Retrofitting Of Concrete Structures Using Fiber-Reinforced Polymer (FRP): A Review

R. Nandhini, Dr. M. M. Saravanan, Karunya Grace .A

Abstract: Retrofitting of structures became popular in the field of civil engineering for repairing and rehabilitation of existing damaged and new buildings which are inadequate to bear the loads acting on them. The concrete structures can also be damaged due to aging, excessive loads, accidental loads, temperature, corrosion, chemicals, and other conditions. Demolishing and reconstructing those structures needs more time and uneconomical hence strengthening was done. Using FRP for strengthening concrete structures is one of the effective methods of strengthening due to its advantages like lightweight, highly resistant to corrosion and chemicals, high tensile strength, high stiffness and also it is easily applied to structures. The most commonly used fibers were steel, carbon, glass, aramid, basalt, polypropylene, nylon, etc. Nowadays natural fibers like jute, kenaf, flax, hemp, etc. were also used. Numerous studies were conducted to find its effectiveness in various conditions like marine, fire, corrosive and other aggressive conditions. In this paper, experimental works on FRP were reviewed and their conclusions were discussed briefly.

Index Terms: Concrete structures, Confinement, Debonding, Fire, FRP, Marine, Retrofitting, Strengthening,

1. INTRODUCTION

Demolishing and reconstructing a structure was considered to be an uneconomical and time-consuming process. Hence strengthening of new and existing structures had become popular in the construction field [1]. One of the most commonly used methods for repair and rehabilitation of structures is Retrofitting. Retrofitting is the modification of the existing structure by the addition of a new component for restoring the original capacities in the structure [2]. Strengthening old structures is necessary as old structures were constructed with old design codes that do not consider the post elastic behavior of the structure [3, 4]. Other reasons to strengthen a structure include faulty design or execution, aging of structure, various environmental conditions like corrosion, change in climate, inadequate maintenance, natural calamities like earthquakes and so on [1]. Jacketing is one of the easiest and effective techniques in retrofitting of structures. There is various type of jacketing is available to enhance the strength in structures such as Concrete jacketing, Steel jacketing, Ferrocement jacketing and Fiber Reinforced Polymer (FRP) jacketing [2]. Concrete jacketing is the first method to strengthen the damaged structures. A new layer of reinforced concrete is constructed around the existing concrete for achieving strength. Steel connectors, roughening of the surface and applying epoxy resin are used to make the bond between existing and new concrete material [2]. Steel jacket helps to restore the strength, ductility, and energy absorption capacity of columns thus it seems to be effective in retrofitting columns [5]. And also the steel jacket helps to increase the flexural strength and ductile behavior of the lap-spliced column thus increasing the lateral performance of columns [81]. The steel jacket helps to increase the performance of RC structures in the seismic region effectively. But corrosion is the only disadvantage [6, 7]. Ferrocement is a low cost thin composite material, easily manufactured, easily adaptable and durable. Hence requires no fire and corrosion protection. With the addition to expanded steel mesh, it is used to strengthen the shear deficient columns [3]. One of the most commonly used methods for retrofitting is Fiber Reinforced Polymer (FRP) jacketing [8]. FRP is widely used for its properties such as high strength to weight ratio, stiffness, good impact properties, high resistance to corrosion in harsh environmental and chemical condition, and also it causes only a minimum alteration to the geometry of structural elements than other methods [1, 9, 10]. In this paper behavior of FRP strengthened structures such as beams, columns were discussed.

- R. Nandhini, P.G. Scholar, Kongu Engineering College, Tamil Nadu, India, Contact – 9688467637. E-mail:er.nandhini11@gmail.com
- Dr. M. M. Saravanan, Assistant Professor, Kongu Engineering College, India, Contact - 9843802035. E-mail: saromms@gmail.com
- Karunya Grace. A, P.G. Scholar, Kongu Engineering College, Tamil Nadu, India, Contact – 8667845955. E-mail: missamaladoss96@gmail.com

