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FIBRE-REINFORCED POLYMERS FOR STRUCTURAL REHABILITATION: A SURVEY OF RECENT PROGRESS

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ABSTRACT

Fibre-reinforced polymers (FRPs) are rapidly being introduced into a wide variety of civil engineering applications. These materials have been found to be particularly attractive for applications involving the strengthening and rehabilitation of existing structures. In this paper, progress since 1997, with regard to the rehabilitation of civil engineering structures using FRPs, is reviewed. The repair techniques include: column strengthening and seismic applications are using FRP wraps, beam strengthening with bonded FRP wraps and laminates, as well as applications to masonry and other types of structures. Durability considerations when using FRPs for rehabilitation are also discussed, and progress regarding field implementations and assessments is reviewed. Finally, initiatives concerning the development of design guidelines and codes of practice are addressed.

Keywords: *FRP, Column, Beam, Flexure, Shear, Masonry, Durability*

1. INTRODUCTION AND BACKGROUND

The introduction of fibre-reinforced polymers (FRPs) in civil engineering structures has progressed at a very rapid rate in recent years. These high-performance materials have unique properties which make them extremely attractive for a wide range of structural applications. The basic concepts relative to the use of FRPs for structural strengthening, along with examples of application, have been presented in ref. (Triantafillou, 1998). The past and potential future uses of FRP strengthening and rehabilitation have also recently been documented in many conference proceedings (Meier and Betti, 1997), keynote lectures (Maruyama, 1997) and journal articles (Thomas, 1998). These references provide an excellent background on this subject, as well as the state-of-the-art regarding research, development and practical applications in this emerging new field. The rapidly expanding body of literature in this area, along with the corresponding increase in level of activity, confirm the fact that these new materials are progressively gaining wider acceptance by the civil engineering community.

The needs for infrastructure rehabilitation are enormous. Many bridges around the world are structurally deficient due to deterioration and corrosion, while others are functionally obsolete because of service loads and traffic volumes that greatly exceed their initial design loads. The situation regarding deterioration is quite similar for many parking structures, as well as for our immense aging municipality infrastructure. Although FRPs are generally more expensive than conventional construction materials, retrofitting using FRP patching and wrapping instead of traditional methods can nevertheless be economically viable due to significant offsetting savings in labour costs. Indeed, FRPs may likely become the materials of choice in the future, for example, for repairing earthquake-damaged bridges and buildings.

This paper focuses on the strengthening and rehabilitation of civil engineering structures using FRPs. Progress on the various methods and applications of FRP strengthening and repair, subsequent to the work covered in Triantaffilou's article (Triantafillou 1998), is reviewed. Questions associated with the long-term durability of FRP repairs, as well as the development of design guidelines and codes, are addressed. An extensive, yet not exhaustive, bibliography is provided and the interested reader is referred to this for more detailed information on the current and potential uses of FRPs in civil engineering rehabilitation applications. A presentation of the entire body of research that has been carried out since 1997 in the field of FRP strengthening and rehabilitation is beyond the scope of this paper. The intent rather is to provide a representative overview of international activities in this field, and to underline current concerns when applying FRP rehabilitation methods.

1.1 Column strengthening and seismic applications

The use of FRP wraps to strengthen and repair existing reinforced concrete columns continues to be an FRP application which generates a great deal of interest among researchers and practitioners. With this technique, external reinforcement and confinement is provided by wrapping unidirectional FRP sheets around the concrete columns. Full-scale tests (Demers and Neale, 1999) clearly show that FRP wrapping can provide substantial axial capacity enhancement, and also significantly increase ductility. Recent advances involve the development

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of fairly accurate predictive models for FRP confinement for both monotonic (Samaan *et al*., 1998) and cyclic (Harmon *et al.*, 1998) loading. These numerical models have been validated against laboratory experiments. Such tests, however, have typically been carried out on small-scale specimens and the extension to large-scale columns remains to be established.

