SEISMIC RETROFIT OF REINFORCED CONCRETE BRIDGES WITH FIBER REINFORCED POLYMER COMPOSITES: STATE-OF-THE-ART REVIEW

Zahra Riahi[1] and Farzad Faridafshin[2]

[1] *MASC in Earthquake Engineering, Energy and Infrastructure Division, Sandwell Engineering INC, Vancouver, BC, Email: zriahi@sandwell.com*
[2] *MASC in Structural Engineering, Concept and Technology Department, Aker Solutions, Bergen, Norway, Email: Farzad.Faridafshin@akersolutions.com*

ABSTRACT:

This state-of-the-art manuscript addresses seismic retrofit of deficient reinforced concrete (RC) bridges whose vulnerability has been demonstrated repeatedly in previous seismic events. A class of high performance materials, Fiber Reinforced Polymer composites (FRP), with versatile applications in repair and rehabilitation has been used for this purpose.

Mechanical and durability properties of externally bonded FRP's, their merits over conventional materials and retrofit techniques, general seismic flaws and failure modes, and the effects of FRP wraps on the seismic performance of lateral load resisting components of RC bridges are investigated, and practical solutions which help improve the efficacy of FRP's are proposed.

KEYWORDS: Seismic Retrofit, RC Bridge, Fiber Reinforced Polymer Composite

1. INTRODUCTION

Fiber reinforced polymer resins, as we know them today, were first introduced in 1940s. The broad use of FRP's in almost every field from aerospace to civil engineering can be attributed primarily to the superior characteristics they have compared to conventional materials.

The application of FRP's is becoming increasingly common in the construction of new structures (e.g. bridge decks, and towers). However, since deterioration and functional deficiency of existing civil infrastructures represent one of the struggling challenges of the world of today, these high performance materials are also vastly used for repair and strengthening of existing structures. Rehabilitation of existing structures alone, as statistical results indicate, comprises 46% of the overall use of FRP composites (Keller, 2003). The technology of external retrofitting was first developed in Japan (sheet wrapping) and Europe (laminate bonding) and USA took upon afterwards. FRP's are normally used in the form of sheets, plates, and prefabricated shells as externally bonded repair materials, and different procedures may be used for their production. The fabrication procedure together with curing conditions and installation process greatly influence the properties and functionality of the final product, and therefore should be performed under close supervision (Pantelides et.al. (2004)).

This study addresses merely seismic retrofit of RC bridges and other applications of FRP composites are out of its scope. The main objectives here are: to examine the mechanical and durability characteristics of FRP materials from the rehabilitation stand point; to investigate the merits of FRP wraps over conventional materials and other retrofit techniques; to investigate the flaws that seismically deficient RC bridges suffer from and the effects of FRP retrofitting on them; and to identify the key factors influencing the efficacy of externally bonded FRP wraps.

2. FIBER REINFORCED POLYMERS

2.1. Mechanical properties and components

The use of fiber reinforced polymers dates back to the application of straws as reinforcement in bricks in 800 B.C. (Tang (1997)). FRP's are composed of four different components: fibers, resins, fillers, and additives. Each of these components is responsible for some of the characteristics that the final product must have. The type and content of each component can be tailored for specific properties and this makes FRP's flexible and versatile.

Fibers are the primer load imparting components, and as the results of experimental tests indicate, the mechanical properties of the composite (e.g. tensile strength, and elastic modulus) are driven by the type, content, architecture (textile configuration), and the orientation of the fibers (Saadatmanesh et.al.(1997),Tang (1997)). As experimental results suggest, tensile strength of an individual fiber is significantly higher than that of the composite. The elastic modulus also differs for various orientations, with 0° being the best angle (i.e. loads parallel to the longitudinal axis of fibers). Due to the dominance of resin characteristics, the lowest elastic modulus, however, is achieved at 90° (Narris et.al. (1997)). The dependence of FRP elastic modulus on fiber orientation, as is evident from Figure 1, makes this class of materials anisotropic in nature (Karbhari and Seible (2000)). This figure also suggests the use of fibers parallel to the loading direction for structural components that should withstand enormous loads. However, where high ductility is required, the application of angled fibers seems to be a better solution.

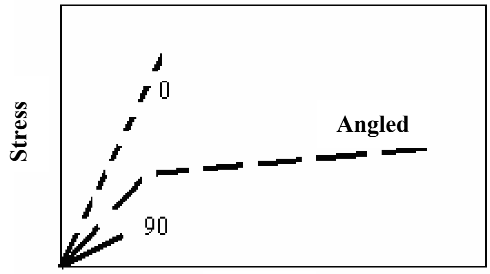

Figure 1 : The influence of fiber orientation on mechanical characteristics of the composite

