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Rehabilitation of the Infrastructure Using Composite Materials: Overview and Applications

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Abstract: The volume of the infrastructure that needs upgrading, strengthening and/or repair is growing worldwide. The traditional techniques of rehabilitation are faced with challenges from new materials and methods that offer convenience in application and lesser degree of financial constraints to the owner. The new advances made with fiber reinforced polymer (FRP) composites, because of their many advantages over steel and other conventional materials, have provided engineers with stimulus in circumventing the difficulties associated with the traditional techniques of rehabilitation process. Although the applicability of the new materials and techniques are verified by more than ten years of field applications and a bulk of experimental data, many engineers, owners, architects and contractors still have hesitation in taking the full advantage of these materials. Some of the major reasons behind this hesitation are: the absence of code of practice, standards, guidelines for design and detailing, and the lack of clear understanding of the structural performance of the composite structure under short- and long-term loads. Although, it might be argued that the material cost of FRP is about 5 to 10 times than that of steel, the total cost of retrofitting with FRP materials in general is more economical as compared to steel. This is true because in a retrofitting operation, material cost is only a fraction of the total retrofitting cost, the remainder being the application, labor and maintenance costs. Moreover, ease of installing, handling, storage, transporting and the life cycle cost benefits of FRP could lead to a great saving in the overall cost that may exceed the difference in the material cost. This paper provides an overview of the engineering properties of FRP as a repair and retrofit material for infrastructure applications. It also presents a state-of-the-art information of research and development undertaken in the area of using advanced composite materials for rehabilitation of infrastructure components.

Introduction

Concrete and steel are considered to be the prime two construction materials in most countries around the world. These materials when properly used and protected against physical and chemical deterioration, become durable enough to last over the design lifetime of the infrastructure and serve for the function that they were designed for. However, lack of protection from ingress of chemical agents endangers their integrity and consequently reduces the life cycle of the structure.

The number of buildings, bridges, pipelines and other components of the infrastructures that have deteriorated in service and in need of repair and maintenance is large and ever increasing. Deterioration or damage to structures may result from different sources, including faulty design and construction practices that ignore the environmental impact, overloading, fire, blast loading, and corrosion of steel.

On the other hand, some of these buildings, bridges, pipelines and other components were originally designed for small size vehicles, lighter loads, and lower traffic volumes than are common today [1,2]. Consequently, a large number of these infrastructure components have shown inadequate load carrying capacity to meet today's demand. Also, existing concrete and steel structures may, for a variety of reasons, be found to be unsatisfactory. This could manifest itself in poor performance under service loading in the form of excessive deflections and cracking, or inadequate strength or damage due to thermal cycling. High temperature, high humidity, severe ambient and ground salinity environments as those prevailing in some areas of the Middle East will adversely affect the life-span of the infrastructure components.

Fiber-reinforced polymers (FRP) are one of the prime contenders in rehabilitation process. FRP composites have many advantages over other materials, including high resistance to corrosion, high specific strength and stiffness, and superior fatigue performance.

Rehabilitation of Structures

Many of the existing structures will soon approach their service life in a period shorter than the anticipated design life. For example, 40% of the highway bridges in USA are either structurally or functionally deficient and require some form of rehabilitation or replacement [3]. The loss due to corrosion alone, amounts to about $100 billions per year [4]. In Canada, 40% of the bridges are also deficient and require rehabilitation or replacement [5]. In Europe, the annual cost of damage due to corrosion has been estimated at being 1000 million English pounds [6].

Rehabilitation can be defined as an operation to bring a structure (or a structural component) that is deficient in design demand to the desired specific performance level. Depending upon the state of the structure and the desired post intervention performance level, rehabilitation can be divided into two categories: repair and strengthening. Repair is the rehabilitation of a damaged structure or a structural component with the aim of restoring the original capacity of the damaged structure. Strengthening, on the other hand, is the process of increasing of the existing capacity of a non-damaged structure (or a structural component) to a specified level.

Conventional Procedures

In the past, several rehabilitation techniques were developed and used to achieve a desired improvement [7]. Among the most common methods are: 1) Replacing non-structural toppings with structural toppings, or with lighter materials, 2) Introduction of extra supports, 3) Application of extra steel reinforcement, 4) External or internal prestressing, and 5) Epoxy injection.

Repairing a damaged concrete surface (geometrical damage) is common for concrete structures. The damaged concrete has to be removed until a sound layer of concrete is reached and then cleaned leaving the cavity ready for proper patching as shown in Fig. 1. The new concrete or mortar mix should be chosen carefully otherwise satisfactory structural performance may not be achieved, [8].

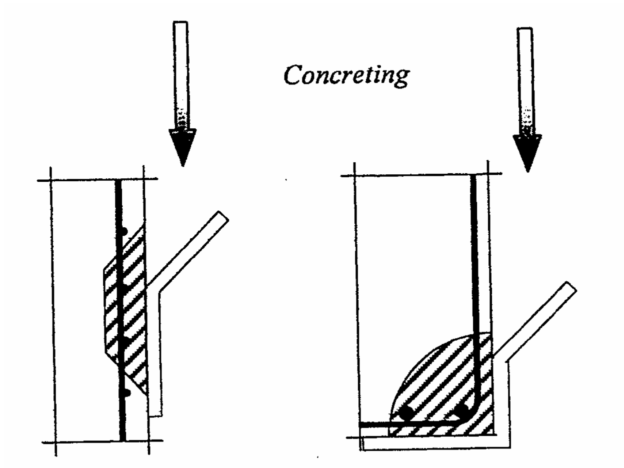


Fig. 1 Patch repairs to damaged concrete surfaces

In some circumstances, where the corrosion of the reinforcement is severe, replacement of corroded reinforcement, together with the damaged concrete should be considered. The replacement bars are usually welded to sound existing part of the old reinforcement as shown in Fig. 2. During this process, the structure may need to be temporarily supported [9].

In some cases, it is required to increase the capacity of the structural element to meet the increased demands of new standards or higher live loads. Increasing the cross section of a concrete member is a simple and frequently been applied as a common strengthening method. Increasing the cross-section of a RC column is quite an efficient strengthening measure. Placing a steel tube around a column and filling the gap with concrete can strengthen the column very effectively. Also, jacketing the column with reinforced concrete jacket has proven to increase both the column carrying capacity and the ductility [8]. (See Fig. 3).

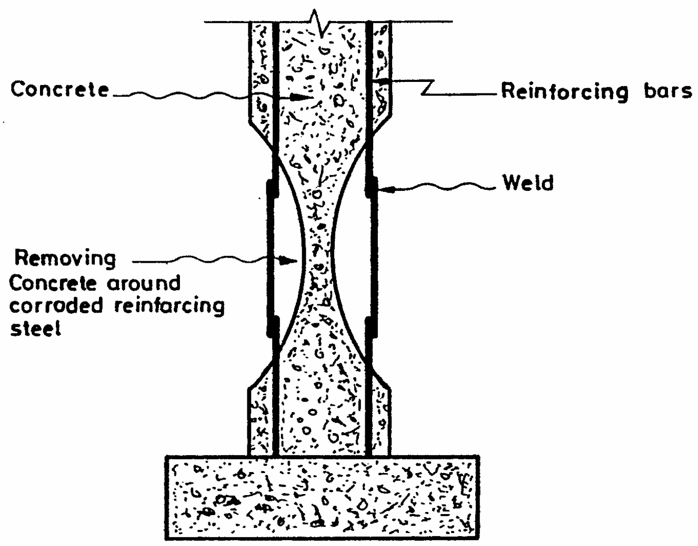


Fig. 2 Replacement of corroded reinforcement

For RC beams, placing additional reinforcement in the tension zone, protected by additional concrete cover or shotcreting, as shown in Fig. 4, is a very efficient method to increase the beam carrying capacity [8,10]. The required time for such work and disruption involved will add to the cost. Evaluation of all or parts of a building, or road closures in the case of bridges, may be necessary while the work is carried out and these all add to the cost.

