FRP INTERNATIONAL

The Official Newsletter of the International Institute for FRP in Construction

Volume 1, Issue 1 ***May 2004***

On behalf of the Executive Committee, welcome to the inaugural issue of the IIFC Newsletter. We hope that the newsletter will provide a link between various constituencies associated with the development and use of fiber reinforced polymer (FRP) composites in construction. We also hope that it will serve as a forum for the exchange of information and views, not only between academics, but also between academia, industry, and government agencies across the globe.

Vistasp M. Karbhari, Editor-in-Chief

Email: vkarbhari@ucsd.edu

In this issue

FRP INTERNATIONAL

The Official Newsletter of the International Institute for FRP in Construction

Volume 1, Issue 1 **May 2004**

Message From The President – Prof. J.G. Teng

Recent years have seen rapidly growing interests in the application of advanced fibre-reinforced polymer (FRP) composites in construction around the world, in terms of both research activities and practical implementations. Indeed, many have hailed FRP composites as a new generation of construction materials following steel and concrete. Against this background, the *International Institute for FRP in Construction* (IIFC) was formed in 2003 to promote and coordinate world-wide activities in this area. One of the important activities of IIFC is the publication of its official newsletter, *FRP International*. *FRP International* was initially founded and run by a group of FRP enthusiasts from different parts of the world, and became the official newsletter of IIFC with their generous support. On behalf of IIFC, I would like to express my appreciation to the founders of *FRP International* for this support.

As the founding President of IIFC, I would like to take this opportunity to provide a brief report on the process that gave birth to IIFC. The first step towards the formation of IIFC was taken at the International Conference on FRP Composites in Civil Engineering held in December 2001 (CICE 2001) at which a meeting of leading researchers attending the conference was convened to discuss the possibility. The idea of forming an international organization dedicated to the application of FRP composites in construction was enthusiastically supported at that meeting. The meeting also led to the establishment of an Ad-Hoc Committee for the formation of the Institute, which consisted of 33 leading figures in the area drawn from 13 countries around the world.

Among the many tasks completed by this Committee was the development of the By-laws of the Institute. Following the finalization of the By-laws in March 2003, the Ad-Hoc Committee was immediately converted into the founding Council of the Institute based on the majority view of the Committee, which signified the formal establishment of IIFC. Elections of the Executive Committee, the first Fellows and the Advisory Committee of IIFC then followed. The Institute became fully functional and started to accept applications for membership on 1 January 2004. In this process, an official web site for IIFC was also established (www.iifc-hq.org).

The founding of IIFC would not have been possible without the willing contributions of many individuals. On behalf of IIFC, I would like to express my sincere gratitude to all of them. The future success of IIFC will hinge on the support of individuals and organizations who share the aim of IIFC. In this connection, you are strongly encouraged to join IIFC by completing the application form enclosed with this issue of the newsletter.

Finally, I would like to congratulate the editors of *FRP International*, particularly the Editor-in-Chief, Professor Vistasp Karbhari, for putting together a fantastic inaugural issue of *FRP International* under the auspices of IIFC.

Reports From Around the World

In this issue we highlight activities from around the world as reported by members of IIFC. As part of the inaugural issue it was thought fitting that the members provide their perspective on developments and the current state-of-the-art as it pertains to their region of the world. We hope this section, both as part of this issue and in future issues, will provide a forum for discussion on topics that transcend boundaries.

Brief State-of-the-Art Report on FRP in Construction in Japan

Prof. Z.S. Wu, Ibaraki University, Japan

In 1997, the annual demand of carbon fiber sheets reached 1,000,000 m^2 (around 250 Ton/y) and since then this demand has been maintained for the past 7 years throughout different kinds of efforts such as the technique innovation, coverage expansion and establishment of guidelines, recommendations and standards. The list of recently established guidelines, recommendations, and standards includes:

1. Recommendations for upgrading of concrete structures with use of continuous fiber sheets, Concrete Engineering Series 41, JSCE, March 2001.
2. Design and construction guideline of continuous fiber reinforced concrete, AIJ, March 2002.
3. Manual for tunnel linings spalling &Falling countermeasures with FRP, Tunnel Safety Countermeasure Research Society, Sannkaidou, March 2003.

Noteworthy recent activities in Japan include:

1. The Society of Fiber Repair and Strengthening "FiRSt" in Japan: FiRSt was established in Japan in October 1999 (http://www.fir-st.com). As a main activity, the society has initiated a training program for skilled FRP technique and construction management.
2. PBO -Prestressing Upgrading Technique Society (P-PUT): The P-PUT society is working recently for the establishment of design & construction manual of concrete structures externally strengthened with prestressed PBO fiber sheets.
3. Association for Civil Engineering Technology of Hokkaidou: The Design Performance Sub-Committee of Concrete Research Committee in the Association recently initiated a working group for durability design with use of continuous fiber reinforcements. This working group is making a trial calculation on reduction in LCC due to the applications of continuous fiber reinforcements.

In addition a number of activities are being initiated by the Society of Fiber Repair and Strengthening "FiRSt". FiRSt was established in Japan in October, 1999 for the purpose of getting diffusions and reliabilities of the method for existing concrete structures with carbon fiber and aramid fiber sheets. The members of the society are composed of construction companies, repair companies, and material manufacturing companies etc. and the total number of the member companies is about 400 all over Japan. The society is operated by the steering committee accompanied with four sub committees of techniques, cultivation, accreditation, and advertisement.

Skilled technique and accurate construction management are demanded to stick fiber sheets on existing concrete structures at the site. Therefore to cultivate the fiber construction technicians and managers accreditation tests are enforced as a main activity of the society, and about 1200 qualification persons are receiving licenses at present. ("FiRSt" E-mail: senihoky@apricot.ocn.ne.jp)

Civil Engineering Composites in Australia

Prof. Gerard Van Erp
University of Southern Queensland (USQ), Toowoomba, QLD, 4350 Australia

As in many other developed nations in Europe and North America, Australian asset owners are actively seeking solutions for the rehabilitation and replacement of deteriorating civil infrastructure. While the reasons for this interest are somewhat different in Australia than in other parts of the world, major asset owners are faced with the same problem of having decreasing budgets to address an ever increasing demand for structural replacements or upgrades. This report presents an overview of Australian research into the use of fibre composites in infrastructure applications and associated industry development programs.

The first fibre composite bridge in the Australian public road network was installed on 19 February 2003. This installation was the culmination of a development and innovation process lasting over 5 years and involving a wide range of interested parties including; Queensland Department of Main Roads (QDMR), the Roads and Traffic Authority of New South Wales (RTA), the Department of Industry Science and Resources (DISR), Fibre Composite Design and Development (FCDD), Wagners Composite Fibre Technologies (WCFT), the Cooperative Research Centre for Advanced

Composite Structures (CRC-ACS), Prof Vistasp Karbhari and consulting engineers Connell Wagner and Cardno MBK.

The project originated with a generic design exercise commissioned by the RTA who sought to identify which particular fibre composite bridge technologies should be encouraged. This involved the development of a performance specification that met RTA requirements and the submission of two conforming design concepts. One of these was a novel local concept developed by FCDD, which was selected as the preferred solution based on a set of agreed selection criteria. The concept combined the high compression capacity of plain concrete with the high strength/low weight characteristics of fibre composites[1]. The design concept was based on the traditional plank bridge concept, where individual beams are adhesively bonded together to create a bridge.