Carbon, aramid, glass, and polyvinyl alcohol are the most common fiber types for various applications. Carbon fibers with three grades: high-strength, high-modulus, and ultra- high modulus are the most frequent fibers for civil engineering applications (Tang (1997)). As elasticity modulus of carbon fibers increases, the strain capacity declines, and this makes ultra-high modulus carbon fibers unsuitable for repair and strengthening purposes. This is of paramount importance for regions of high stress concentration where brittle failures would adversely affect the performance of the structure. This problem, however, may be solved by combination of carbon fibers with relatively low- modulus glass fibers (hybrid effect). At the fracture of carbon fibers, loads are transferred to the glass fibers with more deformation capacity (Keller (2003)). Glass fibers are also categorized in three groups: E-glass, S-glass, and C-glass, with the first group being the most common type for civil applications. What makes glass fibers even more favorable is high strength to cost ratio and the excellent creep and fatigue resistance they have. However, strength and stiffness degradation of glass fibers over time and under environmental effects should be taken into consideration when selecting other composite components in order to minimize such effects.

Kevelar-29 and Kevelar-49 are the most frequent types of aramid fibers for civil engineering applications. Aramid, unlike the two aforementioned fiber types, suffers from a low compressive to tensile strength ratio (Keller (2003)). This makes aramid fibers almost inefficient when subjected to cyclic loading especially when aramid reinforced polymers are used as vertical braces or at joints.

Owing to their low tensile strength and elastic modulus, polyvinyl alcohol is not used for civil applications, and therefore its characteristics are not discussed herein.

Density, elastic modulus, tensile strength, and elongation properties of fibers are listed in Table 1.

In the light of the above information, it is clear that the application and performance criteria should be taken into account when selecting the fiber type. One type that is suitable for a particular application or environmental condition might completely fail to satisfy the requirements of another retrofit project.

Table 1: mechanical characteristics of fibers (Tang (1997))

Properties/ Fiber Type	E-glass	Kevlar-29	Kevlar-49	High-Strength Carbon	High-Modulus Carbon
Density (g/cm^3)	2.60	1.44	1.44	1.80	1.90
Elastic Modulus (GPa)	72	83–100	124	230	370
Tensile Strength (GPa)	1.72	2.27	2.27	2.48	1.79
Elongation (%)	2.4	2.8	1.8	1.1	0.5

In general, fibers take up 30% to 70% of the composite volume (Tang (1997)). Increasing the fiber content (V_f), as is clear from Figure 2, raises the stiffness without changing the strain capacity, provided the resin is capable of connecting fibers effectively.

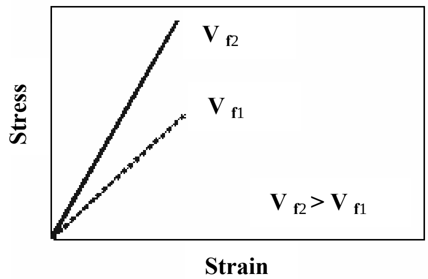

Figure 2: The effect of fiber content on elastic modulus (Saadatmanesh et.al. (1997))

Resins provide the mechanism for load transfer between the fibers and are responsible for composite compressive strength. They also protect the fibers from environmental effects and buckling (Saadatmanesh et.al. (1997), Keller (2003)). Resins are classified into two major groups: thermoplastic resins melt when heated and solidify when cooled, thermoset resins, however, are irreversible, and therefore suitable for civil applications. Thermoset resins have three sub-categories: polyesters, epoxies, and vinyl esters. Polyesters are cost-effective and their application usually leads to a reliable dimensional stability, whereas high viscosity of epoxies makes them unsuitable for certain production processes (e.g. molding, and hand lay-up). Vinyl esters have high toughness and excellent corrosion resistance and are appropriate when such properties are demanded.

Owing to their viscoelastic behavior, resins are highly susceptible to creep and relaxation. However, when combined with appropriate amounts of fibers, which are responsible for creep and shrinkage control, they perform satisfactorily.

The characteristics of the unsaturated polyester, and epoxy, as the most frequent resin types for civil applications, are shown in Table 2. Application environment and the speed of fabrication are the key factors making one type superior to the other for a certain application.

Fillers are utilized to further enhance the mechanical and physical properties of the composites and to make the final product more economical. Provided in appropriate type and amount, fillers are capable of improving the FRP strength and toughness, and enhance fatigue, shrinkage, creep, and chemical resistance of the matrix (Tang (1997)). Additives also enhance some of the characteristics of the final product and are available in the form of catalysts, promoters, inhibitors, coloring dyes, and releasing agents.

Characteristics of individual composite components, compatibility, and adhesion between different materials are the key factors affecting the mechanical and physical properties of FRP's. To work effectively, fiber fracture should precede the development of micro cracks in the matrix (the weak phase). This is achieved by choosing a higher strain capacity for resins compared with fibers (Keller (2003)).

