FRPs for Strengthening and Rehabilitation: Durability Issues

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Abstract

Issues regarding the long-term durability of fibre reinforced polymer (FRP) strengthening and rehabilitation technologies are addressed. A brief overview of some recent research activities in this field is first presented. In particular, we discuss work related to performance in corrosive environments, applications in cold regions, and fatigue behaviour. On the basis of this review, some important needs for future investigation are identified. The importance of developing standardized accelerated laboratory test conditions, as well as of establishing appropriate field sites for calibrating results from accelerated tests, is emphasized.

Introduction

The needs for civil engineering infrastructure rehabilitation are obvious. First, aggressive environments have resulted in the serious deterioration of large numbers of existing structures. In addition, as many structures no longer comply with the load and design criteria specified by current codes, numerous strategies for structural upgrading are being explored. Included in these potential solutions are methods based on the use of fibre reinforced polymers (FRPs) for structural rehabilitation and strengthening.

A particular concern related to the use of FRPs for structural rehabilitation is the long-term performance of this technology in harsh and corrosive environments. As a result, this is a topic that is receiving considerable attention. Indeed, conference proceedings over the past few years (e.g., Meier and Betti 1997, Benmokrane and Rahman 1998, Dolan et al. 1999) contain numerous contributions related to durability aspects of FRP repairs. This is a topic that is currently

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receiving significant research support in the U.S. (Chong 1998). An example of the importance of assessing the environmental durability of FRP retrofitting systems is a recent study which showed that unacceptable reductions in mechanical properties can occur if resins with inadequate moisture absorption characteristics are employed (Hawkins et al. 1998).

In Canada, the major research effort in the field of FRPs for infrastructure rehabilitation is being conducted through the Network of Centres of Excellence *ISIS Canada* ("Intelligent Sensing for Innovative Structures"). An important focus in ISIS Canada is the theme on *FRPs for Structural Rehabilitation*. This theme, which is centred at the University of Sherbrooke (Sherbrooke, Quebec), has as its primary objective the development and field implementation of FRP technologies for the rehabilitation and strengthening of civil engineering structures. Despite the obvious advantages of FRPs, rehabilitation techniques using these high-performance materials are far from being accepted on an everyday basis. Reservations exist in part because of open questions concerning the performance, cost-effectiveness, and long-term durability of FRP retrofit techniques in severe climatic conditions such as those encountered in Canada. The ISIS network is therefore focusing on those aspects of performance and durability that are of particular relevance to Canada. The main objective is to develop and implement FRP rehabilitation methodologies for the maximum service-life extension of corrosion damaged or structurally deficient structures, with a minimum of cost, time and complexity.

In this paper, various issues regarding the long-term durability of FRP rehabilitation techniques are addressed. A brief overview of research related to the performance of FRP repair and strengthening technologies in corrosive environments and cold regions is first given. Fatigue and creep behaviour are also discussed. The needs for future research in this field are identified, and possible opportunities for appropriate fieldwork are suggested.

Overview of the Durability of FRP Rehabilitation Technologies

An exhaustive review of the entire body of work on the long-term durability and performance of FRP strengthening and rehabilitation techniques is beyond the scope of this paper. In this section, a representative overview of the field is given to illustrate the typical areas of interest and concern. The intent is to highlight key areas where progress has been significant, and to identify important unresolved issues.

FRP Repairs in Wet-Dry and Corrosive Environments. A particular concern related to the use of FRPs for structural rehabilitation is the long-term performance of such repairs in wet-dry and severe corrosive environments. In Canada, extensive research on this topic is being conducted at the University of Toronto (Lee et al. 2000, Pantazopoulou et al. 2001), the University of Waterloo (Soudki and Sherwood 2000), and the University of Sherbrooke (Beaudoin et al. 1998, Raîche et al. 1999, Lacasse et al. 2001). These investigations have been limited to ambient temperature environments.

The University of Toronto group has focused on the use of FRP wraps to repair reinforced concrete columns damaged by steel reinforcement corrosion (Lee et al. 2000, Pantazopoulou et al. 2001). In this work, improved techniques for the laboratory simulation of field corrosion in reinforced concrete columns have been developed. Large-scale column specimens with various steel reinforcement configurations were prepared and subjected to accelerated corrosion regimes in the laboratory, leading to extensive cracking and partial delamination of the concrete cover. Various FRP repair procedures were considered, consisting primarily of jacketing the damaged columns with either glass or carbon FRP wraps. The columns were then tested to structural failure and/or subjected to post-repair accelerated corrosion, monitoring, and testing. The results showed that the FRP repairs can greatly improve the strength of the repaired columns, and can also retard the rate of post-repair corrosion. Moreover, subjecting the FRP-repaired columns to extensive post-repair corrosion results in no loss of strength or stiffness, and only slight reductions in ductility.