2 BEHAVIOR OF FRP STRENGTHENED COLUMNS

2.1 Rectangular Columns

Many researchers conducted the experimental study to analyze the behavior of columns strengthened with FRP considering various factors such as a number of confining layers, FRP schemes, etc. Some of the results were discussed in this paper. Polyethylene terephthalate FRP is used to strengthen the corroded rectangular columns considering different levels of corrosion and various volumetric ratios and the test results indicate that shear resistance of FRP and column increases with the increase in volumetric ratio and decreases with increase in different levels of corrosion. And also if shear resistance of FRP decreases bond between the column and FRP is reduced which leads to failure of the column [11]. Corner radius is considered to be one of the factors which affect the confinement of rectangular and square columns [12]. If the corner radius and thickness of FRP increase ultimate axial strain and compressive strength of column increases [13]. CFRP and BFRP confined rectangular columns with varying aspect ratios were constructed and tested under axial compression to analyze whether aspect ratio influences the columns. Results indicate that aspect ratio has no ductility but it has a significant effect on the strength of the column [14]. The cross-section aspect ratio decreases the axial strain [15]. If the CFRP confined columns were prestressed, the strength of column increases than the normal FRP confined columns [15].

2.2 Square Columns

In square columns ductility increases when CFRP is partially confined with one layer whereas in fully CFRP confined columns ductility increases when the diameter of transverse reinforcement increases [16]. Intermittent CFRP strips in FRP increase the strength and ductility of square columns but when eccentricity increases it decreases the load-carrying capacity and ductility [17]. To increase the efficiency of square columns, a new technique namely Externally Bonded Reinforcement On Grooves (EBROG) and Externally Bonded Reinforcement In Grooves (EBRIG) were developed. The technique shows more effectiveness than the externally bonded reinforcement in improving strength and ductility. And also it postpones the buckling of columns [18]. The technique was analyzed in comparison with Near Surface Mount (NSM) technique for both circular and square columns. The result indicates that buckling and debonding of FRP is delayed and is more effective in circular columns than square columns [19]. By increasing the no. of layers, stiffness of the column increases thus helps in improving load-carrying capacity and ductility of eccentrically loaded square columns [20]. Providing corner radius equal to cover increases the load-carrying capacity and smoothening the edges of the square column delay the rupture of FRP from the surface of the column [21].

2.3 Circular Columns

If the stiffness of FRP increases the buckling of columns is resisted as effective confinement is obtained [12]. In addition to longitudinal CFRP confinement, CFRP hoop wraps were provided in which longitudinal confinement helps to increase the load-carrying capacity and hoop wraps provide lateral support to longitudinal CFRP wraps [22]. Various studies were done to examine the effect of eccentricity in columns [23, 24]. When eccentricity increases load-carrying capacity and ductility of column decreases [24]. Stress-Strain relationship of concentrically loaded columns will not apply to eccentrically loaded columns as error increases with an increase in eccentricity. The ultimate failure strain of the eccentrically loaded column is 50% higher than the concentrically loaded column [23]. At low confinement ratio plastic hinge length of circular column increases [25]. Using artificial neural networks, an analysis was conducted to predict the factors affecting the compressive strength FRP confined columns. The thickness of FRP, elastic modulus of FRP, diameter, height and unconfined strength of concrete were some of the factors affecting the compressive strength of columns [26]. Aramid Fiber Reinforced Polymer (AFRP) improves the strength, ductility, and energy absorption characteristics. In wet/dry conditions no strength is reduced and in freeze/thaw conditions the only a little amount of reduction of strength is noted [27]. If horizontal stirrups were added to fiber-reinforced jacket strength and ductility increases than the conventional concrete [28]. If the slenderness ratio of columns increases strength, ductility, toughness and deformation capacities decrease and vice-versa [29]. CFRP and GFRP wrapped columns slow down the rate of corrosion and epoxy are more responsible for resisting the corrosion [30]. If an externally bonded CFRP sheet is provided in addition to near-surface mounted technique in the form of spiral grooves stiffness, strength, ductility, and energy absorption characteristics were improved [82].

2.4 Circularisation

The strength of FRP confined square columns and rectangular columns is less than the circular columns as the FRP confinement is non-uniform over them. To overcome this, square columns are circularised [31]. The circularisation process helps to improve the behavior of the square columns [31, 32] and if high strength concrete is used for circularisation, ductility is also increased [33]. Type of aggregate and type of fiber also influence the behavior of FRP strengthened columns [34, 35, 36 and 83]. If natural (sisal) and artificial (glass) FRP are used as a hybrid, load-carrying capacity increases. If no. of hybrid FRP layers increases load-carrying capacity and ductility increase [83]. If natural fiber namely hemp is used for confinement, its strength, ductility, and energy absorption characteristics were increased [34]. The use of recycled aggregate concrete and crumb rubber concrete improves the behavior of FRP strengthened columns similar to normal FRP confined columns and seems to be an eco-friendly alternative [35, 36].