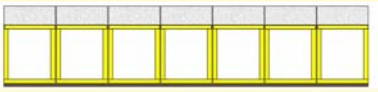

Figure 1. Principle of Australia's first fibre composite bridge deck

The beams in the successful design were a box section formed using glass reinforced, isophthalic polyester pultruded profiles. Additional carbon fibre reinforcement was incorporated into the base of the deck to enhance stiffness. Plain concrete was used to form a compression flange on top of the beams.

FCDD partnered with Wagners Composite Fibre Technologies, the RTA and QDMR to develop the concept into a working prototype which was installed on a Wagner's owned quarry site near Toowoomba, Queensland (Figure 2) in early 2002. An extensive series of field tests followed, revealing that the concept exceeded expectations in terms of its technical performance. Based on this development work, RTA initiated a project to install one of these new generation bridges in the Australian road network for trial purposes.

Figure 2. Full scale prototype of composite bridge under test

The selected installation site was an existing timber span (circa 1940) on a bridge over the Orara River at Coutts Crossing in northern New South Wales. Consulting engineers Connell Wagner were engaged by WCFT to review and modify FCDD's fibre composite bridge concept to suit the site specific requirements at Coutts Crossing. The bridge design was seen to offer substantial benefits over traditional bridge deck design, including installation in only 5 days, instead of 8 to 10 weeks for the conventional alternative, 90% savings on traffic control costs, and 75% saving on bridge transportation costs.

The bridge was constructed by WCFT under the supervision of FCDD and installed in February 2003 (Figure 3). After one year in operation (March 2004) the bridge was subjected to a detailed testing and inspection program. The bridge showed no signs of deterioration and appears to perform extremely well. Annual testing and inspection is to continue for the next few years.

Figure 3. Installation of Australia's first fibre composite bridge at Coutts crossing

An innovative range of fibre composite technologies developed by FCDD will enable an estimated 20,000 Brisbane residents per day to literally walk on water. The new showcase floating walkway of Brisbane's RiverWalk project near

[1] G.M. Van Erp, T.J. Heldt, L. McCormick, D. Carter and C. Tranberg, 'Development of an Innovative Fibre Composite Deck Unit Bridge', Proceedings of the IABSE Symposium. Melbourne. 2002.

New Farm will allow the people of Brisbane to stroll or cycle along one of the most scenic reaches of the river. When engineers looked at providing access to the river through a floating walkway, the extremely high dynamic loads and harsh environment made traditional design solutions a prohibitive option. New state-of-the-art design solutions were required to accommodate the city council's 100 year design life criteria with little or no maintenance. The proven environmental stability of composites over long time periods was seen to offer one of the only options for meeting such criteria.

The walkway includes over 500 three metre long fibre composite beams to tie the floating pontoons together (Figure 4), as well as a number of larger structural composite beams and a 18m composite truss (Figure 5). Although having twice the cost of timber and steel, the whole-of-life costs of these composite components proved to be significantly lower than the traditional design solutions.

Figure 4 Brisbane's floating riverwalk and close up of fibre composite waler.

Figure 5. 18m fibre composite truss and 12m long beam for Brisbane riverwalk project

In 2001 one of the world's largest carbon fibre strengthening programs was undertaken in Melbourne, Victoria. The West Gate Bridge in Melbourne links the western industrial and residential areas to the main city and is one of the cities busiest transport corridors. The 650m long bridge comprises a pre-cast, segmented box girder with pre-cast, post-tensioned cantilever frames and a reinforced concrete deck slab. The structure was designed in the mid 1960's.

The construction of additional approach lanes to the bridge required the placement of an additional traffic lane within the existing roadway. The bridge was originally designed for a maximum of 8 traffic lanes and thus it was determined that strengthening of the structure was required to accommodate the new lanes. URS Australia Pty Ltd undertook a structural assessment of the concrete approach spans on behalf of the Victorian state road authority (VicRoads). This assessment determined that the bridge had insufficient capacity for:

- Global hog of the box girder over piers at serviceability limit state
- Combined shear and torsion near the piers at ultimate limit state
- Local sag moments in the deck slab at ultimate limit state
- Local bending capacity in the cantilever frame at ultimate limit state.

VicRoads decided to undertake the necessary strengthening works via a Design and Construct contract. The overall project cost was of the order of A$10 million. URS Australia Pty Ltd joined with Abigroup and Savcor to launch a successful bid for the project, which was awarded in May 2001. The use of fibre composite laminates was a key component in the winning bid. BBR Systems Ltd (Zurich) supplied the FRP products for the project. FRP was used for both flexural, shear and torsional strengthening. To achieve adequate anchorage, the shear and torsional laminates were slotted into the concrete deck using a special concrete cutting saw.

The scale and complexity of the FRP strengthening undertaken in this project was unprecedented at the time and has demonstrated the cost effectiveness of FRP for strengthening large span concrete bridges in Australia.

Figure 7. Inspection of strengthening system

In addition to real world applications such as the West Gate Bridge, Australian researchers are also involved in fundamental research to better understand this type of system. The Centre for Infrastructure Diagnosis, Assessment and Rehabilitation at the School of Civil and Environmental Engineering, University of Adelaide is involved in research into retrofitting using externally bonded plates[2, 3]. The centre is also working on the development of generic design rules for all forms of plating which allow the designer to develop their own application techniques. Comprehensive design rules have now been developed for plating RC beams and slabs which covers all forms of plating and can be used to quantify both the strength and ductility.

Researchers within the Department of Civil Engineering at Monash University, Melbourne, are also investigating bonded FRP/concrete systems. Research has included the investigation of end cover separation and shear crack debonding failure mechanisms in rectangular concrete beams with bonded FRP plates, shear strengthening of reinforced concrete T-beams with L-shaped CFRP strips, and torsional strengthening of rectangular concrete beams with externally bonded CFRP sheets.

Hardwood timber beams have always been an important structural element in civil infrastructure and construction in Australia. However, the current political, environmental, and economic constraints on the use of native hardwoods and the rapidly diminishing supply of sawn timber with large end sections have created an urgent need for alternative solutions to repair and rehabilitate timber structures. Steel and concrete beams can be used in some applications but in general they are unsuitable due to their high weight and non-compatible stiffness characteristics.

It has been estimated that there are over 10,000 timber bridges in service in Australia. Many are far older than their original design life and require major rehabilitation or replacement now or in the near future. Many other (old) timber structures such as wharfs, warehouses, and buildings are also in poor condition. Some of these structures are important reminders of our heritage; others form part of our essential infrastructure. Unfortunately, in the current economic climate, the authorities responsible for these structures often cannot afford to replace them when technically required. For most of these structures, major rehabilitation or enhancement works will be required just to maintain acceptable factors of safety.

In close collaboration with Roads and Traffic Authority NSW and Qld Main Roads, FCDD has been working on the development of a manufactured beam that can be used to replace large hard wood beams. The concept is based on the use of plantation softwood for the bulk of the beam, with composite reinforcement modules being used to increase the strength and stiffness up to that of a typical Australian hard wood beam. The plantation timber is laminated veneer lumber (LVL), because this type of timber product has less variability than sawn timber, resulting in more predictable properties. The reinforcement modules use a combination of composite materials and have a Modulus of Elasticity of 60GPa with a failure strength of around 200MPa. The modules are bonded to the timber using a high strength epoxy adhesive.

F34 hardwood has a characteristic flexural strength of 100MPa and a Modulus of Elasticity of 21500MPa. This type of beam used to be readily available but is very rare these days. The hybrid beam can be designed to have a ductile failure mode which gives significant warning of failure.