Table 2: Mechanical characteristics of resins (Keller (2003))

Properties/ Resin Type	Unsaturated Polyester	Epoxy
Density (g/cm^3)	1.2–1.3	1.2–1.3
Elastic Modulus (GPa)	2–3	2–4
Tensile Strength (MPa)	20–70	60–80
Elongation (%)	1–5	1–8
Glass transition temperature(ºC)	70–120	100–270

2.2. Durability

FRP composites are said to have acceptable durability against environmental effects. However, different types of fibers and resins are vulnerable to some of these effects, and should be chosen to suit the performance criteria of the application site. Almost all fibers and resins are inflammable, and should be protected against fire. Aramid fibers and resins are very sensitive to ultra violent (UV) radiations and would deteriorate when the composite product is exposed directly to the sun light. External application of FRP composites does not require high level of UV protection, provided FRP layers are used inside the structure or on its underside (Karbhari et.al. (2000)).

Among fibers, as test results and performance of FRP's suggest, carbon possesses the most superior durability characteristics. Aramid, in spite of great abrasion and chemical resistance, is very sensitive to UV radiation (Keller (2003)). Glass fiber is vulnerable to freeze-thaw and wet-drying effects and loses up to 20% of its initial strength when exposed to wet conditions. As a result, glass fibers are recommended to be used with vinyl ester or polyester resins with high water absorption resistance. Furthermore, glass fibers cannot resist acids and alkali effects, and therefore should be protected against these effects (Pantelides et.al. (2004)).

Different fibers behave differently in each environmental condition. However, composite durability is mainly driven by the characteristics of the matrix that is less durable than the reinforcing fibers (Keller (2003)). Epoxy resins, in general, indicate superior chemical resistance which may be altered by high-temperature conditions. The low water resistance of polyester resins, however, may be improved by reducing the density of ester and increasing the styrene content. Additives and fillers play a substantial role in resolving or improving some of the durability problems that FRP composites usually have.

One should bear in mind that many aspects of durability characteristics can only be determined by investigating the long-term performance of FRP's under different environmental conditions, and are still dubious. This would give rise to a higher uncertainty level compared to conventional materials as steel or concrete. Therefore, higher margins of safety should be incorporated in the design of FRP composites (Sheng (2001), Manfredi and Prota (2001)).

3. SEISMIC RETROFIT OF RC BRIDGES WITH FRP COMPOSITES

3.1. Merits and weaknesses of FRP application for seismic retrofit

Seismic vulnerability of bridges constructed prior to 1970s became evident in such seismic events as the 1987 Whittier Narrows, the 1989 Loma Prieta, and the 1994 Northridge earthquakes. This further stresses the need for seismic upgrade of deficient bridges which comprise a considerable portion of civil infrastructures worldwide. Current retrofit methods can be classified in four main categories: 1) thin layers of heavily reinforced concrete for increasing the size of the section, 2) pre-tensioned steel cables covered by thin layers of concrete, 3) steel jacketing; and 4) FRP composite sheets, plates, or shells.

Some of the most important merits of FRP application for seismic retrofitting compared with other conventional techniques are:

- High strength and stiffness to weight ratios: this makes FRP's one of the most suitable alternatives for seismic retrofit where extra weight means additional seismic demand.
- FRP wraps can be produced, handled, and installed easily and without any need for heavy machinery. Therefore, the installation causes minimal disruption to the traffic.
- Corrosion resistance of FRP composites not only is a great advantage on its own, but also it protects the inner reinforcement against further corrosion and volumetric changes (Karbhari (2004)).
- Conformity to any geometrical shape lends more flexibility to FPR materials.
- The mechanical and durability characteristics of FRP materials can be tailored for particular applications by choosing the fiber type, geometry, and the type of the polymer.
- FRP composites may be used for seismic retrofit of historical monuments that should not be covered with concrete or steel for historical considerations. In addition, FRP's don't change the dimensions, and therefore won't reduce the clear height of bridges.
- Although composite materials are susceptible to some environmental effects, they are still highly durable compared with other conventional materials. The reduced maintenance cost, as a result, somewhat compensates for their higher initial cost.
- FRP composites, in contrast to isotropic steel sheets, do not alter the stiffness of the component in other directions other than the orientation of fibers. This is crucially important for retrofit applications where enhancing the performance of one component should not pose additional risk to adjacent members.
- As experimental results suggest, if processed properly, FRP's would be as effective as other conventional retrofit methods in improving the seismic performance of deficient structural components.

FRP composites, however, have a few important disadvantages as follows:

- Design and construction needs highly trained specialists and large safety margins in order to compensate for material, fabrication, curing, and durability uncertainties.
- Composites are very sensitive to transverse actions (corners, and discontinuity effects) and are unable to transfer local shear (Manfredi and Prota (2001)). Furthermore, when subjected to cyclic loads, they do not function effectively in compression.
- Composite and concrete bond, and long-term durability of FRP's are of high concern. Therefore, the history of use should be considered for each specific retrofit project.
- FRP behavior is very process-dependent and is greatly influenced by the quality of the parent concrete. As a result, if designed and applied improperly, some problems as shrinkage, creep, and debonding may adversely affect their performance.