3 BEHAVIOR OF FRP STRENGTHENED BEAMS

Shrinkage is one of the factors responsible for the formation of cracks in structural elements like beams and slab. To reduce the shrinkage hybrid fiber-reinforced polymer (FRP) reinforced shrinkage compensating concrete was used. In this, two expansive agents were used namely lime-system and ettringite-system. Both the expansive agents and FRP postpone the crack formation and eliminates the corrosion thus increasing the ultimate load [37]. Torsional forces will be acting in the beam when they are located at the perimeter of the building. To increase the torsional capacity of the beams, GFRP sheets are used. GFRP strengthened beams show better torsional resistance. If diagonal stripping is done more torsional resistance can be obtained [38]. An innovative hybrid technique in which CFRP sheets were provided at the bottom of the surface and GFRP sheets were hoop-directionally provided. The proposed technique helps to postpone the failure of the FRP shell hence improving the shear strength of the beams [39]. An experimental study was conducted to analyze the effect of beam size and thickness of CFRP on interfacial shear stress and the result showed that increasing thickness of CFRP and beam size increases the interfacial shear stress [40]. CFRP and GFRP confined beams improve the strength and resist the crack formation but the diagonal wrapping of CFRP and GFRP enhances a significant amount of shear strength and stiffness of beam than the vertical stripping [41]. Natural composites such as kenaf, jute, and jute rods increase ductility, shear, and load-carrying capacities of the beam. It offers a good bond with the concrete hence premature debonding will not occur as in CFRP laminates [42]. In pre-cracked beams, CFRP laminates showed good performance than the Near Surface Mounted (NSM) technique [43]. A new fiber namely Hardwire Steel fiber sheets were used for strengthening, it enhances the strength and stiffness but ductility is decreased because of delamination [44]. If anchorage devices are provided for CFRP strengthened beams, the behavior was improved than the NSM technique [45]. If the surface is prepared and connectors are used efficiency of FRP in improving the performance was good [46]. Unless high strength concrete is used in the post-tensioned beams shear resistance is not improved and span to depth ratio decreases shear resistance increases [47]. Shear failure diagrams and compressive failure of FRP before and after yielding of steel for FRP confined beams were given [48]. Side wrapping of FRP increases the shear capacity of beams and the efficiency of FRP depends on the no. of confining layers and type of wrapping [49]. Hybrid CFRP and GFRP sheets for confinement showed better resistance than CFRP and GFRP confined beams. The provision of U-anchorage helps to increase flexural strength [50]. Two new anchorage systems were developed namely by providing 10mm bolts at the end of CFRP and 4mm thick steel plate around CFRP [51]. Providing two layers of FRP only in the tension zone of the beam improves flexural strength and ductility thus seems economical. Failure pattern was changed from ductile to brittle if no. of layers increased but the flexural strength was increased in all lay-up patterns [52]. Effective strain decreases with the decrease of spacing of FRP and an increase in the amount of FRP [53]. CFRP and PBO FRCM composites were used to strengthen the corrosion damaged beams. The result indicates that both the system increases the load-carrying capacity irrespective of the level of corrosion [54]. When axial stiffness of FRP and FRCM increases shear strength increases. By enlarging stirrup spacing in FRCM shear strength is improved [55]. A new technique was developed to strengthen the beam-column joint by extending the CFRP sheets to column surface from beam through chamfers and fillets. If chamfers are large, load-carrying capacity also increases. U-wrapping seems to be the best in strengthening beams [56]. The use of U-jackets over the FRP plate suppresses the intermediate crack debonding in beams. Inclined U-jacketing is more efficient in suppressing the intermediate crack debonding than the vertical U-jacketing [57, 58]. Providing U-jacket in the high moment region increases the ultimate load and decreases the ductility whereas in the low moment region it increases both the ultimate load and ductility [57]. The effect of providing anchorage devices to FRP strengthens the beams. Steel clamps were provided for strengthening and this anchorage device is used to decrease the deflection and increase the ultimate moment [59]. CFRP, GFRP and FRCM systems increase the shear capacity of beams and FRP anchors were provided to prevent the brittle shear failure due to the debonding of FRP [60]. Two bio-based resins were developed namely an epoxidized pine oil resin blend (EP) and Furfural resin (FA). EP resin shows comparative performance to conventional epoxy but FA resin fails to give the strength as curing was affected by concrete alkalinity. But it could be used for preparing the prefabricated CFRP plate which is then bonded by epoxy to increase the strength of the beams [61]. An experimental study was conducted to examine the behavior of FRP confined beams with various shear span to depth ratio. From the obtained results, the curve was plotted which indicates that FRP is more effective for the high shear span to depth ratio compared to low shear span to depth ratio [62]. The flexural capacity of FRP strengthened beams was more than the Textile Reinforced Mortar (TRM). If anchorage devices are provided 90% of strength is increased when compared to unanchored specimens [63]. To strengthen the long span members, CFRP rod panels were used. CFRP rod panels improve the strength of RC beams. If anchorage devices were provided along with CFRP rod panels strength of RC beams was increased further [64]. If the thickness and confinement of HB (Hybrid Bonded) FRP is more load carrying capacity and ductility is increased [65].