A number of tests have been carried out in the development of these hybrid composite/timber

[2] D.J. Oehlers, 'Development of design rules for retrofitting by adhesive bonding or bolting either FRP or steel plates to RC beams or slabs in bridges and buildings', *Composites - Part A: Applied Science and Manufacturing*, v 32, n 9, September, 2001, p 1345-1355.

[3] M.S. Mohamed Ali, D.J. Oehlers and S.M. Park, 'Comparison between FRP and steel plating of reinforced concrete beams' *Composites - Part A: Applied Science and Manufacturing*, v 32, n 9, September, 2001, p 1319-1328

beams, aimed at verifying the strength, stiffness, failure mode, and predictability. The first 5 hybrid beams will be installed in two separate bridges early in 2004.

This report has presented a brief overview of development efforts into infrastructure composites within Australia. It has been shown that several new and innovative structural systems using composites are reaching a point of commercial reality within the Australian market. It is believed that the continuing development of these systems and others like them, in combination with national programs to provide engineers with necessary design guidance, will see composites gain an increasing foothold in the Australian civil engineering market over the coming years.

FRP's in Canadian civil structures: a personal account

Prof. Aftab A. Mufti
ISIS Canada Research Network, Winnipeg, Canada
&
Dr. Baidar Bakht
JMBT Structures Research Inc., Toronto, Canada

Soon after their visit to the EMPA laboratories in Zurich, Switzerland, in 1988, the two authors and their research colleague Dr. Leslie Jaeger wrote in the Canadian Civil Engineer an article, entitled 'Has the time come for advanced composite materials in bridges?' (Mufti et al. 1989). Until that time, research in the use of FRP's in civil structures in Canadian universities was non-existent. Although the lure of a 'durable' alternative reinforcement for concrete had spawned a few FRP manufacturing companies, the Canadian civil engineers were generally wary of using a material that they were not familiar with. The publishing of the article prompted the Canadian Society for Civil Engineering (CSCE) into establishing a Technical Committee on ACM in Bridges and Structures. The first major task of this committee was to send in 1990 a fact-finding mission to those countries in Western Europe in which FRP's were beginning to be used in civil structures. The report of the mission, which was funded by the Government of Canada, was compiled by Mufti et al. (1991). A second fact-finding mission, also funded by the Government of Canada, was sent to Japan in 1991, leading to task force report (Mufti et al. 1992).

In 1992, the CSCE Technical Committee grew into the ACMBS (Advanced Composite Materials in Bridges and Structures) Network of Canada, which was partly funded by the Government of Canada and partly by the industry. The network was very successful in meeting its goal to promote alliance between Canadian universities and industry. The interaction between industry and universities led to a large number of research projects in the civil use of FRP's.

At about the same time when the ACMBS Network was formed, work started on the writing of the first edition of the Canadian Highway Bridge Design Code (CHBDC). The Technical Committee of the CHBDC decided to create a subcommittee on Fibre Reinforced Structures. The task of the subcommittee, which included Canadian engineers and researchers as well as experts from Germany and Japan, was to try to formulate a set of design provisions for some fibre reinforced bridge components. Given that such design provisions had not been published anywhere in the world, it was expected that the subcommittee might not succeed in its task. It is good to note that such apprehensions were proven false, and a set of design provisions for fibre reinforced structures were included in the first edition of the CHBDC (2000).

Utilizing some draft provisions formulated by the CHBDC Technical Subcommittee on Fibre Reinforced Structures, the first Canadian bridge with CFRP tendons was designed. The Beddington Trail Bridge (Fig. 1) in the City of Calgary has six of its 26 precast concrete girders pretensioned with CFRP tendons procured from Japan. As described by Guha-Thakurta et al. (1994), the bridge was constructed in 1993. The CHBDC draft design provisions required that a structure incorporating concrete beams with FRP tendons should have alternative load paths such that the failure of beam does not lead to progressive collapse of the structure. In keeping with the spirit of draft provisions, the Beddington Trail Bridge has been provided with intermediate diaphragms, which can not only support a failed beam, but also contain holes to permit external prestressing in the unlikely event of the failure of the beams with CFRP tendons.

In 1995, ISIS (Intelligent Sensing for Innovative Structures) Canada Research Network was formed to provide Canadian civil engineers with smarter ways to build repair and monitor structures with high strength non-corroding FRP's and fibre optic sensors (FOS). For ISIS website, please refer to www.isiscanada.com. The ISIS Canada team, comprising 33 principal researchers and 276 researchers from 15 Universities and 92 associated organizations, works with public and private sector organizations with a vested interest in using FRP's and integrated FOS technologies for constructing and repairing bridges, buildings and other structures. It is a collaborative research and development program linking Canadian universities with public and private sector organizations which provide matching contributions to funding supplied by the Federal Networks of Centres of Excellence program. By weaving the efforts of several universities into one cohesive program, this research gains all of the advantages of sharing world-class scientists and facilities. A close relationship with industry and the user-sector ensures that all research is relevant and practical.

A number of demonstration projects are ISIS Canada's way of demonstrating the practicality of the new technologies to infrastructure owners. The successful completion of one project generates real-time data, which can be used in another application that, in turn, takes the technology closer to general acceptance. These prototype projects serve to gain the confidence of the design and construction community and provide the basis for proving the technology's long-term performance. With a fundamental mission to move technology from the laboratory to the field, ISIS Canada's success will eventually be measured by the extent to which decision-makers accept the new technology for conventional practice.

Mainly because of the initiatives of the ACMBS Network and ISIS Canada, FRPs are being used increasingly in Canadian civil infrastructure applications, their use ranging from reinforcing bars and tendons to wraps for seismic upgrading of columns. Since 1995, ISIS Canada researchers have been designing innovative structures and components, and monitoring them under actual field conditions, ever expanding the envelope of conventional practice. Some of the innovations include FRP/concrete hybrid systems, filament-wound bridge decks and poles, steel-free concrete bridge decks, glass fibre reinforced polymer (GFRP) tubes filled with concrete, FRP/stainless steel hybrid components, and the use of FRPs to rehabilitate masonry structures, which is particularly applicable for historical buildings. Because of space limitations only some of the demonstration projects are described in this account.

The 50-year old deck slab of the Joffre Bridge, located over the St-François River in Sherbrooke, Quebec, Canada, had deteriorated because of the corrosion of its steel reinforcement. The City of Sherbrooke and the Ministry of Transport of Quebec reconstructed a significant part of the bridge deck, sidewalk and traffic barrier using CFRP and GFRP bars. The bridge was instrumented with 180 sensors of different types. The rehabilitated bridge, opened to traffic in 1997, can be seen in Fig. 1 during a load test in 1998. The deck slab of the Joffre Bridge was the first Canadian bridge deck slab completely reinforced with FRP's (Benmokrane et al. 2000).

Figure 1: The Joffre Bridge during the load test

A significant research milestone was reached in 1998, when Manitoba's Department of Highways and Transportation opened the award winning Taylor Bridge in Headingley. Shown in Figure 2 the two-lane, 165.1-m long structure has four of its 40 precast girders reinforced with carbon FRP stirrups. These girders are pretensioned with carbon FRP tendons. GFRP bars are used in the barrier walls. The bridge was recently tested for its static and dynamic characteristics (Bakht et al. 2003).