The University of Waterloo studies have focused on the viability of using carbon FRP laminates for the strengthening of corrosion damaged reinforced concrete beams (Soudki and Sherwood 2000). Beam specimens with variable chloride levels were constructed, and some of these specimens were strengthened using externally-bonded carbon FRP laminates. The specimens were subjected to accelerated corrosion, and subsequently tested in flexure. The test results revealed that the FRP laminates can successfully confine the corrosion cracking, and that the strengthening scheme is able to restore the capacities of the corrosion damaged beams.

In addition to the durability aspects associated with steel reinforcement corrosion in concrete elements, research has also recently been conducted on the effects of wet-dry environmental conditions on the performance of both FRP materials used for repair (Raîche et al. 1999), as well as on FRP repaired beams (Toutanji and Gomez 1997, Beaudoin et al. 1998). These studies indicate that FRP-strengthened concrete beams are not damaged significantly by exposure to wet-dry environments. Additional studies at the University of Sherbrooke have been conducted on the FRP rehabilitation of concrete beams suffering from alkali aggregate reaction damage (Lacasse et al. 2001). In this investigation, FRPs have been used as external reinforcement, and preliminary results indicate that this technique can be quite effective at reducing the expansions due to alkali aggregate reactions.

FRP Repairs in Cold Regions. The performance of FRP rehabilitation methods in cold regions is another issue of particular concern, and much research has recently been conducted on the behaviour of concrete structures strengthened with FRP sheets and laminates subjected to cold climate conditions. Tests on carbon FRP sheets subjected to natural and accelerated exposure have shown that these materials have adequate weatherproofing properties with regard to tensile strength and bond to concrete, as well as being quite durable under freeze-thaw cycling (Yagi et al. 1997). However, tests on FRP-wrapped concrete cylinders exposed to freeze-thaw action have revealed that freeze-thaw cycling can significantly reduce the strength and ductility of FRP-wrapped concrete in comparison to specimens kept at room temperature (Soudki and Green 1997, Toutanji and Balaguru 1998). Moreover, Soudki and Green (1997) report that FRP-wrapped specimens subjected to freeze-thaw cycling fail in a more brittle manner than similar specimens kept at room temperature. The FRP wraps of their freeze-thawed specimens ruptured suddenly in a series of hoops, in contrast to the more continuous failure line observed for the wrapped cylinders kept at room temperature. Nevertheless, as wrapped cylinders exposed to freeze-thaw action show a significant increase in strength over unwrapped cylinders exposed to freeze-thaw, adequate FRP wrapping is a possible remedy for restoring the strength of a freeze-thawed cylinder to that of an unwrapped specimen kept at room temperature. The temperature ranges in this study were from –18C to +18C.

Research on the effects of freeze-thaw action, for similar temperature ranges, has also recently been reported for FRP-strengthened concrete beams. A preliminary indication is that freeze-thaw cycling does not induce significant deterioration of the bond durability between FRP plate reinforcements and concrete (Green et al. 2000). Other research has been conducted on the behaviour of concrete structures strengthened with FRP sheets subjected to cold climate conditions (Baumert et al. 1996). In these studies beam specimens were strengthened with carbon fibre sheets. One half of the specimens were subjected to short-term low-temperature exposure, of –27C, while the others were kept at room temperature. Unstrengthened control beams were also exposed to either room temperature or low-temperature conditions. The failure mode in these tests was by shear peeling of the sheets, and was unaffected by the low-temperature conditions. Furthermore, the low-temperature specimens generally failed at higher loads than the room-temperature specimens because the concrete exhibited an increase in strength at the lower temperatures. The authors conclude that the carbon fibre sheets were unaffected by the short-term exposure to low temperatures.

Fatigue and Creep Behaviour. Another topic related to the long-term behaviour of FRP strengthened structures is their behaviour under conditions of sustained loads or fatigue loading. The extended use of a structure at loads often greater than the original design loads may compromise the safety of the structure if no provisions are made with regard to creep and fatigue performance. Limited research has been carried out on the behaviour of FRP-strengthened reinforced concrete beams under fatigue-type loading; however, particularly noteworthy contributions are the investigations by Heffernan (1997) and Shahawy and Beitelman (1998). These investigations have shown that the fatigue performance of concrete beams can be enhanced significantly by means of FRP strengthening.