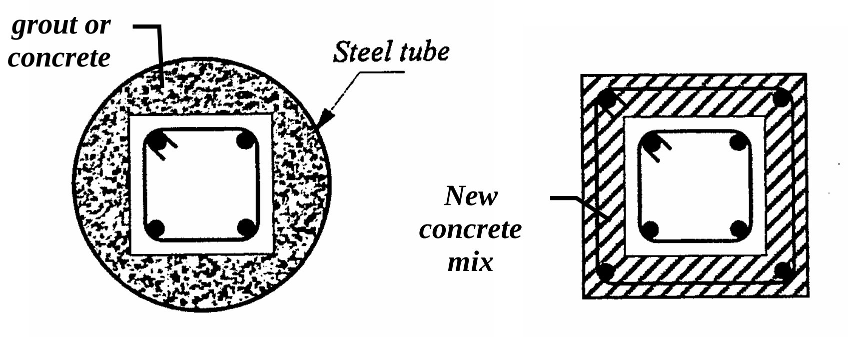


Fig. 3 Increasing cross-sections of columns

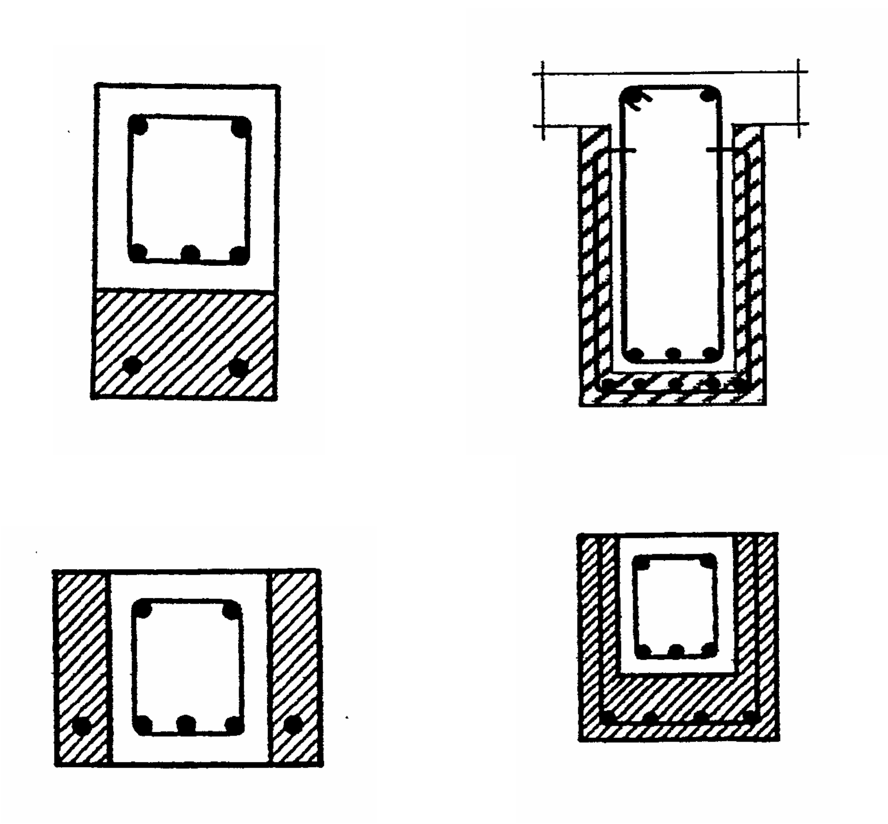
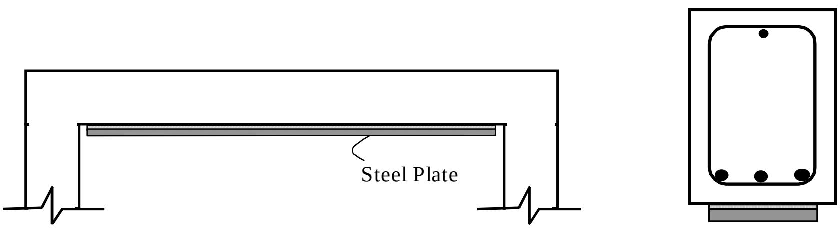


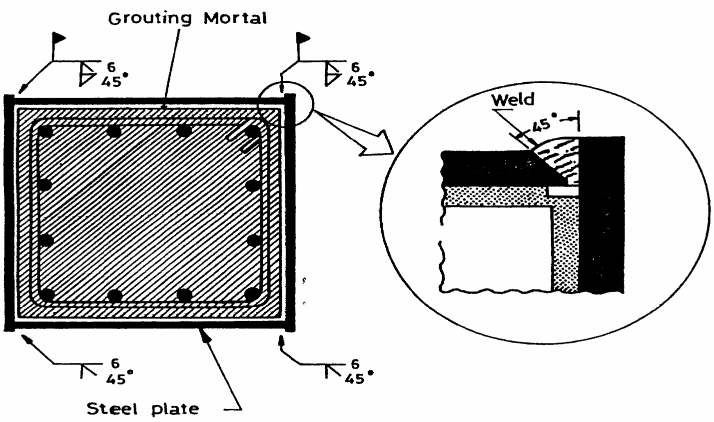
Fig. 4 Additional reinforcements for beams

Rehabilitation Using Steel Plates

In recent years, another method has evolved that involves *bonding of steel plates* to the surfaces of members to be rehabilitated (Fig. 5). This method has considerable potential in the rehabilitation field, and has already been used to strengthen both buildings and bridges in many countries around the world. The major attractions of this technique are the relative simplicity of the implementation, the speed of application, and the relatively small consequential change in structural size. In recent years, extensive experimental investigations on the factors influencing the structural performance of plated concrete beams have been reported by Swamy et al. [11,12]. The results of these investigations have shown that the bonding of thin steel plates to the tension faces of concrete beams can lead to a significant improvement in structural performance, under both service and ultimate loading conditions.