The new Hall's Harbour Wharf in Nova Scotia, built in 1999, incorporates four innovative technologies: (a) the use of FRP reinforcement for concrete elements, (b) the use of short synthetic fibres to produce fibre reinforced concrete (FRC), (c) the patented steel-free bridge deck slab, which exploits fully the internal compressive arching action of the slab, and (d) smart FRP reinforcements with embedded sensors for remote monitoring (Newhook et al. 2000). This innovative wharf project represents the first Canadian application of both glass FRP and steel-free deck slab technology in a marine environment (Fig. 3). The end result is a durable, marine structure with a predicted service life of 60 to 80 years. The award-winning design is also cost-effective.

Figure 2: Taylor Bridge in Headingley, Manitoba

Figure 3: Hall's Harbour Wharf at low tide

Numerous research projects have been carried out to demonstrate the use of FRP wraps and reinforcement in the rehabilitation of concrete structural components. Integration of FOSs and the monitoring program constitute an essential part of the majority of projects. Incorporating ISIS technologies, the City of Sherbrooke undertook the rehabilitation of the 37-year-old Webster Parkade in the fall of 1996. Glass and carbon FRPs were used to (a) rehabilitate the columns, which had lost their initial capacity over the years due to corroding steel rebars, (b) protect column bases exposed to de-icing salts, and (c) strengthen beams. The success of this rehabilitation was acknowledged with the Innovation Award from the Québec Ministry of Municipal Affairs.

The Portage Creek Bridge (Fig. 4) in Victoria, British Columbia, designed in 1982, is a 125 m long three-span steel structure with a reinforced concrete deck supported on two reinforced concrete piers and abutments on steel H piles. The deck has a roadway width of 16 m with two 1.5 m sidewalks and aluminum railings. The superstructure is supported at the ends and has two intermediate supports along the length of the bridge called Pier No. 1 and Pier No. 2. The Portage Creek Bridge is a relatively high profile bridge that has been classified a Disaster-Route Bridge. However, it was built prior to current seismic design codes and construction practices and would not resist potential earthquake forces as required by today's standards. Although some consideration has been given to seismic aspects as evidenced in the original drawings, it requires retrofitting to prevent collapse during a seismic event. The service life of the bridge can thus be increased to 475 years.

Figure 4: Piers of the Portage Bridge requiring seismic upgrade

Most of the bridge is being strengthened by conventional materials and methods. The dynamic analysis of the bridge predicts the two tall columns of Pier No. 1 will form plastic hinges under an earthquake. Once these hinges form, additional shear forces will be attracted by the short columns of Pier No. 2. A nonlinear static pushover analysis indicates that the short columns will not be able to form plastic hinges prior to failure in shear. Therefore, it was decided that FRP wraps should be used to strengthen the short columns for shear without increasing the moment capacity. The bridge is instrumented with 16 foil gauges, 8 fibre optic sensors and 2 accelerometers. The bridge is being remotely monitored. ISIS Canada is assisting with the structural health monitoring of this bridge.

The advent of FRPs in civil engineering applications gives rise to the use of structural health monitoring to prove the material's superior performance. Also, the substantial deterioration of infrastructure results in a strong need for improved techniques for nondestructive evaluation and testing of the structural integrity of reinforced concrete in various applications including bridges, parking garages, dams, large buildings, highways and tunnels. Both new and rehabilitation construction can benefit from non-destructive in-situ structural monitors - FOSs and cables - designed and installed at the time of construction. ISIS Canada is conducting research using four sensors (Fibre Bragg Grating, Fabry-Perot, Long Gauge, and Brillouin Scattering). All have been used in field demonstrations.

Structural health monitoring is designed to provide a vital link between monitored structures and a central monitoring site. This will allow many structures to be monitored at a central site, with information transmitted via the Internet, thus eliminating costly permanent site installation and reducing the number of site visits.

Civil engineers are generally reluctant to use FRPs and FOSs in structures without approved design codes. A major step toward widespread use of FRPs has been the publishing of ISIS Canada's manuals for design engineers, being Installation, Use and Repair of Fibre Optic Sensors, Guidelines for Structural Health Monitoring; Reinforcing Concrete Structures with Fibre Reinforced Polymers; and Strengthening Reinforced Concrete Structures with Externally-Bonded Fibre Reinforced Polymers.

ISIS personnel are prominent in code committees such as the Canadian Highway Bridge Design Code and the Canadian Standards Association code on use of FRP in buildings and structures, and are involved in a worldwide exercise to upgrade design codes so engineers everywhere can take advantage of the knowledge gained and practical solutions developed by the ISIS Network.

References

Bakht, B., Mufti, A.A., Clayton, A., Saltzberg, W., and Klowak, C. 2003. Interpretation of bridge test data to determine dynamic load allowance and its influence on bridge design and evaluation. Proceedings, International Workshop on Structural Health Monitoring / Colloquium on Bridge Vibration '03, held in Kitami, Japan, Sep. 1-2, Japan Society of Civil Engineers, pp. 101-107.

Benmokrane, B., Zhang, B., Nicole, J.F., and Masmoudi, R. 2000. Application of fibre optic sensors for structural health monitoring of bridges and other structures. Research Report, University of Sherbrooke.

CHBDC. 2000. Canadian Highway Bridge Design Code, CAN/CSA-S6-00. CSA International, Toronto.

Guha-Thakurta, A., Abdelrahman, A.A., Rizkalla, S.H., and Tadros, G. 1994. First smart bridge in Canada, Developments in Short and Medium Span Bridge Engineering '94, Edited by A.A. Mufti, B. Bakht and L.G. Jaeger, Canadian Society for Civil Engineering, Montreal, pp. 859-870.

Mufti, A.A., Erki, M.-A., and Jaeger, L.G. 1991. Advanced Composite Materials with Applications to Bridges, Canadian Society for Civil Engineering, Montreal.

Mufti, A.A., Erki, M.-A., and Jaeger, L.G. 1992. Advanced Composite Materials in Bridges and Structures in Japan, Canadian Society for Civil Engineering, Montreal.

Mufti, A.A., Jaeger, L.G. and Bakht, B. 1989. Has the Time Come for Advanced Composite Materials in Bridges? Canadian Civil Engineer, Vol. 6. No. 2.

Newhook, J.P., Bakht, B., Tadros, G., and Mufti, A.A. 2000. Design and construction of a concrete marine structure using innovative technologies, Advanced Composite Materials in Bridges and Structures, Edited by J. Humar and A.G. Razaqpur, Canadian Society for Civil Engineering, Montreal, pp. 777-784.

Development and Review of Advanced Polymer/Fibre Composites used in the European Construction Industry

Prof. L C Hollaway, University of Surrey

There has been considerable activity in the utilisation of advanced polymer/fibre composites in the construction industry within the last 10-15 years and Europe has played a large part in the pioneering, research and development of these materials to form structural units. To enable these developments of FRP to take place some manufacturing techniques have been revolutionised. The property characteristics of fibre reinforced polymer (FRP) composites have demonstrated that they have many advantages over the more conventional civil engineering materials. Furthermore, their properties can be engineered such that when the material is combined with reinforced concrete (RC), steel, cast iron (CI), or wrought iron (WI), the resulting composite structure, utilised for rehabilitation or for new construction, will have been enhanced and will reflect the most advantageous properties of either of the component materials. This article will illustrate the progress made in the utilisation of FRP materials in the European construction industry, and the influences that have helped this achievement to be realised. In addition, the research efforts in these areas, the design guide-lines and the uses of FRP in construction will be mentioned.