3.2. Installation process

Magnitude of interactive forces at the concrete-FRP interface, and long-term performance of the structure are highly influenced by the installation process (Schlick (2004)). The installation surface should be prepared prior to the application of FRP sheets. Removing delaminated concrete from the installation surface and replacing it with sound concrete, grinding the concrete surface and making sure it is dry, and applying the primer and putty to fill the pores of the concrete are some other installation considerations (Pantelides et.al. (2004)) Temperature stabilization during the curing process is also essential to avoid local stress concentration. The first FRP layer is usually applied after surface preparation and application of the adhesive. The second layer of adhesive is then applied over the FRP sheets and additional layers of FRP's may be installed in the same manner, afterwards.

3.3. Deficiencies

As the aftermaths of severe earthquakes indicate, piers of deficient RC bridges are common spots for damage concentration. In addition, bent caps and joints, which have substantial roles in keeping the structure together and helping it work integrally, would also experience some level of damage.

Piers: Insufficient transverse reinforcement is the most frequent seismic deficiency that piers of RC bridges suffer from. This deficiency not only reduces the shear resistance, but can also lead to a sharp decline in the level of core confinement. This flaw is of prominent importance for piers with high longitudinal to transverse reinforcement ratios (substantial flexural to shear capacity ratios). Insufficient lap splice length at the base of piers, not designed for earthquake lateral forces i.e. underestimation of reinforcement and improper detailing, and inadequate anchorage of pier longitudinal reinforcement are amongst the most critical problems that seismically deficient bridge piers suffer from. Performance observations during past severe earthquakes, in-situ examination of as-built bridges, and laboratory tests of deficient columns (Schlick (2004), Ma and Xiao (1999), Pantelides et.al.(2002)) suggest that such piers usually experience a brittle shear failure. Concrete spalling shortly after yielding of longitudinal reinforcement, debonding between concrete and longitudinal reinforcement and the subsequent slippage, buckling and destabilization of longitudinal reinforcement, and extensive shear cracks at the base of the columns usually characterize this non-ductile behavior. Some of these damage patterns are illustrated in Figure 3.

Figure 3: Insufficient transverse reinforcement in the plastic hinge zone and the subsequent extensive damage to the pier (Saadatmanesh et.al. (1997))

Bent caps: Being under-designed for earthquake-induced shear or flexural forces, reinforcement corrosion, delamination of concrete cover, extensive shear and flexural cracks, and formation of plastic hinges at the ends of the cap are the most evident characteristics of a deficient bent cap.

Joints: Failure of joints as spots of high stress concentration, although not important on its own, may result in structural discontinuity and trigger a brittle shear failure. This type of failure is usually attributed to the insufficient shear capacity of the joint. It should be kept in mind that seismic retrofit of piers and bent caps by

FRP wraps or any other method would increase the joint shear demand (Pantelides et.al. (1999)). Therefore, the initially appropriate joints might not be able to withstand the additional forces.

3.4. Retrofit methodology

To overcome the aforementioned seismic deficiencies, externally bonded FRP composites may be used to strengthen or repair the piers, joints, and bent caps to achieve a specific ductility. This ductility demand depends on the seismicity of the region, characteristics of the ground motions, local soil conditions, and structural properties of the deficient bridge. As a result, a specific FRP retrofit technique or the number of FRP layers cannot be directly applied to other similar bridges, because this might result in an unsafe or conservative design. Retrofit of piers, joints, and bent caps with FRP composites are discussed hereafter.

Piers: Depending on the type of deficiencies, FRP wraps might be used for plastic hinge confinement, lap splice clamping, shear strengthening, prevention of longitudinal reinforcement buckling, and to provide them with adequate anchorage.

FRP wraps confine the concrete and withstand a portion of hoop stresses. As experimental studies indicate, adequate core confinement substantially increases the ultimate strain and compressive strength of the concrete. Owing to their high tensile strength, FRP layers in the hoop direction would control the volumetric expansion of the concrete, thus inducing very large confinement stresses on the column concrete core.

Stress-strain curve of such a confined concrete, as shown in Figure 4, is bilinear due to the presence of biaxial stresses (Tian and Chaturvedi (2004)). As a result, concrete compressive strength would get raised and brittle concrete crushing will be delayed up to large load reversals. Since nonlinear response of the columns usually initiates in the plastic hinge zone, providing FRP layers in this region will also prevent the concrete cover from spalling and allow the yielded bars to experience larger strains. As the results of experimental tests indicate, longitudinal reinforcement experience strain hardening and rebar fracture usually precedes concrete crushing, provided the amount of FRP and its bond to the concrete substrate are sufficient (Schlick (2004)).