(a) Beam



(b) Column

Fig. 5 Rehabilitation of beams and columns with steel plates

The shortcoming of the strengthening method with steel plates is the possibility of corrosion at the epoxy-steel interface, which may adversely affect the bond strength. Calder [13] and Lloyd and Calder [14] conducted detailed theoretical and experimental studies on the long-term performance of RC beams externally strengthened by epoxy-bonded steel plates. The beams were subsequently exposed to three typical environmental areas throughout England (high rainfall, industrial, and marine), for duration of up to 2 years. After two years, the majority of the steel plates in all locations had suffered, to some extent, from some corrosion at the resin-steel interface, and this led to a slight reduction in the strength of the exposed beams as compared to the control beams. It was noted that there was a little difference between the failure load for the primed and non-primed test samples. The corrosion appeared to be caused by migration of water through micro-cracks in the concrete and resin through to the steel plate. This corrosion was nearly uniformly distributed over the entire face of the steel plate, suggesting that water seeped in through the concrete and resin, and not between the steel and resin at the ends of the beam. The use of a primer paint applied to the surface of the steel plates appeared to generally prevent corrosion of the steel plates, without affecting the structural strength of the member. However, there was some loss of strength in the bond between the steel and the concrete, which led to a 7-23% reduction of the failure loads for the loaded beams and to a 2-11% reduction for the unloaded beams.

Other drawbacks of steel plating include difficulty in handling the heavy steel plates at the site especially in limited space indoor applications, relative difficulty in shaping the plate to suit the structural element to be repaired, and the problem of forming clean butt joints between the relatively short plates. Also, steel plates are not suitable to be wrapped or jacked around tapered members.

An effective way of eliminating the corrosion problem and other previously listed drawbacks is to replace steel plates with corrosion-resistance synthetic materials such as fiber-reinforced polymer (FRP) composites. In addition to their higher corrosion resistance, many polymer composites have tensile and fatigue strengths that exceed those of steel.

Rehabilitation Using FRP Composites

The drawbacks of using the steel plate technique and the ever-increasing demand for rehabilitation of the infrastructures have prompted engineers and researchers to search for better and more reliable and innovative solutions. The advancements made in the properties of FRP materials and in the adhesives have rendered these as the ideal combination for an innovative solution for many structural problems of rehabilitation.

The use of FRP materials for civil engineering applications is relatively new. However, they have been in use for a long time in other industries such as aircraft, naval and marine boats, automobile, chemical apparatus, and other industries as well as in aeronautical for quite long time. FRP composites have superior engineering characteristics. Among these is the high strength-to-weight ratio. For example, for bridge strengthening, 94 kg of steel can be replaced by about 4.5 kg of FRP carbon composites [15]. FRP composites are non-corrosive and neutral electro-magnetically and electrically. In addition, some types of FRP composites are very flexible such that they can be formed almost to any desired shape, light enough to be handled on the job site with no need for heavy equipment, and they occupy negligible space as compared to the existing structural members.

Properties of FRP Composite Materials

Polymer composites are defined as a matrix of polymeric material reinforced by fibers or other reinforcement with a discernible aspect ratio of length to thickness. FRP composites can be made into many different shapes, including high strength rods, cables, grids, beams, and plates.

The major factors affecting both the physical and mechanical performance of the FRP matrix composite are the orientation, length, shape and composition of the fibers, the mechanical properties of the matrix resin and the adhesion of the bond between the fibers and the matrix (i.e. type of fiber coating material).

Unlike steel, the mechanical properties of FRPs vary significantly from one product to another. Factors such as volume fraction (ratio of volume of fibers to the volume of matrix material) and type of fiber and resin, fiber orientation, dimension and quality control during manufacturing play a major role in establishing the characteristics of the product.

Table 1 shows typical properties of dry fibers of glass and carbon. Dry fiber properties vary greatly depending on the fiber type, fiber grade, and the actual weight/density of fibers. Typical properties of FRP/Epoxy composite systems, which consist of dry fibers saturated with resin are presented in Table 2. FRP system properties can vary depending on the manufacturer and on other factors such as volume fraction, fiber properties, resin properties, aerial weight/density of fibers, and type of weave/stitch.

One of the most important characteristics of FRP materials is their high tensile strength. The strength is about twice that of prestressing steel strands, and fairly high compared with ordinary steel as shown in Fig. 6. The tensile strength of FRP composite system is affected not only by the tensile strength of the fibers, but also by the volume fraction, resin system and the bond performance of fibers and matrix. FRP composites reach their ultimate tensile strength without exhibiting any yielding of the material (i.e. linear up to failure).

Table 1. Typical Properties of Glass and Carbon Dry Fibers

Property	Fiber Type	
	Glass	**Carbon**
Tensile Strength (MPa)	1800 - 4800	2400 - 5000
Elastic Modulus (GPa)	70 - 90	200 - 300
Strain at Failure (%)	> 4.0	> 0.50

Table 2. Typical Properties of Glass and Carbon Composite Systems

Property	Composite Fiber Type	
	Glass/Epoxy	**Carbon/Epoxy**
Tensile Strength (MPa)	500 - 1500	800 - 3000
Elastic Modulus (GPa)	25 - 75	60 - 250
Strain at Failure (%)	2 - 4	1 - 2

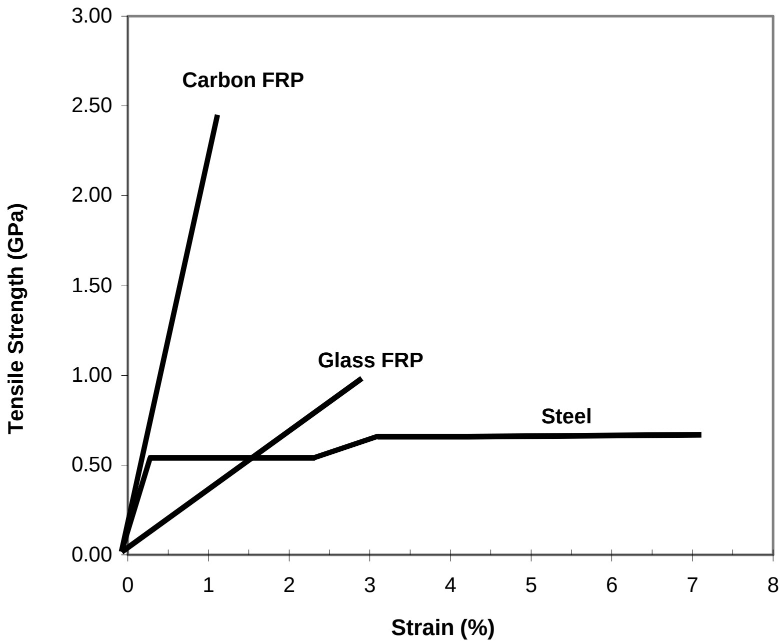


Fig. 6 Typical stress-strain relationships of FRP composites and mild steel

The modulus of elasticity of glass and carbon dry fibers are shown in Table 1, and the modulus of elasticity of E-glass/Epoxy FRP composites (GFRP) and carbon/Epoxy FRP composites (CFRP) are shown in Table 2. For GFRP, the modulus of elasticity is generally lower than that of steel (E_G = 1/8 – 3/8 E_s), whereas for CFRP, it ranges from 0.3 – 1.5 times as much as that of steel. Therefore, when GFRP is used as main reinforcement, special attention should be paid to the deflection as it may control the design. Other mechanical properties were reported in details by Alsayed et al. [16].