Test results have been presented for both rectangular and T-section concrete beams loaded monotonically and cyclically to failure. Up to six million cycles of loading were applied in these experiments. Analytical methods for simulating fatigue behaviour have also been proposed and compared to the experimental results (Heffernan 1997). 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. This study demonstrates the interesting result that equivalent strength beams, conventionally reinforced and strengthened with FRPs, have equivalent fatigue lives.

Field Studies. The use of FRP strengthening and rehabilitation technologies for practical field applications has grown tremendously in recent years. Initially, many of these applications were demonstration projects, in that their main objective was to convince the user sector of the merits of these new and relatively unproven technologies. In Canada, field applications date from 1995 (Neale and Labossière 1998, Rizkalla and Labossière 1999). There is thus very little field data here related to long-term behaviour; nevertheless, to date the performance of the FRP field applications have proven to be very successful. In many of the field projects, provisions have been made for the long-term monitoring of the FRP repairs using fibre optic sensors. This type of monitoring is very beneficial in providing assurance to the user sector.

Research Needs and Opportunities

The above overview shows that, although studies regarding the long-term durability of FRP strengthening and rehabilitation techniques have begun only quite recently, progress has been impressive and quite rapid. A considerable amount of research has been carried out to date, and research productivity continues to escalate. This research is being complemented by a rapidly growing number of important field applications that are providing valuable information on the long-term performance of FRP repairs. The results from such field projects are essential to convince the user sector of the long-term reliability and durability of FRP strengthening and rehabilitation technologies. However, as discussed below, the needs for further research are significant, and there are excellent opportunities for concerted efforts in this field.

Needs for Research. Research into durability-related aspects of FRP strengthening and repair is a relatively new field, and the information currently available is consequently rather limited. There is thus an obvious need for more data on the effects of various environments (wet-dry, marine, freeze-thaw, UV, etc.), temperatures, and loading conditions (fatigue, creep, etc.) on both the properties of FRP material systems used in infrastructure rehabilitation, as well as on the performance of FRP strengthening and repair schemes. Better understanding of differences in behaviour due to changes in resin and fibre types is required. The fire resistance of FRP-repaired structures is also a major concern. In addition, as the effects of sustained loading in combination with environmental aging have generally been neglected, more research is required on this subject. Another topic to be further investigated is the effect of the state of damage in a structure, at the time of an FRP repair, on the long-term performance of the retrofit. In addition to the above needs for data on durability, adequate analytical and numerical models are needed to simulate the various phenomena and to develop appropriate guidelines for design.

Among the outstanding issues that must be addressed are the correlations of accelerated laboratory tests to actual field conditions, as well as the validity of extrapolating results from small-scale specimens to full-scale structures. Furthermore, the literature review indicates that simulated laboratory environments vary considerably from one research establishment to another, with the result that it is extremely difficult to fully synthesize the existing test data. As such, it is virtually impossible at present to arrive at definite conclusions regarding the durability of a given FRP retrofit scheme in a particular environment.

Opportunities for Concerted Activities. The research needs identified above suggest that concerted efforts are required to fully address all issues and, moreover, that there exist many interesting opportunities for collaboration. As the various parameters involved in durability investigations are numerous, strategic planning among researchers in the field is essential to ensure that all critical topics are adequately covered and that unnecessary duplication is avoided. Collaborative endeavours to standardize accelerated laboratory test conditions would undoubtedly contribute greatly towards improving our basic understanding of the durability characteristics of FRP strengthening technologies. Finally, coordinated activities with regard to establishing controlled exposure test sites for FRP repair materials and FRP-repaired elements would be of great value. As part of a joint research program between the University of Sherbrooke and the Public Works Research Institute of Japan, three identical exposure sites (one in Sherbrooke and two in Japan) have been set up to assess long-term durability in three very different climates. A comprehensive international program to construct similar sites elsewhere would undoubtedly represent a significant contribution towards establishing correlations between accelerated laboratory simulations and real environments. This would provide as well invaluable information on the durability of FRP rehabilitation technologies.

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References

Baumert, M.E., Green, M.F. and Erki, M.A. (1996). "Low temperature behaviour of concrete beams strengthened with FRP sheets." *CSCE Annual Conference*, Edmonton, Alberta, 29 May – 1 June, **IIa**, 179–190.

Beaudoin, Y., Labossière, P. and Neale, K.W. (1998). "Wet-dry action on the bond between composite materials and reinforced concrete beams." *Durability of Fibre*

Reinforced Polymer (FRP) Composites for Construction, B. Benmokrane and H. Rahman, Eds., Dept. of Civil Engineering, Université de Sherbrooke, 537–546.