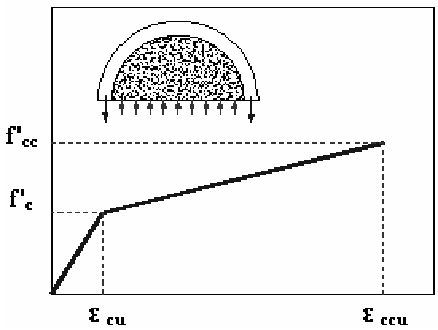

Figure 4: The effect of FRP confinement on the concrete stress-strain curve

Hoop stress division between FRP wraps and transverse reinforcement prevents yielding of insufficient stirrups at small deformations, and large load reversals would take place. Shear strengthening is usually required in the plastic hinge zone. However, for columns with insufficient shear capacity, adequate number of FRP layers should be provided over the entire length. When the rigidity of the FRP wrap is strikingly high compared to the parent concrete, a shift in the plastic hinge zone would adversely affect the pier seismic performance at large deformations (Schlick (2004)). Compatibility of FRP layers and concrete substrate, and/or providing the entire column length with sufficient FRP layers would avoid such a problem.

Due to their anisotropic nature, FRP wraps confine the concrete within the plastic hinge region without increasing the axial stiffness substantially, provided a practical gap is assumed between the wraps and column supports. However, if the flexural capacity of the deficient column is extremely low, both horizontal and vertical wraps should be used. Vertical wraps, in this case, should be adequately anchored into the column supports (Priestly et.al. (1996)).

Column confinement, stabilization of longitudinal reinforcement, preventing premature yielding of transverse reinforcement, and enhancing the bond between the concrete and longitudinal reinforcement would allow the column to achieve a higher energy absorption capacity and to behave in a ductile manner (Pantelides et.al. (1999), Yeh and Mo (2005)). Such a behavior is characterized by enhanced load and deformation capacities, a jump in ductility (up to 10), and a noticeable decline in the rate at which strength and stiffness degrade. Depending on the condition of as-built piers and the effectiveness of FRP wrapping, a transition from a brittle shear failure to flexural-shear or a completely ductile flexural failure would happen. The additional flexural capacity of a confined pier, however, may result in the occurrence of a premature shear failure in the unwrapped portion of the pier (Saadatmanesh et.al. (1997)). As a result, for confined piers with high flexural to shear capacity rations, the remainder of the length should also be provided with adequate number of FRP layers.

Seismic deficiencies, fiber characteristics, and the positive effects of FRP wrapping on the seismic performance of some laboratory specimens are shown in Table 3. As is apparent from the table, column response is influenced by various factors (e.g. the type, content, and strength of fibers) and retrofitting alone would not guarantee the safety of the structure under future earthquake loads.

Table 3: Results of some as-built and retrofitted lab experiments

Prototype	Seismic Deficiencies	Specimen ID	State	Type of FRP , F_t,E,ε_u	F_{max}/F_{max0}	μ
Chelmsford bridge, New England	Insufficient transverse reinforcement, Inadequate lap splice length	SP-C-15	As-built	None	1.00	1.90
		SP-CFRP-15	Strengthened	C,3.8,227,1.67	1.48	3.94
		SP-KERP-15	Strengthened	K,2,120,1.55	1.45	4.46
Typical pre-1971 designed bridge in California	Poor lap splice detailing	CF1-A	As-built	None	1.00	3.17
		CF1-E-R	Epoxy repaired	None	1.00	3.90
		CF1-E-5IS-RP	Epoxy injection + FRP wrapping	G,0.69,38,1.80	1.25	6.07

The effectiveness of FRP wrapping is influenced by several factors listed below:

- The type of deficiency: the thickness of FRP layer, with the exception of plastic hinge confinement, is driven by FRP elastic modulus in the hoop direction (Karbhari and Seible (2006)). This favors selection of such high-modulus fibers as carbon and aramid. However, for hinge zone confinement the strength and ultimate strain capacity would be controlling. Therefore, application of E-glass fiber satisfies these two criteria simultaneously and is desirable.
- Column configuration: departure from rectangular shape and approaching circular configuration is one viable technique which helps enhance effectiveness of FRP wraps. For circular columns, membrane forces would develop better and stress concentration at the corners would be somewhat relaxed. The effectiveness of FRP layers in confining rectangular columns is recommended to be taken half the circular columns (Seible et.al. (1997), Bakis et.al. (2002)). To increase FRP effectiveness, the corners of rectangular columns may be rounded. However, the presence of transverse reinforcement limits the amount of roundness (Pantelides et.al. (2006)). Modification of column configuration from rectangular/square to oval/circle, as shown in Figure 5, may be considered one other viable alternative for enhancing the efficacy of FRP wraps. The expansive cement paste between the concrete pier and the surrounding prefabricated FRP shell induces additional tension in FRP wraps and this, in turn, leads to a better concrete confinement and an enhanced seismic performance. As the results of experimental work by Pantelides et.al. (2006) suggest, for modified piers the fracture of FRP layers precedes concrete crushing. The effectiveness of FRP layers in confining rectangular piers is also driven by the section aspect ratio. This sensitivity varies from one type of fiber to another with glass fibers being the most sensitive

type (Pantelides et.al. (2006)). For columns with aspect rations greater than 1.5, shape modification is not economically viable. FRP wraps anchored adequately by mechanical devices may be used for partial confinement of columns with high aspect ratios (Manos and Kourtides (2006)).