The technique of retrofitting reinforced concrete columns using FRP jackets to improve seismic performance continues to be a topic of immense practical interest. Recent research has involved investigating the behaviour of columns initially damaged by earthquake-type loadings, subsequently repaired with FRP wraps, and then subjected again to seismic-type loadings (Saadatmanesh *et al.*, 1997). These studies provide valuable experimental data for large-scale specimens and also demonstrate the effectiveness of this retrofit technique. The enhancement of lap-splice behaviour in flexure as well as confinement in shear has also been demonstrated (Haroun *et al.*, 1997). The experimental results show that properly designed composite wraps for reinforced concrete columns can inhibit lap-splice failures in hinge regions, enhance flexural ductility, and also provide sufficient shear strength to the extent that brittle shear failure modes are converted to inelastic flexural deformation modes (Wong *et al.*, 2008).

1.2 Beam strengthening with FRP wraps and laminates

Important pioneering work on increasing the flexural capacity of existing reinforced concrete beams and girders by bonding FRP laminates was initiated over 15 years ago by Meier's group at the Swiss Federal Laboratories for Materials Testing and Research (EMPA)(Meier, 1997). Extensive previous work at EMPA with bonded steel plates had indicated that, although steel plate strengthening proved to be successful, it had certain disadvantages. Among these were the difficulty in handling heavy steel plates at the installation site, the possibility of corrosion at the steel/adhesive interface, and the problem of obtaining clean butt joints between the steel plates. These difficulties prompted the EMPA group to investigate the possibility of replacing steel plates with lightweight carbon FRP laminates. Others have subsequently taken interest in this technique and much research, as discussed below, continues to be carried out on this topic.

Flexural Strengthening and Analysis

Appreciable strength increases can be gained by bonding FRP wraps and laminates to reinforced concrete beams. However, this is generally accompanied by a loss of ductility in the sense that the deflections at ultimate failure are reduced somewhat. Various failure modes can occur including tensile failure of the bonded plate, concrete failure in the compressive zone, and sudden or continuous peeling off of the laminate (Triantafillou, 1998).

Much of the most recent research for reinforced concrete beams strengthened with FRP laminates has focused on studying the various failure modes and developing analytical and numerical models for predicting the structural response up to ultimate failure. Fairly accurate models which capture the complexities of material non-linearities, concrete post cracking behaviour, as well as the interactions between the concrete and the steel and FRP reinforcements, are now available (Varastehpour and Hamelin, 1997). Efficient web anchorages for preventing peeling-type failures have also been proposed (Mukhopadhyaya *et al.*, 1998). Another important recent contribution is the applicability of this strengthening technique to pre-cracked concrete beams (Arduini and Nanni, 1997). For the flexural strengthening, the NSM technique is the most effective, increase of 83% load carrying capacity was found by Barros *et al.* 2005.

The stiffness and strength of the beams strengthened with adhesively bonded FRP composite plates is substantially increased. The ultimate load-carrying capacity of the beams can be increased by as much as 230% over their unplated counterparts (Hamid Rahimi and Allan, 2001).

Bond and Load Transfer

One aspect of FRP beam strengthening that has recently received special attention concerns the bond and load transfer characteristics at the interface between a concrete beam and the bonded FRP reinforcement. Important analytical and experimental research has been carried out to improve understanding of the stress distributions and the prediction of failure (Taljsten, 1997). The results of this work should contribute towards developing FRP reinforcement schemes where premature delamination failures will be avoided.

Prestressed FRP Sheets

A particularly notable recent contribution in the field of FRP flexural strengthening has been the post-strengthening of concrete beams with *Prestressed* FRP sheets and laminates (Garden *et al.,* 1998). This research has involved the development of novel systems for anchoring and applying prestress to the FRP reinforcement. Methods have been proposed to post-strengthen both reinforced and prestressed concrete beams. This work has involved both laboratory investigations, as well as the development of appropriate numerical models.

Prestressing the FRP reinforcement has been shown to be effective at reducing crack widths and delaying the onset of cracking. Thus, the serviceability of beams strengthened with FRPs is improved when the sheets or laminates are prestressed. Prestressing can also lead to a slight enhancement of the strength of the beams when compared to beams strengthened with non-prestressed FRPs. Prestressing leads to amore efficient use of the FRP reinforcement, in comparison to a non-prestressed bonded FRP, since a given FRP strain becomes associated with a lower overall structural deformation in a prestressed beam (Garden *et al.*, 1998). Furthermore, prestressing lowers the position of the neutral axis with the result that more of the concrete section is stressed in compression, thus making more efficient use of the concrete.