Rehabilitation Using FRP Composite Laminates

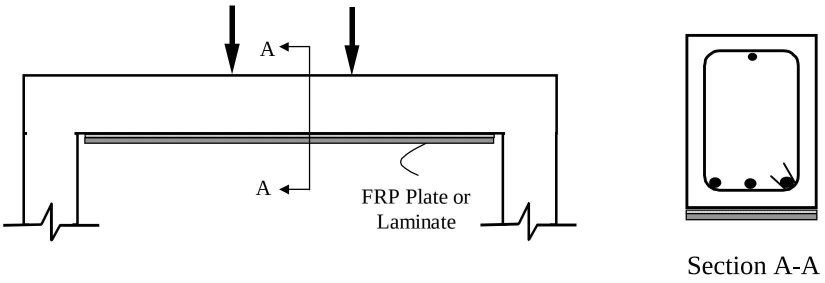
Rehabilitation of RC Beams

This application involves external bonding of FRP laminates on the tension face of the beam for flexural strengthening and/or the vertical faces of beams for shear strengthening as shown in Fig. 7. Initial developments in this area took place in Japan and was developed commercially in Switzerland [17].

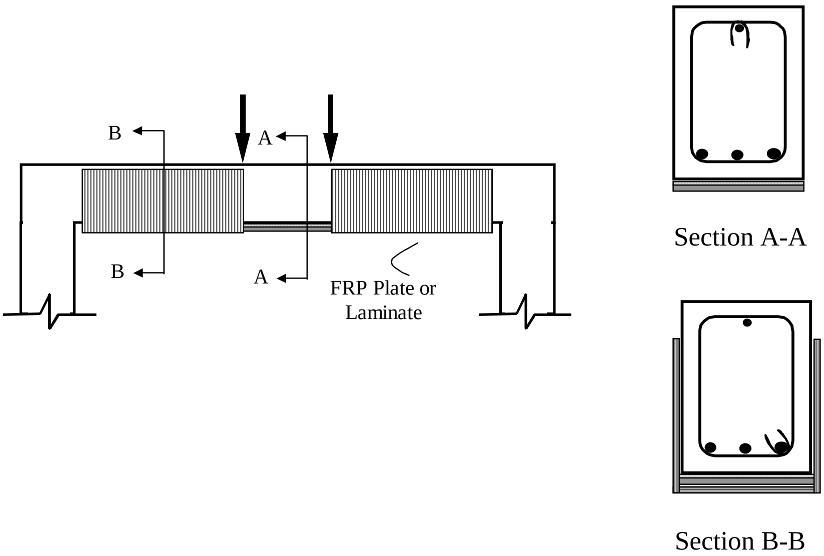
Meier [18] reported the use of thin CFRP sheets as reinforcement for flexural strengthening of concrete beams. In his work, he reported that CFRP can replace steel with overall cost savings in the order of 25%. Kaiser [17] tested CFRP composites applied to the tension side of full-scale reinforced concrete beams and the strain compatibility over the cross-section was verified. It was suggested that inclined cracking might lead to premature failure by peeling-off of the strengthening laminate. The study also developed an analytical model for composite plate anchoring, which was shown to be in agreement with test results.

Saadatmanesh and Ehsani [19] tested four simply supported beams that were internally reinforced by a single 9.5 mm diameter steel rebar and externally reinforced by epoxy bonded FRP laminates. It was noticed that by using a tough rubber epoxy with consistence cement paste, the test specimens reached an increase in ultimate load of 100% over the control beam and no cracks were observed up to 70% of the ultimate load. The failure was the result of delamination of a strip of concrete just above the bond line, a long the full length of the beam.

Triantafillou and Plevris [20] used the strain compatibility method, concepts of fracture mechanics, and an analytical model for the FRP peeling-off mechanism based on the shearing dowel actions of both the steel reinforcement and the FRP plate, to study the short-term flexural behavior of reinforced concrete beams strengthened with FRP laminates. The analytical results of failure mechanisms and corresponding loads were validated through a series of experiments employing thin CFRP laminates.



(a) Flexural strengthening



(b) Flexural and shear strengthening

Fig. 7 Rehabilitation of beams with FRP laminates

Spadea et al. [21] investigated the influence of end anchorage on the strength and ductility of concrete beams strengthened with bonded FRP plates. The researchers observed that without using end anchorage to the plate, the benefit of increasing the strength is counteracted by the undesirable brittle failure caused by the plate debonding. The researchers suggested that for the composite materials to be effectively and efficiently utilized, and for realization of cost effectiveness and structural reliability, a global design strategy that integrates material characteristics with structural performance has to be adopted.

Berset [22] performed a feasibility study on the use of composites to strengthen concrete beams in shear. It was concluded that bonding FRP plates to the vertical faces of reinforced concrete beams have a high potential as shear strengthening reinforcement. It was recommended that the composite plates should be reinforced bi-directionally, with a relatively high fiber volume fraction in the direction perpendicular to potential shear cracks in the concrete (at approximately 45°). Tests on beams strengthened in shear with various area fractions of GFRP showed a consistent increase in strength, stiffness, and ductility with increase in composite area fraction. A major failure mechanisms observed in these tests was buckling and delamination of the plate portion extending into the compression zone, indicating that full use of the composite strength can hardly be achieved.

Al-Sulaimani et al. [23] tested sixteen simply supported reinforced concrete beams to study the effectiveness of the use of FRP laminates in improving the shear capacity of beams. FRP laminates were externally bonded to the webs and the tension side of the beams. The beam specimens were designed to have a deficiency in shear capacity. Prior to strengthening, the beams were damaged to a predetermined load level. Test results show that the use of composite laminates not only effectively restored stiffness of the degraded beam but also increased it beyond the pre-loading stage.

Sharif et al. [24] conducted experimental work to study the effect of repairing of initially loaded reinforced concrete beams using FRP plates. The RC beams were loaded up to 85% of their ultimate flexural capacity before repairing. It was concluded that initially cracked beams can develop their ultimate load capacity by repairing them with FRP plates. It was also noticed that the repaired beams developed enough ductility although the FRP plates are brittle.

Sato et al. [25] studied the shear reinforcing effect of CFRP sheets attached to the sides of RC beams with and without stirrups. Experimental parameters were the location and amount of CFRP and amount of stirrups. The results indicated that CFRP significantly increased the shear strength of most of the tested specimens; especially CFRP sheets attached to three faces of beam (side-bottom-side) was effective. The failure mode with delamination of CFRP along a shear crack was observed in specimens without stirrup. A model for predicting the shear reinforcing effect of CFRP was also proposed.

Bazaa et al. [26] tested a series of beams strengthened with CFRP laminates. The objectives of their study were optimization of the length and orientation of CFRP reinforcement to attain increased beam strength and ductility, evaluation of the shear stress at the interface between the laminate and concrete and establishment of the anchorage length of the laminates. The results provide good indication on possible ways to optimize the design of beams reinforced with CFRP laminates.

Nanni et al. [27] proposed a design procedure for RC flexural members strengthened with FRP laminates. The model is based on ultimate state and employs the classical failure mode of yielding of steel followed by concrete crushing or FRP rupture. Acceptable stress levels in all the materials at working loads and deflection were studied and the residual stresses were also accounted for.

Alsayed et al. [28] tested thirty-six simply supported RC beams to study the effectiveness of the use of GFRP laminates in improving the flexural capacity of beams. GFRP laminates were externally bonded to the tension side of the beams. The behavior was presented in terms of load-deflection, load-strain, failure patterns and structural ductility. In addition to that, different anchorage systems were considered. All beams showed a considerable increase in ultimate load capacity (10 to 40%) with a good energy absorption capability. Strengthening of existing concrete beams is particularly effective when the internal steel reinforcement ratio is relatively low. Almusallam and Al-Salloum [29] used GFRP and CFRP laminates to strengthen eighteen simply supported RC beams with $\rho = 0.384\ \rho_{max}$. In this case, a considerable increase in ultimate load capacity (100 to 200%) was recorded.