4 BEHAVIOR OF FRP STRENGTHENED STRUCTURAL MEMBERS IN MARINE ENVIRONMENTAL CONDITIONS

Old structures built in the seismic region were most vulnerable to earthquake loads as they are constructed using old codal provisions which do not have a proper seismic design, detailing, etc. and prove to be a deficient structure [66, 67]. Even newly constructed structures such as a bridge with proper design as per codal provisions cannot withstand for heavy earthquakes [68]. Hence these structures need strengthening. Many methods were available for strengthening these structures like steel jacketing, providing shear walls, externally bonding with FRP, etc. Externally bonding FRP was commonly used as it can be easily adopted and it provides strength quicker than other methods. Various experiments were conducted to examine the efficiency of FRP in the seismic strengthening of structures. In rectangular columns, increasing the confinement ratio of CFRP proves that the columns were capable of sustaining three times the ultimate drift and by increasing no. of pinned dowels confinement of FRP increases thus increasing the seismic performance [66]. FRP confinement increases strength and decreases the energy dissipation level of the columns even under biaxial loading [67]. Columns were considered to be the most affecting part in the structure and it mainly fails near the lap-splice region. To overcome the effect on columns an emergency technique was proposed. After removing loose concrete grout was cast and also a trench was cut at the base of the column then they were filled with CFRP strips then the CFRP laminates were externally bonded to the column extending the same to the trench. The technique restores the stiffness, lateral and torsional strength, and ductility but with low torsional stiffness. It can also be used as a permanent repair technique [68]. Old buildings were constructed with old design provisions that do not include the post elastic behavior of the structure or an element. Hence it accounts for insufficient anchorage length at lap-spliced regions, an insufficient amount of transverse reinforcement, smaller dimension to columns, no proper detailing, etc. results in the failure of structures [4, 69, 70, 71]. The proper method should be adopted to strengthen the old structures as demolition and reconstruction were not easy and it has many disadvantages. If FRP confinement is more, small anchorage length is enough and an increase in FRP stiffness, anchorage length increases the working stress [4]. CFRP jacketing increases the strength and drift capacity by postponing the buckling of reinforcement, crushing and spalling of concrete, the shear failure and so on [69]. If columns having plain re-bars are strengthened with CFRP sheets, its ductility, and energy dissipation capacity [71]. De-icing salts and chloride attack were the main reasons for corrosion. If corrosion occurs, the bond between steel and concrete is decreased and also the cross-sectional area of steel is reduced thus resulting in the reduction of the load-carrying capacity of the column or structure. To strengthen the column further corrosion must be prevented. CFRP wrapping helps to prevent corrosion as CFRP offers good resistance to corrosion [72]. Strengthening columns with CFRP sheets enhance the ductility. If it is combined with a steel jacket, both strength, and ductility increase [6]. Another FRP namely PET-600 shows better hysteric response to columns than CFRP wrapped columns because of its higher ultimate drift and toughness index [72]. A new method namely Durable Retrofit Method was proposed to increase the strength of corroded RC columns in marine environmental conditions. In this method after removing damaged concrete GFRP sheets were placed and then the repair mortar is applied [7]. The failure of the bond between concrete and FRP is the main reason for the failure of the strengthened structures. To maintain the bond