Currently one of the major European activities involving the use of FRP composite materials in construction is in the rehabilitation of structural members. The FRP plate bonding technique was initially introduced as a replacement for steel to overcome some of the latter's shortcomings. The method was pioneered at the EMPA in Switzerland in the middle to late 1980s (Meier, 1987; Kaiser, 1989) and (Ladner *et al.,* 1990) but it was not until 1991 that commercial use of FRP externally bonded plates commenced with Ibach bridge in the County of Lucerne. Investigative work was followed by other European countries, some of which are referenced, (Arduini et al., 1994; Arduini et al., 1995), Triantafillou, and Plevris, (1992), (Quantrill et al., 1996a), (Varastehpour and Hamelin, 1995), (Garden and Hollaway, 1997), (He *et al,* 1997b), Bencardino *et al* (1997). It was realised that, unlike steel, FRP is unaffected by electrochemical deterioration and can resist the corrosive effects of acids, alkalis, salts and similar aggressive materials under a wide range of temperatures (Hollaway, 2001). The research workers recognised that corrosion resistant systems were not required when using FRP composites and this made the preparation prior to bonding, and maintenance after installation, less arduous than for steel. Furthermore, researchers in the mid 1990s (ROBUST) made cost comparisons and showed that, for the tendering process for installation projects, CFRP plate bonding was very competitive against steel plate bonding in first cost, before even future maintenance costs were added to the whole life cost equation.

Initial research, at EMPA in Switzerland, on the strengthening of reinforced concrete beams by prestressing external plates was widely reported (Meier et al., 1992, Deuring, 1993). This work included the cyclic loading of a beam, the plate of which was prestressed to 50% of its strength; although this prestress ensured the mean stress level in the cyclic loading was high, there was no evidence of damage to the plate after 30 x 10^7 cycles and the cracking of the concrete was well controlled. Further tests on prestressed external plates were carried out during the 1990 by other countries in Europe, references include Tranatafillou et al (1992), (Quantrill and Hollaway 1998), Garden and Hollaway (1998).

Since the initial investigations, many Research Institutions and Universities throughout Europe have undertaken considerable research into the stress analysis of the plate bonding technique. These investigations include analyses of de-bonding or peeling at the free end, relieving stress concentrations that occur at any crack that intercepts a plate or at a critical diagonal crack. Research has been undertaken on the effect of soffit curvature on CFRP strengthening. Furthermore, many investigations have been undertaken on the bonding mechanisms between adhesive/concrete adherend and adhesive/CFRP plate adherends and adhesive selections and long term loadings investigations

Fire tests on plate bonding systems have been carried out during the last 10 years with the preliminary work being carried out at EMPA, Switzerland in which the performance of steel and CFRP plated beams were compared when exposed to extreme high temperatures (Deuring, 1994). It was found that steel plates (joined only by adhesive bond) became detached after a matter of minutes of exposure, whereas the CFRP laminates progressively lost cross-sectional area due to burning at the surface, causing a gradual loss of stiffness of the member. It was realised that this superior behaviour was a consequence of the low thermal conductivity of the composite. Some of the research work, which has been undertaken in Europe, concerned with the behaviour of polymer composites in fire is given in Davies *et al* 2004.

It is important to investigate the shear capacity of a strengthened beam as flexural upgrading may have caused a deficiency in its shear resistance. The shear mode of failure tends to be brittle and therefore to prevent this failure mode shear strengthening is critically important during the upgrading of an RC beam. The work relating to shear upgrading is limited compared with that undertaken on flexural upgrading. The European investigations have been mainly undertaken in universities and research institutions. Taljsten (1997) studied the shear force capacity of beams when these had been strengthened by CFRP composites applied to the beams by three different techniques; these were: (i) wet lay-up system, (ii) prepreg in conjunction with vacuum and (iii) heat and vacuum injection. The results of the four point loaded tests showed, in all cases, a very good strengthening effect in shear when the CFRP-composites were bonded to the vertical faces of the concrete beams. The strengthening effect of almost 300% was achieved, although it must be stated that this value is dependent upon the degree to which the beam was reinforced in shear initially. Investigative analysis has been undertaken on the shear strength of slabs and bridge beams at the Universit of Bath, UK.

One of the most attractive applications for FRP is their use to achieve confinement of concrete columns; the reason for this lies in the high tensile strength of the fibres and of the orthotropy built in by their orientation. Furthermore, the use of FRP for strengthening is made attractive by the easiness and speed of application due to their lightweight and by their minimal thickness that does not produce any change in the shape and size of the strengthened elements. There has been a gradual increase in the publications concerned with confinement of concrete since the mid 1990s. Some of the references from European investigative work are La Tegola and Manni, (1999), Matthys *et al* (1999), La Tegola *et* al (2000), Micelli, *et al* (2001), Shahin *et al* (2002), Hussein and Ashit, M. (2003). Despite a large research effort expended, a relevant analytical tool to predict the behaviour has not yet been established. The majority of the work on confinement has been for seismic loading, predominately in Japan and the USA. In Europe only a relatively small number of bridge piers and columns have been confined. The piers of the Bible Christian bridge in Cornwall, UK, although not truly a confined situation, were strengthened against Heavy Goods Vehicle (HVG) impact. Glass fibre, aramid fibre and carbon fibre fabric materials were used and were placed longitudinally up the column as opposed to the normal confinement of columns in the hoop direction.

The utilisation of the NSM FRP members is a valid alternative to the externally bonded FRP plates. There are three main benefits to using this technique (i) the reinforcement is buried beneath the surface of the element and therefore protected from the external environment, (ii) the possibility of anchoring the reinforcement into adjacent members, (iii) the installation time is minimal. There is limited literature available in Europe to date, and only a limited amount of field application, De Lorenzis, *et al* (2000[a]), De Lorenzis, *et al* (2000[b]). A European practical example of this technique is the Trenchard Street Car Park, Bristol UK and Smithdown Lane Car Park, Liverpool, UK, Farmer (2004).

Corrosion is the major cause of the deterioration of the civil infrastructure especially of steel bridges. Furthermore, much of the infrastructure of the 19th and early 20th centuries was constructed using cast iron, wrought iron and early steel all of which had variations in the material quality and imperfections in the castings. To bring these structures up to their original or improved design requirement, it is necessary to strengthen them; invariably this is using advanced polymer composites. However, to date, only a relatively small number of metallic structures, compared with RC ones, have been upgraded using composite materials. It is necessary to consider which type of carbon fibre should be used to form the composite, namely the high stiffness (but with a slightly lower modulus of Elasticity value than that of steel) or ultra high stiffness (but having a low ultimate strain usually less than 0.4%). Research work in Europe has been and is being undertaken to strengthen Cast Iron, Wrought Iron and Steel structural systems. Hill *et al* (1999), Moy, (2000), Photiou *et al* (2003), a design guide has been published by CIRIC, RP 645, (2004).

Three examples of strengthening cast iron bridges in Europe are as follows:
<u>Bures Bridge in Suffolk UK</u> which is an arch bridge of 20 metres span. The structure consists of five arched cast-iron segmentally bolted girders, which support 1.5 metres wide brick jack arches spanning transversely between them. This bridge suffered a number of fatigue cracks. The best option for rehabilitation of the bridge was to use a two-part cold cured resin adhesive, rather than a heat cured resin, as the temperature control under the bridge could be difficult. The CFRP composite plates were pre-curved to fit each arch. Maunsell Cardiff UK were the consulting engineers.

<u>Hythe Bridge Oxford, UK</u>; this cast iron bridge is shown in Figure 1. The bridge was constructed in 1874 and carries a busy city centre road over a stream of the River Thames in two square clear spans of 7.8 metres.