Al-Salloum et al. [30] studied the shear reinforcing effect of continuous and strip GFRP laminates bonded to the sides or sides and bottom of RC beams. The beam specimens were designed to have a deficiency in shear capacity. The results indicated that GFRP strips increased the shear strength of the tested specimens by about 10%; and GFRP continuous laminates increased the shear strength of the tested specimens by about 50%. The continuous GFRP laminates contributed significantly in delaying the yield of stirrups and the shear failure. In other words, the FRP composites can increase the shear capacity of a beam such that the failure mode can be changed from a pure brittle shear to a gradual ductile flexural failure.

Rehabilitation of RC Columns

It is well known that concrete expands laterally due to the Poisson's effect before failure. If the lateral expansion is prevented, a substantial concrete strength and deformation enhancement will be attained.

Several tests were performed to assess the effectiveness of the use of GFRP or CFRP laminates for increasing the strength and flexural ductility of rectangular and circular columns reinforced with steel reinforcement and subjected to monotonic, cyclic flexural loading [31-34]. The main target in the studies was the use of FRP composite jackets to enhance the structural performance of RC columns. Some of the techniques used are [34]: 1) wet winding, 2) wet lay-up, 3) winding of prepreg laps, 4) lay-up tapes, 5) adhesive bonding of prefabricated shells of in situ resin infusion of jacket, and 7) the use of composite cables wrapped around the concrete core.

Saadatmanesh et al. [32] conducted several experiments to study the seismic behavior of reinforced concrete columns strengthened with fiber composite straps. Ten concrete column-footing assemblages were constructed with a 1/5 dimensional scale factor. The unidirectional composite straps were impregnated with epoxy resin and wrapped around the plastic hinge zone of the columns. All specimens were tested under inelastic reversal loading under a constant axial load. Test results showed that the seismic resistance of retrofitted columns was improved significantly due to the confining action provided by the composite straps, which prevented the longitudinal reinforcement bars from buckling during an earthquake load.

Mirmiran et al. [35] discussed how FRP materials significantly enhance the strength, ductility and durability of concrete columns. The longitudinal fibers serve as flexural reinforcement, while hoop fibers provided confinement and shear strength. Analytical and experimental studies indicated higher compression and flexural strength as well as excellent pseudo-ductile characteristics. A new confinement model was proposed to quantify the gain in strength of column, which was confined with FRP materials. Test results indicated that the strength of a fiberglass/epoxy tube with 3-mm thickness filled with concrete is about triple the strength of a standard concrete cylinder.

A model to assess the strength of concrete externally confined with FRP composites was proposed by Alsayed et al. [36]. A modification to the existing ACI Equation was suggested for determining the capacity of confined RC columns. A considerable reduction in the confined concrete strength for large size or full size specimen was observed.

Most of these studies have shown that wrapping the columns with FRP laminates helps in mitigating the deficiency associated with inadequate transverse reinforcement and lap-splice length, and greatly increases not only their ductility, but also their shear resistance. It was also reported that enhancing the confinement through FRP wrapping turns both the shear and bond failure into a ductile one, prevents buckling of longitudinal bars, and increases the longitudinal bar strains corresponding to the ultimate load. Furthermore, the studies revealed that the efficiency in improving the structural performance of the columns due to FRP wrapping is highly affected by column's shape (e.g. circular versus rectangular) and the degree of confinement which, in turn, is influenced by the type and thickness of composites and the intensity of the applied axial load.

Some of the other noteworthy features of rehabilitating column using FRP laminates, includes: 1) Flexibility of the FRP straps: FRP straps are flexible and can be easily shaped into the actual shape of the columns; 2) Uniform confinement: unlike the confinement provided by the ties, straps provide uniform confinement along the periphery of the column that includes the concrete cover; 3) Aesthetics: the laminates are very thin and, therefore, they do not alter the appearance of the repaired part of the column. Sketches of column rehabilitation using FRP composites are presented in Fig.8.

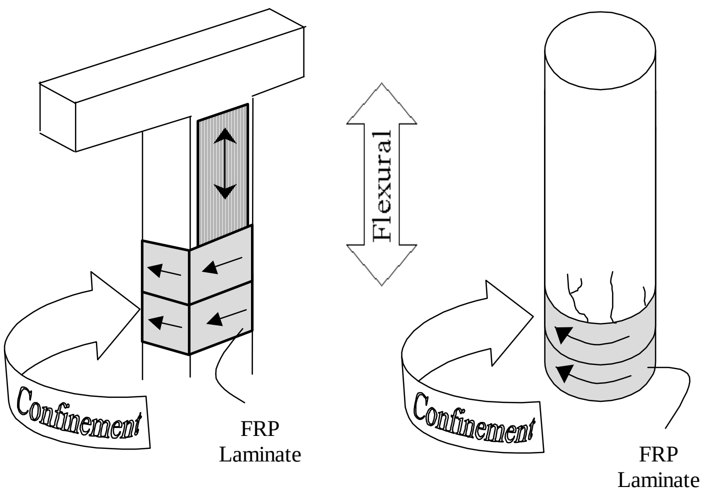


Fig. 8 Rehabilitation of columns with FRP composites

Rehabilitation of Walls

Another application of FRP strengthening is in the area of concrete walls or masonry structures. Unreinforced masonry (URM), or plain masonry, comprises the largest type of construction in existence worldwide. Due to lower tensile and shear capacity, URM buildings can be severely damaged when they suffer foundation settlement, blast loading, or earthquake forces.

A thin laminate of composite materials bonded to the exterior or interior surface of the walls integrates the individual brick elements in to a unified structural member. The high tensile strength of composite can be utilized to significantly increase the shear and flexural capacity of URM members (Fig. 9).

Tests on URM beams have demonstrated that with proper design, it is possible to attain full capacity of masonry at failure, and sustain large deflection before the ultimate capacity of the strengthened system is reached [37].

Schwegler [38] conducted one of the early studies on the use of CFRP laminates as seismic strengthening elements of masonry structures. The laminates were epoxy-bonded to the masonry surface, serving the role of tensile reinforcement. The results of this study demonstrated the effectiveness of this technique using full-scale, in-plane and out-of-plane, cyclic testing of one-story masonry walls. An analytical model for the in-plane behavior of CFRP-strengthened walls within the framework of stress fields theory was developed. One of the first field applications of this technique to some of the load-bearing walls was on a six story-residential building in Zurich [39].