FRP anchors are provided. The results show that FRP anchors help to prevent the premature bonding of FRP thus the strength of the structure is increased [73]. Beam-Column joint should also be strengthened as it was also considered as an important load-carrying member. If CFRP is properly confined in the beam-column joints, the strength and ductility increases [74]. Both FRP and FRCM composites do not restore the original capacity of the column but it increases the strength and energy absorption capacities to a certain percentage [75].

5 BEHAVIOR OF FRP STRENGTHENED STRUCTURAL MEMBERS IN FIRE EXPOSURE

When exposed to fire, concrete offers good resistance to fire as it has low thermal conductivity. But if exposed to fire for a long time, the structure gets damaged as it loses its strength and stiffness [8]. Mechanical behavior of fire-damaged concrete varies depending on many factors such as age, duration of exposure, max. The temperature of the fire, properties, and material of concrete, etc. [8]. The deteriorated structure can easily be strengthened [76]. FRP is the most commonly used material for strengthening as it possesses good stiffness, strength, good resistance to corrosion, etc. But these properties were reduced when exposed to high temperature as it was bonded to the concrete surface by polymeric resin [10]. Epoxy is the matrix normally used to bond FRP on the structure. Epoxy provides good bonding because of its rigid characteristics. At elevated temperature i.e., when the temperature exceeds glass transition temperature, epoxy changes its rigid character to a soft one. Hence the bonding between FRP and the concrete surface reduced [77]. To overcome this, proper fire insulation materials are laid over them [10]. Many pieces of researches had been done to strengthen to investigate the fire-damaged concrete structure using various materials. Some of them were discussed in this paper. Wrapping GFRP or CFRP seems effective in strengthening the fire-damaged columns as it increases the strength and ductility of columns [76]. FRP hoop wraps are effective in enhancing the strength of fire-damaged concrete but fail to increase stiffness. The increase of strength depends upon the fundamental characteristics of the concrete [8]. As already stated, above the glass transition temperature, epoxy cannot provide an effective bond between concrete and FRP. Hence CFRP or GFRP wrapping fails to increase strength, strength may be increased by providing insulation for fire protection [78, 77]. Another material namely Textile Reinforced Mortar (TRM) was effective in increasing strength and flexural capacity of beams. If TRM is coated with adhesives such as epoxy or if no. of confining layers is increased, then it will be more effective in increasing the performance of fire-damaged beams [1]. Debonding of FRP from the structure can be prevented by providing insulation. Cooling anchorages were used to increase the performance of the beam and it shows good results [9]. A new supplementary insulation technique was developed, a cement-based mortar was applied in spray type for protection. And the develop insulation helps to increase the strength, stiffness, and ductility of columns [10]. CFRP strengthening system helps to bear the load until it fails under high temperature. If the thickness of CFRP is increased, the system may bear the load for more time. Vermiculite perlite, a sprayed fire protection material of low thermal conductivity is used for preventing the FRP [79]. Epoxy resin bonded FRP confined beams showed better fire resistance than the geopolymer resin bonded FRP confined beams and if the primer is applied performance of them was improved [80].

6. CONCLUSIONS

From the experimental works reviewed in this paper the following conclusions were made:

- FRP strengthening improves the flexural, shear and compressive strength of RC elements. It is preferred for its advantages like easy application, lightweight, stiffness, high tensile strength, etc.
- FRP exhibits good bonds with concrete by the use of epoxy resin. The bond gets failed when only the temperature exceeds the glass transition temperature. Nowadays bio-based resins were also developed to bond FRP on the surface of the damaged structures.
- Different types of wraps were followed. Partial wrapping shows better performance than full wrapping and is economical.
- FRP commonly fails due to debonding from the concrete surface. It anchorage devices are provided to them, the concrete elements showed better performance than the unanchored.
- If no. of confining layers were increased the performance of the RC elements was also increased.
- FRP was also used in the form of rods which is placed at the distance less than the cover of reinforcement. This method increases both load-carrying capacity and ductility. Their failure mode is the separation of concrete cover with the crushing of concrete.

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