Figure 1: Hythe Bridge, Oxford, UK (Kind Permission Mouchel Parkman Byfleet)

The deck comprises of eight inverted Tee section cast iron beams, with cast iron channel section edge beams supporting a decorative parapet; its capacity was 7.5 tonnes. The objective of the strengthening scheme was to raise its capacity form 7.5 tonnes to 40 tonnes. The bridge, which was week in mid span bending but was able to carry the full 40 tonnes assessment load in shear, was eventually strengthened in flexure by prestressing the upgrading carbon fibre composite plates. The degree of pre-stress was designed to remove all tensile stresses from the cast iron beams under the full 40 tonnes loading. Mouchel Parkman, West Byfleet, UK were the Consulting engineers.

Figure 2: Final placement of the carbon fibre prepreg around flange and web of beam (By kind permission of Taywood Engineering London, UK and ACG Derbyshire UK.

A principal curved steel beam was strengthened using a low temperature moulding advanced polymer composite prepreg material. The prepreg comprised of a unidirectional, $0^0/90^0$ and $\pm$ 45^0 fibre orientation, the fibres of the unidirectional prepreg were aligned along the direction of the beam and the $0^0/90^0$ were used to resist the shear and torsional loading. The prepreg composites were based upon carbon and glass fibres. Figure 2 shows the completed upgrade to the beam.

A major European activity is the renovation and rehabilitation of historic structures, which form a significant portion of the structural/building infrastructure; FRP composites are playing some part in maintaining this building heritage. Structures suffer varying degrees of degradation throughout their lives from environmental influences, inadequate initial construction techniques and mismanagement of materials. Furthermore, over the years many structures/buildings will have had a change of usage and with ever more stringent design requirements will require strengthening.

The requirements of the Historical Commission Authorities are very severe and will only reluctantly accept many of the recognised strengthening procedures, preferring instead that the historic structure be strengthened and renovated by replacing failed/degraded units with an identical material to the original one. However, some structures do require strengthening by other means and a unique option to that of conventional material is the utilisation of FRP composites. This latter material has the advantage of strength, stiffness, and lightweight, resistant to corrosion and is readily handled on site. However, in spite of the recognised advantages of this material, and the vast amount of work being undertaken to restore historic structures/monument in Europe, FRP material has not been employed to any great extent to strengthen structures. The following is a short review of the state-of-the-art in Europe.

Masonry

Triantafillou and Fardis (1993) pioneered the strengthening of masonry structures, the authors presented details concepts, models and analytical results on the applicability and effectiveness of un-bonded prestressed FRP tendons applied circumferentially to the external walls of an historic masonry building. Schwegler (1994) demonstrated the effectiveness of epoxy bonded composite strips to strengthen masonry structures under in-plane and out-of-plane loading. This was followed by the work of Triatafillou (1998), developing and verifying experimentally, simple design models for (i) epoxy-bonded FRP reinforcement to masonry walls under in-plane models (ii) for these systems under in-plane bending or out-of-plane bending in addition to axial loading. Tumialan *et al* (2001) discuss the use of FRP systems strengthening masonry elements including impact of such systems in the laboratory and in the field. This investigation was undertaken in the US but F Micelli University of Lecce, Italy was one of the investigators and authors.

Timber

Unpublished work in the late 1980s was undertaken by material scientists at the RAE (now QINETIQ) Farnborough UK to demonstrate the increased stiffness of timber upgraded with carbon fibre and glass fibre composite over that with no upgrade. However, the first major application of CFRP composite applied to historic timber was pioneered by (Meier 1995) when the 185-year-old covered wooden bridge in Sins, Switzerland was strengthened with 1 mm thick CFRP plate epoxy bonded to the upper and lower sides of the bridge. Kempe (1995) pioneered the application of CFRP tendons as strengthening materials for a timber truss roof structure at the Gothic Frauenkirche Church built in the 15th century in Meissen, Germany.

Metallic

The upgrading of metallic structures (bridges) has already been discussed and some samples given, (Bures Bridge in Suffolk UK and the Hythe Bridges in Oxford).

The first major European all composite structure, manufactured from an automated unit building block, was a versatile modular system produced by Maunsell Structural Plastics, Croydon, UK in 1989 and was introduced into the construction industry as the Advanced Composite Construction System (ACCS). It was first used in Europe in modular form as the bridge enclosure to the A19 Tees Viaduct at Middlesborough UK. The system was utilised to fabricate the cable stayed advanced composite Aberfeldy foot-bridge over the river Tay in Scotland, for the Aberfeldy Golf Course; the structure was designed in 1992. The tower and footbridge, which has a main span of 63 metres and an overall length of 113 metres, were manufactured by bonding together composites of the ACCS. The cable stays are made from aramid fibres.

The ACCS can be assembled into a large range of different high performance structures for use in the construction industry. It was fabricated (in 1995) into an interlocking all composite multi-cell box beam road bridge at Bonds Mill UK, (1995) Figure 3.

Figure 3: Bonds Mill Lift Bridge Shrivensham UK

The requirements of this road bridge were that it should carry concentrated wheel loads and resist the large number of load cycles without fatigue damage. The key to solving this problem was the development by CIBA Polymers (now Vantico) of a slow foaming epoxy, which could be used to fill the 80 x 80 mm x 9 m long cells of the ACCS modules.

In 1997 the architect to the City of Kolding, Denmark, conceived and designed, in conjunction with Fibreline Components, Denmark, a cable stay pedestrian and cyclist bridge of 40 metre span with a load bearing capacity of 500 kg/m^2 to cross an overhead electrification main railway line which runs in a narrow cutting bordered on one side by a salt water fjord.

The Wilcott Bridge, Shropshire UK shown in Figure 4 was erected in 2003 and is an innovative footbridge spanning a dual two lane trunk road (A5 Nesscliffe Bypass). It is a lightweight suspension bridge with inclined towers. The deck is entirely constructed from modular preformed FRP components (ACCS) produced from fibre reinforced polyester material; the span is 51.3 metres and width 2.2 metres. The live load has a value of 5.0 KPa. A maintenance manual has been issued, and a detailed inspection of the bridge will be undertaken at the end of the first year of service and thereafter inspections will take place every 6 years and a one year routine inspection.

In 2003 an advanced polymer composite roof system was erected over a new platform at Lindevang Station in Copenhagen. The Khras Architects designed the roof, which is 60 metres long and has a thickness of 600 mm at its greatest point. Fibreline Composites A/S developed the roof construction and it is one of their product range, Figure 5 shows the roof system.

Figure 4:Wilcott Bridge Shropshire UK

Figure 5: Roof system over platform at Lindevang Station - Copenhage

A building system designed by ETH, Zurich and Lausanne, Switzerland is the Eye-catcher residential/ office building shown in Figure 6. It was manufactured and erected by Fiberline for the Swissbau 99 exhibition and was then dismantled and rebuilt at Münchensteinerstrasse 210, Basel. The structure has a height of 15 metres and a ground area of 10 x 12 metres. The load bearing members are Fiberline profiles.

The advantages of the strength to weight ratio of fibre reinforced polymers are most important in very long span structures and these characteristics are best illustrated by their potential for forming the main supporting cables of suspension bridges. The theoretical limit of suspension bridge spans constructed from currently available high strength steel wire is of the order of 5000 metres; the cables can only just support their own weight at this span. If, however, aramid or carbon fibre/polymer composites were utilised for the construction of the cables this value would increase to over 10 000 metres, Richmond and Head, (1988). Meier (1987) proposed to use carbon fibre reinforced polymer cables for a 10 000 metre span bridge across the straight of Gibraltar. Assuming that such structures were technically feasible, investigations suggest that the economic span of advanced composite cables in suspension bridges would be around 4 000 metres.