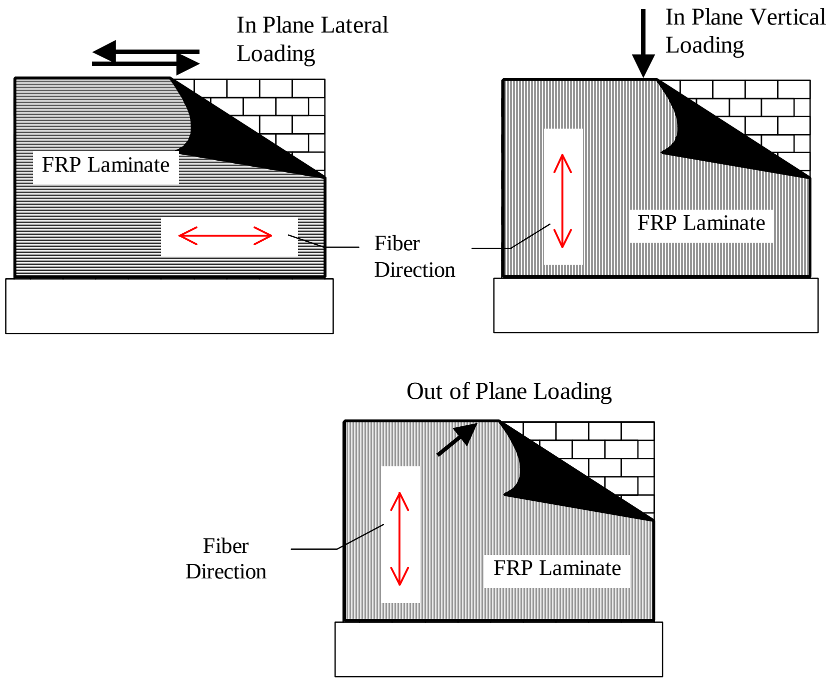


Fig. 9 Rehabilitation of walls with FRP composites

The work of Saadatmanesh [40] and Ehsani [41] focused on experimental studies (involving monotonic static tests) conducted on unreinforced masonry specimens strengthened with glass/Epoxy composite laminates. This technique was used at the field on external wall of a one-story commercial building in California. The building was severely damaged by the Northridge earthquake (magnitude of 6.7). From all the contending methods, this rehabilitation technique was selected for its cost-effectiveness. It was also reported that this system satisfied health, environmental, and fire safety requirements of the city engineer office.

Triantafillou [42] studied the application of unidirectional FRP in strengthening of masonry monuments. The materials were applied in the form of either externally applied circumferential tendon to provide horizontal confinement, or laminate, which were epoxy-bonded to the facades of masonry buildings to serve as tensile reinforcement. In another study, Triantafillou [43] presented a systematic analysis for the short-term strength of masonry walls, strengthened with externally bonded FRP laminates, under monotonic out-of-plane bending, in-plane bending and in-plane shear, all combined with axial load, within the framework of modern design codes (e.g. Eurocode No. 6 [44]). The results were presented in the form of both design equations and interaction diagrams. His results showed that: (a) in situations where plane bending response dominates, as in the case of low axial loads in upper story levels, the bending capacity increases significantly; (b) in case of in-plane bending where high area fractions of reinforcement are placed near the high-stress zones the strength increases considerably regardless of the axial load; and (c) in case of FRP-strengthened walls the in-plane shear capacity increases only under low axial loads.

Almusallam et al. [45] tested URM walls to investigate the capability of GFRP laminates in strengthening walls when subjected to out-of-plane and in-plane flexural and shear stresses. Six masonry walls were tested after the composite retrofit. Two of the walls (flexure specimens) were loaded with out-of-plane bending, and four of the walls were subjected to in-plane loading (shear specimens). A significant strength increase was observed for all strengthened shear and bending specimens. Failure occurred for most of the cases due to either compression failure of bricks or due to wall damage in the anchor area specially for shear specimens.

In general, FRP laminates are capable of transferring the masonry wall from a one with individual bricks to another wall with full integrity, and diminish the danger of falling debris from the damaged building. Walls that are strengthened with FRP laminates can resist lateral and vertical in-plane shear stresses and out-of-plane flexural stresses. However, the resistance is function of the geometry of the wall and the properties of the FRP laminates.

Rehabilitation of Pipes

Steel, concrete and PVC pipes form a major part of infrastructure. They are heavily used in chemical and other industrial plants, oil transmission lines, water system, waste treatment plants, sewage or process plants, steel gas pipelines, and chimneys. Just as other parts of infrastructure, pipes are suffering from deterioration for the same reasons cited earlier in this paper. In many cases, these pipelines, which operate under high pressures, cannot be repaired by traditional methods such as welding steel plate to them. FRP straps can be wrapped around the pipes in several layers in and around the weakened locations to significantly increase the strength of the pipes as shown in Fig. 10. Pipes above ground level can be rehabilitated using the same technique that is used for columns. However, for buried ones repairs need excavation, removal of the damaged part of concrete and steel around the pipe, placing new steel tendons and placing concrete or shotcrete over the damaged part. Unfortunately, repairing by such technique, although provides acceptable results at least for a short period of time, it does not warrant integral action of the new and old materials. This is simply because there is an interfacial or dimensional variation caused by shrinkage and temperature changes. Such variations are regarded as the main cause of the interfacial stresses between the new and old concrete [46].

In the Middle East, due to the high rate of corrosion, pipes of the firewater and the cooling system of offshore oil platforms corroded fast enough to warrant repair or replacement within eight month of their installation [47]. Similar situation was faced by other oil industry in Europe [48,49]. The oil industry considered remedial approach to this problem by using composites for repair or total replacement with fiber reinforced epoxy-piping system.

In Japan [50] some of the chimneys that were damaged by earthquake were rehabilitated using CFRP prepreg material and the concept of bridge column retrofitting. Due to the vast number of damaged chimneys and their height, an automated wrapping machine was developed to do the wrapping. However, scaffolding technique can be used when the cost of automatic machine is not justified.

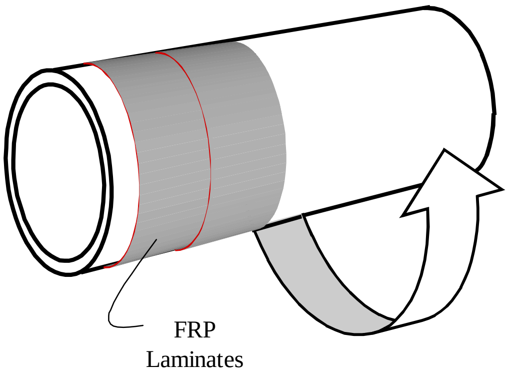


Fig. 10 Rehabilitation of pipes with FRP composites

Investment in the Rehabilitation

Traditionally there has been a trend toward demolition and reconstruction option when the structure shows, to some extent, unacceptable size of deterioration. However, in recent years, for economical as well as cultural reasons, there has been a shift in attitude with greater attention being devoted to the rehabilitation option. In other words, even if the structure reaches its service life (which may be reduced which is due to numerous unpredictable factors), the decision of replacing such a structure may not be immediately taken. There is always a chance in extending its service life. This is particularly the case due to the new advances made in composite materials. Because of this, there is a clear trend toward investing in developing and implementing new techniques in rehabilitation process.

In this country, hundreds of billions of Saudi Riyals were spent in constructing the infrastructure. Unfortunately the major part of the infrastructure, especially that built during the boom years, was constructed in the absence of national code or code of practice and lack of good engineering supervisions. As a result, the number of buildings, bridges, pipelines, and other parts of the infrastructure that is in need of repair, and/or strengthening is enormous and the list is growing rapidly every day. Great deal of the national economy will be saved from the success of utilization of this new technique to rehabilitate the infrastructure.