Fatigue Performance

Research has also advanced on the behaviour of FRP strengthened beams under *cyclic* loading. Particularly, noteworthy contributions are recent investigations on the fatigue behaviour of reinforced concrete beams post-strengthened for flexure by bonding carbon FRP sheets to their tension faces (Shahawy and Beitelman, 1998. These investigations show that the fatigue properties of concrete beams are enhanced significantly by FRP strengthening. Test results have been presented for rectangular and T-section concrete beams loaded monotonically and cyclically to failure. Analytical methods for fatigue performance have also been proposed and compared to the experimental results. The ability of the post-strengthened beams to carry the stresses through repeated cycles has been assessed, and a design model has been proposed for the use of FRP sheets to forestall fatigue failure. This analytical model provides good, yet conservative, results for the fatigue life prediction of both conventional reinforced concrete beams as well as for reinforced concrete beams strengthened with carbon FRP sheets.

Shear Strengthening

In addition to research on flexural strengthening, work has also been carried out recently on retrofitting with FRP sheets and laminates to accommodate shear deficiencies in conventional and prestressed concrete beams. Different shear repair schemes have been examined such as using either strips or plates bonded to the sides of the beams, as well as wrapping U-shaped FRP sheets continuously around the sides and bottom faces. The experimental studies have been complemented by analytical and numerical modelling. A particularly original contribution has been the development of a novel active shear strengthening system (Winistoerfer and Mottram, 1997).

The results show that significant increases in shear capacity are possible with this FRP repair technique. The failure modes and degree of strength enhancement, however, are strongly dependent on the details of the bonding scheme and anchorage method. Combined flexural and shear strengthening using bonded FRP sheets has been investigated, and it has been shown that a properly designed FRP strengthening can convert a potentially brittle type of shear failure into a more ductile flexural failure mode (Lamothe *et al.*, 1998). An enhancement of shear strength in the order of about 40% is found by Islam *et al.* 2004.

2. SLAB

The strength of slab can be increased by applying a concrete overlay. In increasing flexure extra reinforcing FRP can be added by NSM technique or epoxy bonded techniques. The combination of both concrete overlay and NSM FRP bar will yield the most strength and ductility (Bonaldo *et al.*, 2006).

Based on the structural evaluation of full-scale tests conducted on unreinforced and reinforced concrete slab specimens strengthened with carbon/epoxy and E-glass/epoxy composite systems, it is evident that the FRP systems have succeeded in upgrading the structural capacity of both two-way unreinforced and reinforced concrete slabs (Tamer and Khaled, 2009). For repair applications of unreinforced concrete slabs, test results indicated that the composite system restored not only the original capacity of the damaged slabs but also resulted in an appreciable increase of the strength of the repaired slabs to an average increase of more than 540% the original capacity of the as-built slabs (Ayman and Khalid, 2002). For retrofitting applications, the use of FRP systems resulted in appreciable upgrade of the structural capacity of the as-built slabs up to 500% for unreinforced specimens and 200% for steel reinforced specimens (Ayman and Khalid, 2002).

a. MASONRY STRUCTURES AND OTHER APPLICATIONS

Although the vast majority of FRP rehabilitation research has involved reinforced concrete structures, other interesting applications have nonetheless been considered. Early work on masonry structures has been reported in ref. (Triantafillou, 1998) .More recently, further in-depth experimental and numerical studies have been carried out on this topic (Triantafillou and Fardis, 1997). This work has involved the use of both FRP tendons and laminates, and among the parameters investigated were anchorage systems, prestressing, temperature effects, and various types of loading conditions. This important work demonstrates the undeniable potential of FRPs for enhancing the strength and ductility of masonry structures.