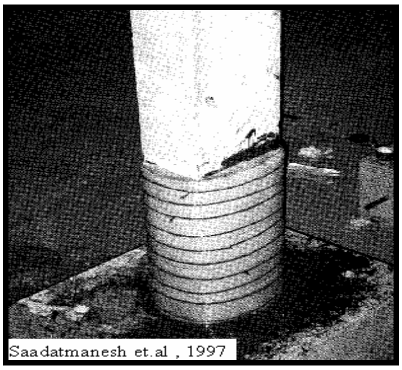

Figure 5: **FRP wrapping of a modified rectangular column**

- Earthquake Severity: FRP wrapping highly relies on the formation of large strains in the layers. Therefore, this retrofit technique is only effective for severe earthquakes during which structures are supposed to undergo substantial nonlinear behavior. For moderate earthquakes, however, the structure would remain elastic, thus making the retrofit redundant. As the results of experimental tests by Chen et.al. (2006) indicate, a system consisting of two FRP layers and a thin intermediate viscoelastic layer is more efficient for moderate earthquakes. The viscoelastic material plays the role of a damper, thus decreasing the displacement and force demands up to 50%. The interior FRP wrap, in this system, is a typical layer. However, the exterior layer should be anchored appropriately into the column supports (Chen et.al. (2006)).
- The extent of damage: the more damaged the pier, the less effective the FRP wraps would be. In the case of severe damage, FRP wraps may be used in combination with epoxy injection in the hinging zone. This technique helps piers partially regain their capacity. Epoxy injection may lead to a shift in the plastic hinge zone, and this necessitates the application of sufficient FRP layers over the entire length. (Ma and Xiao (1999)). Furthermore, underestimation of concrete compressive strength, and longitudinal reinforcement yield strength, on one hand, and overestimation of transverse reinforcement, on the other, may lead to over-prediction of shear capacity, and an unsafe design of FRP thickness. Piers with small intermediate reinforcement, high axial stress, or small shear span to depth ratio, likewise, need more FRP layers to meet a certain ductility demand (Galal (2006)).

Although continuous FRP wraps are commonly used for retrofit purposes, prestressed FRP belts are also sometimes relied on for retrofitting the piers of damaged bridges. The initial belt lateral pressure is recommended to be limited to 17% of the tensile strength of fibers (Nasrollahzadeh and Meguro (2006)). This pressure would close the existing cracks and the additional confinement would help the pier to regain its shear capacity. Such a method, however, is not aimed for developing a ductile flexural failure. Therefore, strength and stiffness degradation in the descending portion of stress-strain curve may still be fast. Pier confinement with FRP belts does not require the replacement of delaminated layers by sound concrete and is fast to apply. As a result, this method may be used for temporary retrofit of vital bridges in seismic regions, or when application speed is the first priority.

Bent caps: FRP layers may be used at the end of bent caps, as the potential, in the portion of the concrete substrate that is in tension, or for improving the shear capacity of the cap. The concept of concrete confinement in plastic hinge region is identical to pier confinement except for lap splice clamping. For flexural and shear strengthening, the thickness of the FRP layer is driven by elastic modulus, and stiff fibers are therefore appropriate.

Flexural strengthening of bent caps may trigger a premature shear failure. Therefore, the ends of longitudinal wraps, as the spots of high stress concentration, should be provided with L-shape FRP layers. These L-shape FRP wraps, as previous studies suggest, are capable of improving the shear capacity and providing adequate anchorage to longitudinal wraps that are vulnerable to discontinuity effects (Gones et.al. (2006)).

Shear strengthening of bent caps with FRP wraps, similar to flexural strengthening, is highly dependent on the bond at concrete-FRP interface. For beams with FRP wraps in the transverse direction, the shear capacity may improve by 60-150 % (Pantelides et.al. (1999)). This broad range depicts the dependence of FRP effectiveness on the failure mode (concrete peeling near the concrete-FRP interface, or fracture of FRP fibers at stresses less than their tensile capacity due to the stress concentration) which is a function of bonding conditions, available anchorage length, axial rigidity of FRP layers, and concrete compressive strength (Bkis et.al. (2002)). Limiting FRP strain to some effective level would prevent the cracks from opening up considerably, and prevent debouding. Increasing the bond area is another viable solution to improve the bond, and thus the effectiveness of the FRP layers.

Joints: As the results of previous studies and in-situ tests suggest, deficient joints usually experience extensive diagonal cracks, rupture of transverse reinforcement, and concrete spalling (shear failure). The optimum orientation for FRP straps, as determined by Pantelides et.al. (1999) and Narris et.al (1997), is ±45 degrees. Owing to the cyclic nature of earthquakes, FRP layers should be provided in both diagonal directions. Fiber orientation at ±45 degrees would limit the stiffness and shear capacity improvement. However, such a pattern (Figure 1) would result in a much more ductile behavior and is called for seismic retrofit of these regions of high stress concentration. Provided for shear strengthening, the thickness of the FRP layer is governed by elastic modulus.