Conclusions

FRP composite materials have been recently introduced to the civil engineering community. Three types of fabrics are currently produced commercially. Namely Glass Composites, Carbon Composites and Aramid Composites. These materials are durable, have long fatigue life and have a superior resistant to corrosion and chemical attack. They have high strength-to-weight ratio. Composites are easy to handle in the field and pliable enough to configure to the shape of structure under rehabilitation. Composites are versatile and adaptable to almost any shape and size. Furthermore, considering the fact that in repair and strengthening work, labor and operational costs often far outweigh material costs, low weight of FRPs substantially reduces labor costs, which usually attain 80% of the total operational costs. Therefore, it is strongly believed that significant savings could be attained from successful utilization of the new technique of rehabilitation of the infrastructure. Examples of field applications that will directly benefit from such work include, but are not limited to:

1) Repair problems associated with design and construction errors, lack of supervision, low quality assurance, and bad infrastructure construction practice.
2) Strengthening of different parts of structures that are subjected to unpredictable overloads during their service life. These include foundation settlement and those resulting from the deviation of as-built structures from the design intent.
3) Augmenting of the existing capacity of the structural elements to meet the increased demands of new standards or higher traffic loads.
4) Upgrading the capacity of the industrial parts such as pipes to meet the new expansion plans.
5) Providing quick and effective solution in assuring integral function of the old and new parts of the structure.

References

[1] Klaiber, F.W., Dunker, K.F., Wipf, T.J., and Sanders, W.W.J., "Methods of Strengthening Existing Highway Bridge," NCHRP Research Report No. 293, Transportation Research Board, Sept. 1986, 114 pp.

[2] Kent, D.C., and Park, R., “Flexural Members with Confined Concrete,” J. of the Structural Engineering Division, ASCE, Vol. 97, No. ST7, July 1971, pp. 1969-1990.

[3] Fickelhorn, M., (Editorial), “Material and Structures,” RILEM, Vol. 23, No. 137, Sep. 1990.

[4] Chong, K.P., “Durability of Composite Materials and Structures,” Proceedings of the First International Conference on Durability of Fiber Reinforced Polymer (FRP) Composites for Construction (CDCC’98), Sherbrooke, Quebec, Canada, 5-7 Aug. 1998, pp. 1-12.

[5] McKenn, J.K., and Erki, M.A., “Strengthening of Reinforced Concrete Flexural Members Using Externally Applied Steel Plates and Fiber Composite Sheets,” Canadian Journal of Civil Engineering, Vol. 21, 1991, pp. 16-24.

[6] Clarke, J.L., “Non-Ferrous Reinforcement for Structural Concrete,” Proceedings of the International Conference: Economic and Durable Construction through Excellence, The University of Dundee, Scotland, UK, September 1993, Vol. I, pp. 229-238.

[7] Dritsos, S.P. and Kotsira, E., “Effectiveness of Flexural Strengthening of RC Members,” Journal of Construction and Building Materials, Vol. 9, No. 3, June 1995, pp. 165-172.

[8] Etman, E.E, “Repair of Concrete Beams Using Carbon Fibre Reinforced Polymer Composite,” PhD Dissertation, University of Leeds, UK, 1999.

[9] Cairns, J., “Alternate Strategies for Temporary Support During Structural Repair of Reinforced Concrete Beams,” Journal of Structural Engineering, March 1996, pp. 238-246.

[10] Moussa, M., Tarkhan, M., Helmy, S. and El-Sanadely, H., “Repair and Strengthening of Partially Loaded RC Beams,” Proceedings of the First International Conference on Civil Engineering, Volume 2, Cairo, Egypt, 1998, pp. 315-328.

[11] Swamy, R.N., and Jones, R., "Behaviour of Plated Reinforced Concrete Beams Subjected to Cyclic Loading During Glue Hardening,” Int. J. Cement Composites, 1, No. 4, Nov. 1983, pp. 233-234.

[12] Jones, R., Swamy, R.N., and Charif, A., "Plate Separation and Anchorage of Reinforced Concrete Beams Strengthened by Epoxy-Bonded Steel Plates,” The Structural Engineer, 66, No. 5, 1 March 1988, pp. 85-94.

[13] Calder, A.J.J, “Exposure Tests on Externally Reinforced Concrete Beams – First Two Years,” Transport and Road Research Laboratory, Crowthorne, England, Report SR 529, 1982.

[14] Lloyd, G.O., and Calder, A.J.J, “The Microstructure of Epoxy Bonded Steel - to - Concrete Plates,” Transport and Road Research Laboratory, Crowthorne, England, Report SR 705, 1982.

[15] Meier, U., and Kaiser, H., “Strengthening of Structures with CFRP Laminates,” Proceedings of the Speciality Conference: Advanced Composite Materials in Civil Engineering Structures, ASCE, 1991, pp. 224-232.

[16] Alsayed, S.H., Al-Salloum, Y.A., and Almusallam, T.H., "Fibre-Reinforced Polymer repair Materials – Some Facts”, Civil Engineering - Journal of the Institution of Civil Engineers, Vol. 38, August 2000, pp. 131-134.

[17] Kaiser, H., “Strengthening of Reinforced Concrete with Epoxy Bonded Carbon-Fiber Plastics,” ETH-Dissertation No. 8918, ETH Zurich, CH8092 Zurich, Switzerland.

[18] Meier, U., “Bridge Repair with High Performance Composite Materials,” Material and technik, Vol. 15, 1987, pp. 125-128. (In German).

[19] Saadatmanesh, H. and Ehsani, M.R., "Fiber Composite Plates can Strengthen Beams,” Concrete International, Vol. 12, No. 3, 1990, pp. 65-71.

[20] Triantafillou, T.C. and Plevris, N., "Flexural Behavior of Concrete Structures Strengthened with Epoxy-Bonded Fiber Reinforced Plastics,” International Seminar on Structural Repairs/Strengthening by the Plate Bonding Technique, Univ. of Sheffield, England, Sept. 1990.

[21] Spadea, G., Bencardino, F., and Swamy, N., “Strengthening and Upgrading Structures with Bonded CFRP Sheets Design Aspects for Structural Integrity,” Proceedings of the Third International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures, Sapporo, Japan, 14-16 Oct. 97, Vol. 1, pp. 629-636.

[22] Berset, J.D., "Strengthening of reinforced concrete structures for shear using composite materials,” Thesis submitted to the Massachusetts Institute of Technology, in Partial Fulfilment of the Requirements for the Degree of Master of Science, 1992.

[23] Al-Sulaimani, G.J., Sharif, A., Basunbul, I.A., Baluch, M.H., and Ghaleb, B.N., "Shear Repair for Reinforced Concrete by Fiberglass Plate Bonding," ACI Structural Journal, Vol. 91, No. 3, July-August 1994, pp. 458-463.

[24] Sharif, A., AL-Sulaimani, G.J., Basunbul, I.A., Baluch, M.H., and Ghaleb, B.N., "Strengthening of Initially Loaded Reinforced Concrete Beams Using FRP Plates," ACI Structural Journal, March-April 1994, pp. 160-168.

[25] Sato, Y., Ueda, T., Kakuta, Y., and Tanaka, T., "Shear Reinforcing Effect of Carbon Fiber Sheet Attached to Side of Reinforced Concrete Beams," Proceedings of 2nd International Conference on Advanced Composite Materials in Bridges and Structures (ACMBS' 96), Montreal, Quebec, Canada, August 11-14, 1996, pp. 621-628.