Research has also been conducted on other specialized applications of FRPs for structural rehabilitation. An illustration is the use of FRP sheet strengthening for structurally deficient wall-type reinforced concrete columns; that is, concrete columns with conventional steel reinforcement but having width-to-thickness ratios of the order of five or six (Neale *et al.*, 1997). This research led to the development of a new FRP axial reinforcing scheme that was able to produce wall-column strength increases in the range of 40%. The effectiveness of using FRPs for the flexural reinforcement of natural stone (Kurtis and Dharan, 1997) and the strengthening of timber joints (Chen and Rastogi, 1998) have also recently been demonstrated. FRP strengthening schemes for both concrete and steel [50] beam-column joints have also been developed and applied in the field (Gergely *et al.*, 1998). Another novel application is the repair of cracked steel elements using FRP patching (Kennedy and Cheng, 1998).

3.1 Wall

The potentialities of FRP for strengthening of masonry wall can be depicted by the following figure. In a research of Professor Ayman M. of California University shows that the ultimate capacity of out of plane flexure strength can be increased several times. The Fig. 1 shows the effect of three layers of E-glass, two layers of carbon fiber and the two layers of carbon placed in cross fashion. Here though two layers of unidirectional carbon yield highest strength, the two cross layers of carbon yield highest ductility.

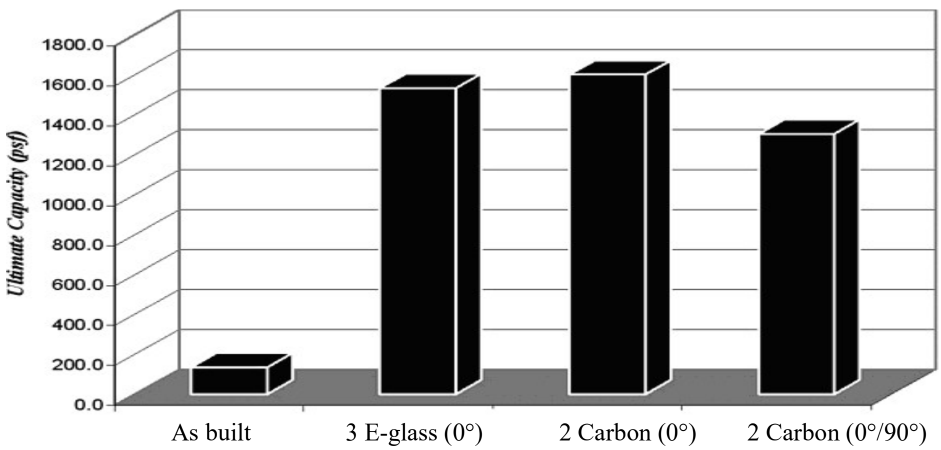

Figure 1: Ultimate capacity for all wall specimens (Ayman, 2007)

3.2 Columns

For the case of masonry column a research outcome has been described here. Columns confined with three 100 mm wide sheets shows higher mechanical properties (generally strength increase around 73% and strain increase 331%) with respect to the same columns confined with two 150 mm wide sheets (normally strength increase 15 % and strain increase 138%). In former case the failure is generally by tensile rupture of the composite where as in later case the failure is occurred by the expulsion of materials from the unwrapped zones, without fibers ruptures (Maria e*t al*., 2007). The detail result is summarised in Table 1.

Table 1: Increase of performance after strengthening (Maria e*t al*., 2007).

Name	Axial load increase	Ultimate displacement Increase	Strain at peak increase	Failure mode
Continuous wrapping	93%	285%	389%	Tensile rupture of FRP
2- 150mm CFRP sheets	15 %	635%	138%	Expulsion of materials
3- 100mm sheets	73%	316%	331%	Tensile rupture of FRP

Hollow (unreinforced) concrete masonry walls had been tested, retrofitted with CFRP laminates on both sides of the walls by Gergely and Young, 2001. Three walls had been tested with in-plane reverse cyclic loading and three with out-of-plane loading. The addition of the CFRP increased capacity in terms of displacement by a factor of 4 in shear and 8 in bending, but 31 times in terms of load.