Figure 6 : Eye-catcher residential/office building Zurich (Kind permission Fiberline Composites Denmark)

The requirements for ropes and cables are that they should have high strength and stiffness. The two most common fibres used in the Parafil systems are the polyesters and the aramids. The parallel filaments are placed in an extruded thermoplastic sheath, which gives the rope its structure and protects the fibres from external influences. The ropes offer high strength, high stiffness and consequently are ideal for use as stay cables. The Oppegaard footbridge in Norway is basically a tied arch and Parafil ropes provide the tension tie, Grostad, (1997),

FRP rebars in concrete are used for anticorrosion purposes in structural applications, which are exposed to marine environments, chemical or other industrial plants. However, their use in construction is less well established compared to the externally bonded reinforcement and the main reason for this is the possible moisture diffusion through the surface of the polymer leading to changes in the mechanical and chemical characteristics; the changes are reversible upon drying. If, however, moisture is present at the fibre/matrix interface, this will cause breakdown of the bond in this region. The FRP rebar will be exposed to an alkaline environment, when embedded into concrete, which will have a pH value of 13; glass fibres are severely attacked in an alkaline environment and will degrade. However, the development of improved chemical resistant matrices and the production of an alkaline resistant glass, Almenara and Thornburrow (2004), has now given GFRP composites an advantage over traditional materials. Example of GFRP reinforced concrete bridges in Europe are (i) the Fidgett Footbridge at Chalgrove Oxfordshire erected in 1995 and the Oppegaard footbridge situated in Oslo; in both cases EUROCRETE glass FRP rebars were used. FRP prestressing reinforcement is available in some European countries and examples of these systems are (i) a prefabricated CFRP prestressed girders for a bridge which passes over a high-speed railway line at Kortenberg (Belgium) and (ii) CFRP, PC poles in Switzerland. Extensive use of CFRP reinforcement, (i) as cable stays. (ii) prestressing reinforcement in a cable stayed bridge at Herning, Denmark. (iii) external post-tensioning with CFRP cables in the Dintelhaven bridge in Rotterdam (The Netherlands).

The bridge deck weight is an important part of the overall design of a long span bridge and its form and stiffness are important with respect to aerodynamic stability. Furthermore the demand for the development of more efficient and durable bridge decks is at the forefront of the priority of highway authorities worldwide.

In Europe, the first 'all composite' bridge deck was analysed and developed by a consortium of industrial firms. The highway bridge deck, (known as the ASSET bridge deck, Advanced Structural Systems for Tomorrow's Infrastructure) was designed (i) to carry 40 tonnes vehicle wheel load and (ii) to ensure that all the vital connection details achieved a complete decking system. Conventional connecting parts such as parapets, lampposts, existing main girders etc. fitted into the system. An ASSET highway bridge was constructed for Oxford County Council, UK, in 2002. The bridge, which replaced the existing West Mill Bridge over the river Cole at Shrivenham, was manufactured mainly from GFRP consisting of the ASSET deck and main girders; the latter were constructed from four box-shaped GFRP sections bonded together. On to the external surfaces at the top and bottom of the beams were bonded CFRP plates to provide extra stiffness to the beams**.** Figure 7 shows the bridge deck being placed into position.

Some APC areas currently under investigation are: Thermal isolating load-transmission components for concrete structures; New road concepts - Switzerland École polytechnique Fédérale de Lausanne; Developing Code requirements for FRP's in Civil Engineering at RWTH Aachen, Germany; Sensory systems for health monitoring of structures using fibre optic sensors - This topic is being undertaken in a number of Research Universities and Institutes in Europe. (Schwesinger, P. and Wittman, F (2000), Inaudi, D. (2000), Bergmeister, K. and Santa, U. (1999), Del Grosso, A, *et al* (2000)); The development of 'next generation' of advanced fiber-based strengthening systems for the fast, reliable user friendly and effective retrofitting of concrete and masonry structures. This is being carried out in collaboration with 12 partners (6 industrial and 6 research) within the framework of a large national project funded by the Greek general Secretariat for Research and Technology; the project is co-ordinated by the University of Patras. Greece; Development, design and experimental verification of a new lightweight slab system for buildings based on FRP sandwich panel Construction. - University of Patras. Greece; Analysis and investigation into the mechanical barrier and fire properties of exfoliated epoxy-layered silicate nanocomposites for use, particularly in corrosive environments in the civil engineering industry. .University of Surrey, UK; FRP patch repair to extend the fatigue life of civil engineering metallic structures to be able to design effective patch repairs on metallic girders and connections. - University of Surrey. UK; Classification and Qualification of Composite Materials Systems for use in the Civil Infrastructure. DTI funded and Oxford Brookes University, project Manager; Low Intrusion Conservation Systems for Restoration of Timber Structures. EC CRAFT Project. Managed by Rotafix Academic Partner Oxford Brookes University; EMPA focuses its activities on the innovative implementation of acquired fundamental knowledge. Key activities are sustainability, reliability and safety of materials, components systems and materials and systems in construction and the engineering sciences. EMPA, Switzerland.

Currently there are no mature design codes for designing with FRP composites because of the diverse lay-up possibilities of material. The following guidance documents are some of those that are available to the civil engineering industry in Europe.

Figure 7: ASSET Highway Bridge Deck Being Placed in Position (Kind permission of Fiberline Composites Denmark)

Over the last 10 years a considerable effort has been devoted to the production of the Fib Design Guide for strengthening, upgrading and reinforcing concrete with FRP composites. Researchers and designers in many European Countries have undertaken the production of this model code and it has been quite impossible in this short article to mention all those or their Institutions that were involved.

Composites

- 'Structural Design of Polymer Composites: Eurocomp Design Code and Handbook' Clarke (1996)
- 'Design and construction of vessels and tanks in reinforced plastics: BS 4994' (BSI, 1987)
- 'Fibre-reinforced polymer composites in construction' CIRIA (2001)
- Highways Agency (1994) Strengthening of concrete highway structures using externally bonded plates: BA 30/94. The Highways Agency, London.

Externally-bonded FRP, applied to concrete

- Design guidance for strengthening concrete structures using fibre composite materials Technical Report (TR) 55, December 2000.
- Strengthening concrete structures using fibre composite materials: acceptance, inspection and monitoring Technical Report (TR) 57, February 2003
- Revision of TR55 (to be used in association with TR 55) Autumn 2004.
- 'Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures' ACI440.2R (2002). [Used in Europe]
- FIB (CEB-FIP) Technical Report 'Externally bonded FRP reinforcement for RC Structures', fib bulletin 14, (2001). Fédération internationale du béton, Lausanne, Switzerland.

Externally-bonded FRP, applied to metallic structures

- Institution of Civil Engineers (2001) FRP composites – life extension and strengthening of metallic structures' ICE Design and Practice Guide, ed. Moy, London
- CIRIA RP 645 (2004) 'Strengthening metallic structures using externally-bonded fibre-reinforced polymers'. March 2004.
- Die Norske Veritas Offshore Standard OS-C501, Composite Materials.

Adhesive applied to composites and dissimilar adherends.

- The Institution of Structural Engineers (1999). Guide to the structural use of adhesives. SETO London.