[26] Bazaa, I., Missihoun, M., and Labossieve, P., "Strengthening of Reinforced Concrete Beams with CFRP Sheets," Proceedings of the 1st International Conference on Composites in Infrastructures (ICC'96): Fiber Composites in Infrastructure, Tucson, Arizona, USA, 15-17 January 1996, pp. 746-759.

[27] Nanni, A., Focacci, F., and Cobb, C.A., "Proposed Procedure for the Design of RC Flexural Members Strengthened with FRP Sheets," Proceedings of the Second International Conference on Composites in Infrastructures (ICC'98): Fiber Composites in Infrastructure, Tucson, Arizona, USA, 5-7 January 1998, Vol. 1, pp. 187-210.

[28] Alsayed, S.H., Al-Salloum, Y.A., and Almusallam, T.H., "Rehabilitation of the Infrastructure Using Composite Fabrics", Third Progress Report - Research project AR-16-52, King Abdulaziz City for Science and Technology (KACST), 2002, Riyadh, Saudi Arabia.

[29] Almusallam, T.H. and Al-Salloum,Y.A., "Ultimate Strength Prediction for RC Beams Externally Strengthened by Composite Materials", Journal of Composites: Part B Engineering,32, 2001, pp. 609-619.

[30] Al-Salloum, Y.A., Almusallam, T.H. and Alsayed, S.H., "Contribution of Externally-Bonded FRP Sheets to the Shear Capacity of RC Beams", Proceedings of the ICPIC Tenth International Congress on Polymers in Concrete, 21-24 May 2001, Honolulu, Hawaii.

[31] Saadatmanesh, H., Ehsani, M.R., and Li, M.W., "Strength and Ductility of Concrete Columns Externally Reinforced with Fiber Composite Straps," ACI Structural Journal Vol. 91, No. 4, 1994, pp. 434-447.

[32] Saadatmanesh, H., Ehsani, M.R., and Lin, J., "Behavior of Concrete Columns Retrofitted with Fiber Composite Straps under Cyclic Loading," Proceedings of the First International Conference on Composites in Infrastructures (ICCI '96): Fiber Composites in Infrastructure, Tucson, Arizona, USA, 15-17 January 1996, pp. 842-856.

[33] Saadatmanesh, H., "Wrapping with Composite Materials," Proceedings of the Second International RILEM Symposium (FRPRCS-2): Non-Metallic (FRP) Reinforcement for Concrete Structures, Edited by L. Taerwe, Ghent, 23-25 August 1995, pp. 593-600.

[34] Karbhari, V.M. and Seible, F., "Durability and Systems Level Design Guidelines for the Use of Fiber Reinforced Composite Reinforcement in Civil Infrastructure," Proceedings of the Third International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures, Sapporo, Japan, 14-16 Oct. 97, Vol. 1, pp. 191-198.

[35] Mirmiran, A., Kargahi, M., Samaan, M., and Shahawy, M., "Composite FRP-Concrete Column with Bi-Directional External Reinforcement," Proceedings of the 1st International Conference on Composites in Infrastructures (ICC'96): Fiber Composites in Infrastructure, Tucson, Arizona, USA, 15-17 January 1996, pp. 888-902.

[36] Alsayed, S.H., Al-Salloum, Y.A., and Almusallam, T.H., "Rehabilitation of the Infrastructure Using Composite Fabrics", Fourth Progress Report - Research project AR-16-52, King Abdulaziz City for Science and Technology (KACST), Dec. 1999, Riyadh, Saudi Arabia.

[37] Ehsani, M.R., Saadatmanesh, H., Abdelghany, I.H., and Elkafrawy, W., "Flextural Behavior of Masonry Walls Strengthened with Composite Fabrics," Proceedings, ACI International Symposium of Non-Metallic Continuous Reinforcement, Vancouver, Canada, 1993, pp. 497-507.

[38] Schwegler, G., “Strengthening of Masonry with Fiber Composites,” Doctoral thesis, Federal Institute of Technology, Zurich, 1994 (in German).

[39] Schwegler, G. and Kelterborn, P., "Earthquake Resistance of Masonry Structures Strengthened with Fiber Composites," Ernst Basler & Partners Ltd., Internal Report, 1996.

[40] Saadatmanesh, H., "Fiber Composite for New Existing Structures,” ACI Structural Journal, Vol. 91, No. 3, 1994, pp. 346-354.

[41] Ehsani, M.R., “Strengthening of Earthquake-Damaged Structures with Composite Materials,” Proceedings of the Second International RILEM Symposium (FRPRCS-2): Non-Metallic (FRP) Reinforcement for Concrete Structures, Edited by L. Taerwe, Ghent, Belgium, 23-25 August 1995, pp. 616-623.

[42] Triantafillou, T.C., "Innovative Strengthening of Masonry Monuments with Composites,” Proceedings of 2nd International Conference on Advanced Composite Materials in Bridges and Structures (ACMBS' 96), Montreal, Quebec, Canada, August 11-14, 1996, pp. 473-480.

[43] Triantafillou, T.C., "Strengthening of Masonry Structures Using Epoxy-Bonded FRP Laminates,” Report Prepared at University of Patras, Patras, Greece, 1996.

[44] Eurocode No. 6, “Design of Masonry Structures,” Comite’ Euro-International du Be’ton, Lausanne, 1994.

[45] Almusallam, T.H., Al-Salloum, Y.A., Alsayed, S.H. and Mosallam, A.S. “Behavior of Unreinforced Masonry Walls Strengthened with FRP Composite Materials”, Proceedings of the SAMPE 2001 Symposium, Society for the Advancement of Material and Process Engineering, 6-10 May 2001, Long Beach, California.

[46] Granju, J.L., Pigeon, M., Grandhaie, F., Banthia, N., “Pavement Repairs with Non-Metallic Glass Fiber Reinforced Concrete: Laboratory and Field Studies of Durability,” Evaluation and Rehabilitation of Concrete Structures and Innovations in Design, Proceedings ACI International Conference, Hong Kong 1991, pp. 161-182.

[47] Aubert, C.F.P., “Use of GFRP Materials in Piping: The Experience of Total,” Materials Engineering Proceedings of International Conference on Offshore Mechanics and Arctic Engineering - OMAE, ASME, New York, NY, Vol. 3, 1993, pp. 279-283.

[48] Sundt, J.L., “ Fire Water System in Composite Materials,” Materials Engineering Proceedings of International Conference on Offshore Mechanics and Arctic Engineering - OMAE, ASME, New York, NY, 3, 1993, pp. 293-302.

[49] Winkel, J.D., “Maintenance and Cost Performance of Glass Fiber Reinforced Plastic Piping at Ekofisk,” Materials Engineering Proceedings of International Conference on Offshore Mechanics and Arctic Engineering - OMAE, ASME, New York, NY, V. 3, 1993, pp. 285-292.

[50] Ballinger, C., Maeda, T., and Hoshijima, T., “ Strengthening of Reinforced Concrete Chimneys, Columns and Beams with Carbon Fiber Reinforced Plastics,” ACI-SP 138, American Concrete Institute, 1993, pp. 233-248.