4. DURABILITY OF FRP REPAIRS

FRP material used for strengthening should be durable in the environment in which it is used for the expected duration of the repair and strengthening. As the majority of the field applications relate to corrosion damage in cold climates, its performance under freeze–thaw conditions is of critical importance. As glass fibre is vulnerable in an alkaline environment, its durability in wrap applications is also a concern. But the application of FRP is a new technology. Its long term behaviour is still unknown. Before applying this issue must be considered as best as possible. It is also affected by a lot of agent listed in Table 2; some other agencies have been discussed in chapter two.

Table 2: Influencing agent (Desiderio and Feo, 2005)

No	Group of agents	Influencing agents
1	Climate agents	Main temperature, UV exposure, humidity and moisture, freeze-thaw cycles
2	Environmental agents	Chemical agents, exposure to salts, sustained loading
3	Configuration	Shape/lying, extension, presence od discontinuity
4	Technological characteristics	Application surface state, protection

This article focuses on the effects of three of the climatic agents: UV exposure and freeze-thaw cycles and temperatures for CFRP externally bonded to masonry structures.

5. FREEZE-THAW CYCLING

In a FRP-interface-masonry composite system, self-equilibrating stresses develop in two cases: differential thermal expansion and contraction of the FRP, interface and masonry and when the distribution of temperature over the cross-section of the FRP is non-linear. In the longitudinal direction, CFRP laminates have a thermal expansion coefficient less then that of the substrate; even negative (Desiderio and Feo, 2005). In regions of drastic temperature changes, this can negatively affect the bond characteristics and lead to the failure of the lamina.

5.1 UV Exposure

Ultraviolet radiations rarely degrade the mechanical performance of FRP-based systems, although this may cause some resins to have a certain degree of brittleness and surface erosion. Thus it can affect the performance of bond capacity. In the research of Desiderio and Feo (2005) the effect of UV on bond capacity is evaluated. The experimental values of the first results are summarized in Table 3.

Table 3: Effect of freeze-thaw cycles and UV exposure (Desiderio and Feo, 2005)

Conditioning type	No. of cycles	Ultimate stress (MPa)	Decay (%)	Failure modality
No conditioning	-	0.43	0	Tuff masonry failure
Freeze-thaw cycles	50	0.39	9	Lamina-substrate failure
UV exposure cycles	50	0.24	44	Lamina-substrate failure

The analysis of the data contained in the table shows the decrease of bond capacity in case of exposure to freeze–thaw cycles or UV. This degradation is also shown in terms of percentage decay of bond capacity with respect to control samples. It is important to note that in non-conditioned samples the failure is always on the tuff masonry, while in the conditioned ones the failure is at the lamina – substrate interface on the epoxy adhesive layer. The decay is higher for the UV exposure (44%) of the samples, the bond stress decrease by 10% for freeze-thaw cycles where as for UV exposure it becomes as high as 44%.

The results of an experiment performed by Katz *et al.* (1999) on concrete specimen and strengthened with four types of FRP bars of diameter around 12 mm show a severe reduction in the bond strength as the temperature is raised to 180–200°C. A reduction of 92% is seen for FRP rebars where the bond strength dropped from 13.2 to 1.1 MPa at a temperature of 250°C. The variation of strength with increasing temperature is distinct in Fig. 2. Though this experimental is purely on concrete specimen the result will be similar to masonry specimen.

