GFRP increased the flexural strength of the RC beams by 125% and CFRP increased the flexural strength of the RC beams by 150% when full wrapping technique was applied. Similarly, when the strip wrapping technique was used JFRP strengthening increased the flexural strength of the RC beams by 25%, GFRP increased the flexural strength of the RC beams by 37.5% and CFRP increased the flexural strength of the RC beams by 50%.

H.R. Ronagh et al.'s [19] evaluated the use of Glass fibre reinforced polymers (GFRP) and Carbon fibre reinforced polymers (CFRP) in flexural strengthening of Reinforced Concrete structures. This strengthening was adopted to and aimed at increasing the lateral resistance of the structure. Findings revealed that by using both the composites' materials the lateral load carrying capacity remarkably increased. Is should be noted that CFRP strengthening improved the lateral resistance twice that of GFRP. However. GFRP provided higher ductility.

Guo Yongchang et al. [20] experimentally investigated 60 cylindrical specimens of dimension 150mm (diameter)x 300mm (height) under axial compression. The axial compressive behavior of Carbon FRP jacketed damaged concrete containing both High Strength Concrete (HSC) and Normal Strength Concrete (NSC) were studied. The test procedure comprised of 2 types of concrete, 2 levels of damage to the specimens and 3 amounts of CFRP wrapping.

The investigations revealed that most of the studies in the used of CFRP sheets only focused on the confinement of normal strength concrete (NSC) whereas the confinement of high strength concrete (HSC) with CFRP is still less explored. Furthermost, it was concluded that the axial strain and the ultimate strength of both damaged and sound specimens was appreciably enhanced by CFRP confinement.

For smidgen Carbon FRP reinforcement, the pre-existing damage little effect on Carbon FRP-confined High Strength Concrete. But, a significant effect on the compressive performance of CFRP-confined Normal Strength Concrete

Nawal Kishor Banjara et al.'s [21] study is centered at the experimental exploration and nonlinear finite element simulations of shear deficient and GFRP retrofitted bolstered concrete beams.14beams specimens were casted and their test results were compared with the controlled specimen. The main aim of this research was to study the load carrying capacity of beams strengthened with corrugated laminates and plain sheets. Development of mathematical models was incorporated for the prediction of load carrying capacity of pre-cracked strengthened beams. In the GFRP retrofitted beams the mode of failure changed from shear to flexural failure. There was a remarkable improvement observed **in** the ductile behavior too. Study concluded that application of GFRP to strengthen RC beams is one of the impressive rehabilitation techniques.

CONCLUSION

This paper presents a concise review of the study by various researchers on application of Fiber Reinforced Polymer (FRP) in strengthening of structural members. In the above discussion, most of the researchers studied the use of FRP laminates to repair/retrofit concrete specimens which were deteriorated but the grade of concrete was not taken into consideration. These studies were conducted either analytically or experimentally. Thus, Comparison of analytical and experimental results are lacking. Also, the researchers have studied the bonding effect of FRP and concrete. These studies suggested that the FRP has good a bonding with concrete. Studies have been carried out on possibilities of using Glass fibre reinforced polymers, Carbon fibre reinforced polymers and Aramid fibre reinforced polymers to repair and strengthen the concrete specimens. But there are few studies bases on use of Carbon FRP for structural strengthening, hence needs further exploration. The review of the work done by the researchers in last two decades show that a considerable progress has been made in terms of availability of laboratory research and experimental data on the use of Fiber Reinforced Polymer (FRP) in structural repair. But, information of FRP wrapped models that are exposed long term to the atmosphere are still lagging. The effects of FRP retrofitting on large scale specimens should be explored further because there is gap in the knowledge. Most of the models developed and investigated experimentally are established on test results columns and beams which are small-scale so their relevancy to large scale FRP retrofitted rectangular RC columns and beams are still to be properly authenticate. Cost comparison models for traditional retrofitting using steel jacketing and use of FRP composite for structural repair are still lacking.

REFERENCES

[1] Sangeeta Gadve, A. Mukherjee, S.N. Malhotra “Corrosion of steel reinforcements embedded in FRP wrapped concrete” Construction and Building Materials 23 (2009) 153–161.

[2] A.H. Al-Saidy, A.S. Al-Harthy, K.S. Al-Jabri , M. Abdul-Halim , N.M. Al-Shidi “Structural performance of corroded RC beams repaired with CFRP sheets” Composite Structures 92 (2010) 1931–1938

[3] Scott T. Smith, Shenghua Hu, Seo Jin Kim, Rudolf Seracino “FRP-strengthened RC slabs anchored with FRP anchors” Engineering Structures 33 (2011) 1075–1087.

[4] Yasmeen Taleb Obaidat, Susanne Heyden, Ola Dahlblom, Ghazi Abu-Farsakh “Retrofitting of reinforced concrete beams using composite laminates” Construction and Building Materials 25 (2011) 591–597.