As Table 3 suggests, experimental tests of isolated bridge components have a leading role in improving the retrofit techniques and providing insight into the real behavior of these components under earthquake loads. However, in-situ validation of retrofit techniques with FRP wraps installed and cured under real environmental conditions, are rare in nature. In-situ inspection of deficient bridges together with test results of as-built and retrofitted bridges would provide a comprehensive understanding of the seismic performance and allow for developing cost-effective retrofit techniques. Table 4 represents the seismic deficiencies, retrofit techniques, and the results of in-site tests for two deficient bridges.

Table 4: In-situ testing of bridge bents retrofitted by FRP layers

Bridge Description	Deficiencies	Retrofit Techniques	In-site Test Results
Highland drive bridge at I-80, Salt Lake city	Designed merely for wind loads, inadequate plastic hinge zone confinement, insufficient shear capacity of piers, bent cap hinging zones and joints, inadequate lap splice length, and deterioration of reinforcement due to corrosion	Piers: lap splice clamping and hinge zone confinement; Bent cap: flexural strengthening in the positive moment region and shear strengthening at ends; Joints: shear strengthening using ±45 CFPR layers and U-shape straps in order to improve the longitudinal reinforcement anchorage	$_{\text{as-built}}=2.9$, $_{\text{retrofitted}}=5.1$, Retrofitted bridge survives both 10% in 50 years and 10% in 250 years earthquakes, where the as-built bridge was only enable to take the latter with repairable damage
Temple Bridge at I-15	Inadequate transverse reinforcement in the column hinge zone, insufficient anchorage of the column longitudinal reinforcement into piles and bent caps, inadequate shear resistance at bent cap ends and in joints.	Columns: lap splice clamping, shear strengthening of plastic hinge zones; Joints: shear strengthening	$_{\text{as-built}}=2.28$ $_{\text{retrofitted}}=6.27$ improvement in the load bearing capacity by 20 %.

4. CONCLUSIONS AND RECOMMENDATIONS

High strength and stiffness, low density, high corrosion resistance, minimal disruption to traffic, low maintenance cost, and being as effective as conventional retrofit techniques make FRP wrapping one of the most superior available retrofit methods. However, the type and content of different composite components should be tailored for the performance criteria and the environmental requirements of the application site in order to let the FRP composites work properly. Furthermore, concrete quality, production and installation procedures, FRP sheet and concrete bond, and curing conditions, on one hand, and the seismicity of the region, soil type, and severity of the damage and seismic flaws, on the other, all combine to influence the seismic performance of FRP composites. Failure to meet certain criteria may substantially alter the efficacy of wraps and make the retrofit totally redundant. Seismic applications of very stiff fibers with small strain capacities, resins with deformation capacities less than fibers, and fibers with very low compressive to tensile strength ratios should be limited. In cases where strength and deformation capacities are equally important the combination of fibers with high elastic modulus (e.g. carbon) with glass fibers may be considered helpful.

Retrofit of piers and bent caps by FRP wraps may induce additional shear stresses in joints. Therefore, shear capacity of these spots of high stress concentration should be checked after retrofitting, and if inadequate, FRP wraps with orientation of ±45 should be applied to prevent a brittle shear failure and a non-ductile seismic behavior.

The stiffness of FRP wraps and the concrete substrate should be compatible in order to avoid shifting of hinge zone and the occurrence of premature shear failure in the unwrapped portion of piers. However, for piers with substantial flexural capacities, or those injected with epoxy, the difference in stiffness is very high. Therefore, an adequate number of FRP layers should be provided over the entire length of such piers.

The inability of FRP wraps to confine rectangular piers as effectively as circular piers should be considered when determining the FRP thickness. When high seismic performance or high margins of safety is sought, the modification of the column shape by means of expansive cement concrete may be considered a viable solution.

The efficacy of FRP wraps highly depends on the formation of large strains in the layers during severe seismic events. However, for moderate earthquakes viscous damping should be introduced to the system and FRP wrapping would lose its efficacy considerably. As a result, for moderate seismic regions FRP wrapping would not be as effective as highly seismic zones. In addition, introduction of FRP layers to the system would lengthen the natural period, and therefore FRP wrapping of relatively soft bridges located on soft soil sites would pose additional risk to the structure. However, this topic has not been studied in depth and further research in this area is required. Uncertainty (sometimes called "epistemic uncertainty") results from inaccurate or incomplete information and can be reduced or eliminated given additional observations. As a result, long term performance of FRP composites is the other topic that should be further investigated. This helps reduce the uncertainties, thus leading to a safe and cost-effective retrofit design.