Benmokrane, B. and Rahman, H. (Eds.) (1998). *Durability of Fibre Reinforced Polymer (FRP) Composites for Construction*, Dept. of Civil Engineering, Université de Sherbrooke.

Chong, K.P. (1998). "Durability of composite materials and structures." *Durability of Fibre Reinforced Polymer (FRP) Composites for Construction*, B. Benmokrane and H. Rahman, Eds., Dept. of Civil Engineering, Université de Sherbrooke, 1–12.

Dolan, C.W., Rizkalla, S.H. and Nanni, A. (1999). *Fourth International Symposium on Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures*, SP-188, American Concrete Institute.

Green, M.F., Bisby, L.A., Beaudoin, Y. and Labossière, P. (2000). "Effect of freeze-thaw cycles on the bond durability between fibre reinforced polymer plate reinforcement and concrete." *Canadian Journal of Civil Engineering,* **27**, 949–959.

Hawkins, G.F., Steckel, G.L, Bauer, Jr., J.L. and Sultan M. (1998). "Qualification of composites for seismic retrofit of bridge columns." *Durability of Fibre Reinforced Polymer (FRP) Composites for Construction*. B. Benmokrane and H. Rahman, Eds., Dept. of Civil Engineering, Université de Sherbrooke, 25–36.

Heffernan, P.J. (1997). "Fatigue behaviour of reinforced concrete beams strengthened with CFRP laminates." *Ph.D. Thesis*, Royal Military College of Canada, Kingston, Ontario.

Lacasse, C., Labossière, P. and Neale, K.W (2001). "FRPs for the rehabilitation of concrete beams exhibiting alkali-aggregate reactions." *Fifth International Symposium on Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures FRPRCS*-5, Cambridge, U.K., 16–18 July, (in press).

Lee, C., Bonacci, J.F., Thomas, M.D.A., Maalej, M., Khajehpour, S., Hearn, N., Pantazopoulou, S. and Sheikh, S. (2000). "Accelerated corrosion and repair of reinforced concrete columns using carbon fibre reinforced polymer sheets." *Canadian Journal of Civil Engineering*, **27**, 941–948.

Meier, U. and Betti, R. (Eds.) (1997). *Recent Advances in Bridge Engineering – Advanced Rehabilitation, Durable Materials, Nondestructive Evaluation and Management*, EMPA, Switzerland.

Neale, K.W. and Labossière, P. (1998). "Fiber composite sheets in cold climate rehab." *Concrete International,* **20**(6), 22–24.

Pantazopoulou, S.J., Bonacci, J.F., Sheikh, S., Thomas, M.D.A. and Hearn, N. (2001). "Repair of corrosion-damaged columns with FRP wraps." *Journal of Composites for Construction, ASCE*, **5**, 3–11.

Raîche, A., Beaudoin, Y. and Labossière, P. (1999). "Durability of composite materials used as external reinforcement for RC beams." *CSCE Annual Conference*, Regina, Saskatchewan, 2–5 June, **1**, 155–164.

Rizkalla, S. and Labossière, P. (1999). "Structural engineering with FRP – in Canada." *Concrete International*, **21**(10), 25–28.

Shahawy, M. and Beitelman, T.E**.** (1998). "Fatigue performance of RC beams strengthened with CFRP laminates." *Durability of Fibre Reinforced Polymer (FRP) Composites for Construction*, B. Benmokrane and H. Rahman, Eds., Dept. of Civil Engineering, Université de Sherbrooke, 169–178.

Soudki, K.A. and Green, M.F. (1997). "Freeze-thaw response of CFRP wrapped concrete." *Concrete International*, **19**(8), 64–67.

Soudki, K.A. and Sherwood, T.G. (2000). "Behaviour of reinforced concrete beams strengthened with carbon fibre reinforced laminates subjected to corrosion damage." *Canadian Journal of Civil Engineering*, **27**, 1005–1010.

Toutanji, H. and Balaguru P. (1998). "Durability characteristics of concrete columns wrapped with FRP tow sheets." *Journal of Materials in Civil Engineering, ASCE*, **10**, 52–57.

Toutanji, H. and Gomez, W. (1997). "Durability characteristics of concrete beams externally bonded with FRP composite sheets." *Cement and Concrete Composites*, **19**, 351–358.

Yagi, K., Tanaka, T., Sakai, H. and Otaguro H. (1997). "Durability of carbon fiber sheet for repair and retrofitting." *Non-Metallic (FRP) Reinforcement for Concrete Structures*, Japan Concrete Institute, **2**, 259–266.