[5] Yousef A. Al-Salloum , Hussein M. Elsanadedy, Aref A. Abadel “Behavior of FRP-confined concrete after high temperature exposure” Construction and Building Materials 25 (2011) 838–850.

[6] C.G. Bailey, M. Yaqub “Seismic strengthening of shear critical post-heated circular concrete columns wrapped with FRP composite jackets” Composite Structures 94 (2012) 851–864.

[7] H.W. Zhang, S.T. Smith “FRP-to-concrete joint assemblages anchored with multiple FRP anchors” Composite Structures 94 (2012) 403–414.

[8] Renata Kotynia “Bond between FRP and concrete in reinforced concrete beams strengthened with near surface mounted and externally bonded reinforcement” Construction and Building Materials 32 (2012) 41–54.

[9] G. Promis, E. Ferrier “Performance indices to assess the efficiency of external FRP retrofitting of reinforced concrete short columns for seismic strengthening” Construction and Building Materials 26 (2012) 32–40.

[10] Rajeh Z. Al-Zaid, Abdulaziz I. Al-Negheimish, Mohammed A. Al-Saawani, Ahmed K. “Analytical study on RC beams strengthened for flexure with externally bonded FRP reinforcement” Composites: Part B 43 (2012) 129–141.

[11] Davood Mostofinejad, Elaheh Ilia “Confining of square RC columns with FRP sheets using corner strip–batten technique” Construction and Building Materials 70 (2014) 269–278.

[12] J.H. Gonzalez-Libreros, L.H. Sneed, T. D’Antino, C. Pellegrino “Behavior of RC beams strengthened in shear with FRP and FRCM composites” Engineering Structures 150 (2017) 830–842.

[13] Jikai Zhou, Fengtong Bi, Zhiqiang Wang, Jian Zhang “Experimental investigation of size effect on mechanical properties of carbon fiber reinforced polymer (CFRP) confined concrete circular specimens” Construction and Building Materials 127 (2016) 643–652

[14] Anh Duc Mai, M. Neaz Sheikh, Muhammad N.S. Hadi “Investigation on the behaviour of partial wrapping in comparison with full wrapping of square RC columns under different loading conditions” Construction and Building Materials 168 (2018) 153-168

[15] Haytham F. Isleema, Daiyu Wanga, Zhenyu Wanga “Modeling the axial compressive stress-strain behavior of CFRP-confined rectangular RC columns under monotonic and cyclic loading” Composite Structures 185 (2018) 229–240

[16] Alireza Rahai, Hamed Akbarpour “Experimental investigation on rectangular RC columns strengthened with CFRP composites under axial load and biaxial bending” Composite Structures 108 (2014) 538–546

[17] J.J. Zenga, G. Linb, J.G. Teng, L.J. Lia “Behavior of large-scale FRP-confined rectangular RC columns under axial compression” Engineering Structures 174 (2018) 629–645

[18] Tara Sen, H.N. Jagannatha Reddy “Strengthening of RC beams in flexure using natural jute fibre textile reinforced composite system and its comparative study with CFRP and GFRP strengthening systems” International Journal of Sustainable Built Environment (2013) 2, 41–55

[19] H.R. Ronagh, A. Eslami "Flexural retrofitting of RC buildings using GFRP/CFRP - A comparative study" Composites: Part B 46 (2013) 188–196.

[20] Guo Yongchang, Xie Jianhe, Xie Zhihong, Zhong Jian "Experimental study on compressive behavior of damaged normaland high-strength concrete confined with CFRP laminates" Construction and Building Materials 107 (2016) 411–425.

[21] Nawal Kishor Banjara, K. Ramanjaneyulu "Experimental and numerical investigations on the performance evaluation of shear deficient and GFRP strengthened reinforced concrete beams" Construction and Building Materials 137 (2017) 520–534

[22] N. Aravind, Amiya K. Samanta, Joseph V. Thanikal, Dilip Kr. Singha Roy "An experimental study on the effectiveness of externally bonded corrugated GFRP laminates for flexural cracks of RC beams" Construction and Building Materials 136 (2017) 348–360.

[23] J.H. Gonzalez-Libreros, C. Sabau, L.H. Sneed, C. Pellegrino, G. Sas "State of research on shear strengthening of RC beams with FRCM composites" Construction and Building Materials 149 (2017) 444–458

[24] Ciro Del Vecchio, Marco Di Ludovico, Andrea Prota, Gaetano Manfredi "Modelling beam-column joints and FRP strengthening in the seismic performance assessment of RC existing frames" Composite Structures 142 (2016) 107–116

[25] Jiuk Shin, David W. Scott, Lauren K. Stewart, Chuang-Sheng Yang, Timothy R. Wright, Reginald Des Roches "Dynamic response of a full-scale reinforced concrete building frame retrofitted with FRP column jackets" Engineering Structures 125 (2016) 244–253

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