5. REFERENCES

Bakis, C.E., Bank, L.C., Brown, V.L., Cosenza, E., Davalos, J.F., Lesko, J.J., Machida, A., Rizkalla, S.H., and Triantafillou, T.C. (2002). Fiber-reinforced polymer composites for construction -State-of-the-art review. Journal of Composites for Construction, Vol. 6, No. 2, p 73-87

Chen, G. D.,Wang, W. J., and Huang, X. (2006). Optimal design of RC column seismic retrofitting for multiple reinforcement objectives with an integrated damping and strengthening methodology. Proceedings of the 8th U.S. National Conference on Earthquake Engineering, San Francisco, California, USA, Paper No 510

Galal, K. (2006). Effect of design variables on displacement ductility of FRP rehabilitated RC squat columns. Proceedings of the 8th U.S. National Conference on Earthquake Engineering, San Francisco, California, USA, Paper No 1910

Karbhari V.M. (2004). Fiber reinforced composite bridge systems - transition from the laboratory to the field. Journal of composite structures, Vol. 66, No.5

Karbhari, V.M., Chin, J.W., and Reynaud D. (2000). Critical gaps in durability data for FRP composites in civil infrastructure. Proceedings of international SAMPE symposium and exhibition, Vol. 45 (I), p 549-563

Karbhari, V. M., and Seible, F. (2000). Fiber reinforced composites - advanced materials for the renewal of civil infrastructure. Journal of Applied Composite Materials, Vol. 7, No. 2-3, p 95-124

Keller, T. (2003). Use of fiber reinforced polymers in bridge construction. International Association for Bridge and Structural Engineering, Zurich, Switzerland.

Ma, R., and Xiao, Y. (1999). Seismic retrofit and repair of circular bridge columns with advanced composite materials. Earthquake Spectra, Vol. 15, No. 4, p 747-764

Manfredi, G., and Prota, A. (2001). Seismic strengthening with FRP: Opportunities and limitations. Proceedings of the International Workshop on Composites in Construction: A reality, Jul 20-21, Capri, Italy, p 231-240

Manos, G. C., and Kourtides, V. (2006). Retrofitting R/C bridge pier type cross-sections with partial confinement employing carbon fiber reinforcing plastics. Proceedings of the 8th U.S. National Conference on Earthquake Engineering, San Francisco, California, USA, Paper No 1965

Narris, T., Saadatmanesh, H., and Ehsani M.R.(1997). Shear and flexural strengthening of R/C beams with carbon fiber sheets. Journal of structural engineering, Vol. 123, No. 7, p 903-911

Nasrollahzadeh Nesheli K., and Meguro K. (2006). Seismic retrofitting of earthquake damaged concrete columns by lateral pre-tensioning of FPR belts. Proceedings of the 8th U.S. National Conference on Earthquake Engineering, San Francisco, California, USA, Paper No 841

Pantelides, C.P., Cercone, L., and Policelli, F. (2004). Development of a specification for bridge seismic retrofit with carbon fiber reinforced polymer composites. Journal of Composites for Construction, Vol. 8, No. 1, p 88-96

Pantelides, C. P., Duffin, J. B., Ward, J., Delahunty, C., and Reaveley, L.D. (2002). In-situ tests of as-is and retrofitted RC bridges with FRP composites. Proceedings of the 3rd National Seismic Conf. & Workshop on Bridges & Highways, MCEER Publications, Buffalo, N.Y., P 383–395.

Pantelides, C. P., Gergely, J., Reaveley, L. D., and Volnyy, V. A. (1999). Retrofit of RC bridge pier with CFRP advanced composites. Journal of Structural Engineering, Vol. 125, No. 10, P 1094–1099

Pantelides, C.P., Yan, Z., and Reaveley, L. D. (2006). FRP-jacketing and shape modified columns using chemical post tentioning. Proceedings of the 8th U.S. National Conference on Earthquake Engineering, San Francisco, California, USA, Paper No 50

Priestley, M. J. N., Seible, F., and Calvi, G. M. (1996). Seismic design and retrofit of bridges, Wiley, New York.

Saadatmanesh, H., Ehsani M.R, and Jin, L. (1997). Seismic retrofit of rectangular bridge columns with composite straps. Journal of earthquake spectra, Vol. 13, No. 4

Schlick, B.M. (2004). Seismic retrofitting of RC bridge columns in the northeast United States with the use of fiber reinforcing polymers. Master Thesis, University of Massachusetts at Amherst

Sheng, L.H. (2001). Summary of CALTRANS' FRP composite pre-qualification program. Proceedings of international SAMPE symposium and exhibition,Vol. 46I, p 923-930

Tang, B. (1997). Fiber reinforced polymer composites applications in USA. Korea/U.S.A. Road Workshop Proceedings, January 28-29

Tian, Y., and Chaturvedi, Shive K.(2004). A seismic retrofit design methodology for R/C bridge columns using fiber composites. Earthquake Spectra, Vol. 20, No. 2, p 483-502

Yeh, Y.K., and Mo, Y.L. (2005). Shear retrofit of hollow bridge piers with carbon fiber-reinforced polymer sheets. Journal of Composites for Construction,Vol. 9, No. 4, p 32