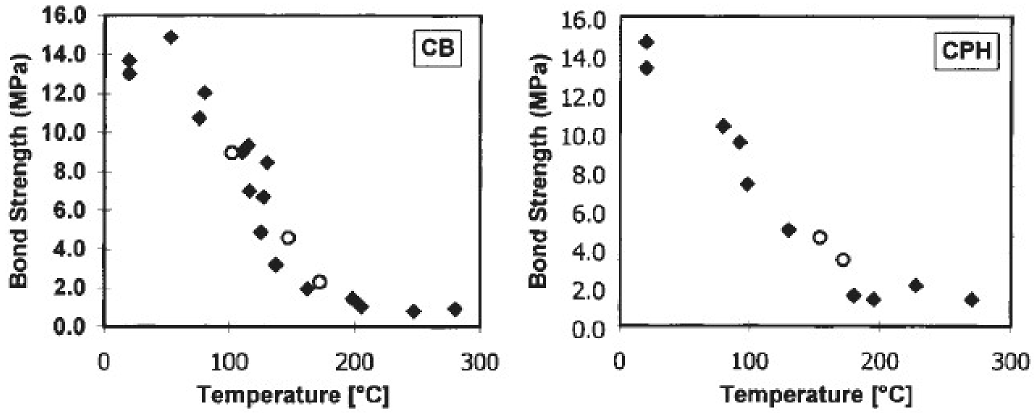

Figure 2: Variation of bond strength with temperature increase (Katz *et al.,* 1999)

6. FIELD APPLICATIONS AND ASSESSMENTS

Arguably, the most remarkable development over the past few years in the field of FRP strengthening and repair has been the rapidly growing acceptance worldwide of these new technologies for an enormous range of practical applications. Typical field applications to reinforced concrete, masonry and timber structures are described in refs (Triantafillou, 1998; Maruyama, 1997; Thomas, 1998). Recent FRP rehabilitation projects have been extremely varied in nature and have included, for example, column and beam strengthening, seismic retrofitting, the FRP repair of corrosion-damaged beams and columns; as well as applications to numerous structural components such as: bridge decks, piles, precast pre-stressed concrete shells, chimney stacks, lighthouses, roof structures, and pre-stressed concrete water tanks. Furthermore, these field rehabilitation projects have been carried out in regions encompassing a wide variety of environmental conditions.

A few years ago, many of the field applications were 'demonstrations', in that their main objective consisted of convincing the user sector of the merits of the new and relatively unknown FRP rehabilitation technologies. However, due to the proven success of FRP field retrofits, the practical applications of these technologies have begun increasing at a tremendous rate. For example, in Japan the demand for carbon FRP sheets for field repairs has essentially trebled each year since 1993 and grew to an estimated 125 tons in 1996 (Maruyama, 1997; Fukuyama *et al.*, 1997). Similarly, the potential market for FRPs in rehabilitation applications in the Southeast Asian region is now estimated to be worth more than US$120 million annually (Tan, 1997). Meier (1997) cites that more than one thousand structures worldwide have been post-strengthened with FRP laminates since 1991. Another indication of the extent to which the FRP retrofitting market is growing is a projected parking structure upgrade in the US which will require approximately 18 500 m^2 of FRP materials (Thomas, 1998).

An important aspect of FRP field implementations has been the on-site evaluation of the various strengthening techniques. This has involved both in situ load testing (Nanni and Gold, 1998), as well as the long-term monitoring of structural performance using fibre optic sensors (Neale and Labossie, 1998). The positive findings of such field assessments will undoubtedly promote more widespread confidence in FRP rehabilitation methods; and also convince potential users of the reliability, durability and overall cost benefits of this relatively new technology.

7. DESIGN GUIDELINES AND CODE DEVELOPMENT

Before FRPs become routinely proposed as everyday solutions for problems of structural strengthening and repair, codes of practice must be made readily available. Recently, many practical guidelines and design equations have been proposed by individual researchers, and a number of design manuals have been produced by the promoters of commercially available proprietary FRP repair systems. In addition, initiatives are currently underway to formulate appropriate codes (e.g., Maruyama, 1997; ACI, 1998). The results of some of these efforts are expected to materialize in the very near future. Obviously, a harmonization of international activities in the development of codes and design guidelines for FRP strengthening and rehabilitation would be a worthwhile endeavour.

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8. CONCLUSION

There is significant potential for the application of FRP's in the construction industry, both in new construction and for rehabilitation of old structures. FRPs can improve not just the strength capacity of the material, but also the ability to resist crack propagation and retain structural integrity and increase ductility through increased toughness. So, it is claimed that the available methods of FRP application on structural members such as NSM bars, laminates and post tension are quite effective and pose good potentiality. In the context of Bangladeshi climate, economy and construction trends the FRP material can be the best substitute of steel and may be better than steel as a construction materials.

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