References

Almenara, P C and Thornburrow, P. (2004) 'A New Glass Fibre Reinforcement for Anti-corrosion Composites' in Advanced Polymer Composites for Structural Applications in Construction – ACIC 2004. Ed. L C Hollaway, M K Chryssanthopoulos, Publishers Woodhead Publishing, Cambridge.

Arduini, M., D-Ambrisi, A. and Di Tommaso, A. (1994) Shear Failure of Concrete Beams Reinforced with FRP Plates, in Infrastructure: New Materials and Methods of Repair, (ed. K. Bashan), Proc. 3rd Materials Engineering Conf., ASCE, San Diego, 13-16th Nov. 1994, pp.123-130.

Arduini, M., Di Tommaso, A. and Manfroni, O. (1995) Fracture Mechanisms of Concrete Beams Bonded with Composite Plates, in Non-Metallic (FRP) Reinforcement for Concrete Structures, (ed. L. Taerwe), E & FN Spon, London, pp.483-491.

Bencardino, F., Spades, G. and Swamy, R.N. (1997), 'Design to repair/up-grade R.C. structures: the key to a successful utilisation of CFRP laminates', Proc. 7th International Conference on Structural Faults and Repair, University of Edinburgh, July 8th - 10th 1997, Vol.2, pp183-190.

Bergmeister, K and Santa, U. (1999), 'Global Monitoring Concepts for Bridges' Proceedings of the fib-TG 5.1, Institute of Structural Engineering, Vienna.

Davies, J M , Wang, Y C and Wong, M H. (2004) ‘Polymer Composites in Fire’ In ACIC 2004 Conference proceedings ‘Advanced Polymer Composites for Structural Applications in Construction – ACIC 2004’. ed. L Hollaway, M K Chryssanthopoulos and S S J Moy. Pub. Woodhead Publishing, Ltd. Cambridge.

De Lorenzis, L., Nanni, A and La Tegola, A. (2000[a]). ‘Flexural and Shear Strengthening of Reinforced Concrete Structures with Near Surface Mounted FRP Rods’ , Proc. 3rd International Conference on Advanced Composite Materials in Bridges and Structures, Ottawa, Canada, J.Humar and A G Razaqpur, Editors, 15-18 Aug. 2000, pp 521-528.

De Lorenzis, L., Nanni, A and La Tegola, A. (2000[b]), ‘Strengthenig of Reinforced Concrete Structures with |Near Surface Mounted FRP Rods’, International Meeting on Composite Materials, PLAST 2000, Milan, Italy, May 9-11 2000.

Del Grosso, A. Inaudi, D. and Lanata, F. (2000), ‘Strain and Displacement Monitoring of a Quay Wall in the Port of Genoa ny means of Fiber Optic Sensors’ 2nd European Conference on Structural Control, ENPC, Paris, July 2000.

Deuring, M. (1993), Verstarken von Stahlbeton mit Gespannten Faserverbundwerkstoffen, (Poststrengthening of Concrete Structures with Prestressed Advanced Composites), EMPA Research Report No. 224, EMPA, Dubendorf, CH-8600, Dubendorf, Switzerland, (in German).

Deuring, M. (1994), Brandversuche an Nachtraglich Verstarkten Tragem aus Beton, EMPA Report No.148795, EMPA, Dubendorf, CH-8600, Dubendorf, Switzerland, (in German).

FIB (CEB-FIP) Technical Report ‘Externally bonded FRP reinforcement for RC Structures’, fib bulletin 14, (2001). Fédération internationale du béton, Lausanne, Switzerland

Farmer, N. (2004), ‘Near Surface Mounted Reinforcement for Strengthening – UK Experience and Development of Best Practice’ In ACIC 2004 Conf. Proceedings ‘Advanced Polymer Composites for Structural Applications in Construction – ACIC 2004’. ed. L Hollaway, M K Chryssanthopoulos and S S J Moy. Pub. Woodhead Publishing, Ltd. Cambridge.

Garden and Hollaway, L.C. (1997), ‘FRP for Concrete Construction: Activities in Europe’ ACI – Concrete International, October 1999, Vol. 21, No. 10 pp33-36.

Garden, H N, Hollaway, L C. (1998) ’An experimental study of the failure modes of reinforced concrete beams strengthened with prestressed carbon composite plates’ Composites, Part B, Vol.29B, pp411-424, 1998. ISSN 1359-8368

Grostad, T. (1997), ‘Case Studies within Eurocrete, Fender in Qatar and Bridge in Norway’ Proc. 3rd International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures, Sapporo, Vol1, pp 657-664.

He. J.H., Pilakoutas, K. and Waldron, P. (1997), ‘Analysis of externally strengthened R. C. beams with steel and CFRP plates’, \proc. 7th International Conference on Structural Faults and Repair, University of Edinburgh, July 8th - 10th 1997, Vol. 2 pp. 83-92.

Hill, P S, Smith, S and Barnes, F J. (1999), ‘Use of High Modulus Carbon Fibres for Reinforcement of Cast Iron Compression Strts within Lindon Underground: Project details. Conference on Composites and Plastics in Construction, Nov. 1999, BRE, Watford, UK. RAPRA Technology, Shawbury, Shrewsbury, UK. Paper 16 1-6.

Hollaway, L.C. and Head, P R (2001), ‘Advanced polymer Composites and Polymers in the Civil Infrastructure’ Elsevier Science Ltd. Oxford.

Hussein, Y. and Ashit, M. (2003), ‘Retrofitting of Exterior Beam-Columns Joint Subjected to Seismic loading’ Proceedings of the Arabic Conference for Composite Materials, Nov. 17-30, 2003, Abo-Dabi, UAE.

Inaudi, D. (2000), ‘Appliocation of Fibre Optic Sensors to Structural Monitoring’ n Trends in Optical Nondestructive Testing and Inspection, P.K. Rastogi and D. Inaudi Eds., Elsevier, pp 459-472.

Kaiser, H.P. (1989) ‘Strengthening of Reinforced Concrete with Epoxy Bonded Carbon-Fiber Plastics’ Doctoral Thesis Diss. ETH, Nr 8918 Zurich, CH-8092, Zurich, Switzerland, 1989 (in German).

Kempe, O (1995), ‘The Stabilisation of the Gothic Roof Supports of the Frauenkirche Meissen with Carbon Fibre-Reinforced Plastic Bracing’, 7th Internationales techtextil Symposium Teil 5,4, Frankfurt, Section 5.41.

Meier, U. (1987) Bridge Repair with High Performance Composite Materials, Material und Technik, Vol.15, pp.125-128, 1987 (in French and German).

Meier, U. and Kaiser, H.P. (1991) Strengthening of Structures with CFRP Laminates, Proc. Advanced Composite Materials in Civil

Engineering Structures, Mats. Div. ASCE, Las Vegas, Jan. 1991, pp.224-232.

Meier, U., Deuring, M., Meier, H. and Schegler, G (1992) 'Strengthening of structures with CFRP laminates: research and application in Switzerland', In:Neale, K. W. and Labossière, P (eds) Advanced Composite Materials in Bridges and Structures, Proc. 1st International Conference, Sherbrooke, 1992, pp 243-251.

Meier, U., Deuring, M., Meier, H. and Schwegler, G. (1993) Strengthening of Structures with Advanced Composites, in Alternative Materials for the Reinforcement and Prestressing of Concrete, (ed. J.L. Clarke), Blackie Academic and Professional, Glasgow, pp.153-171.

Meier, U (1995), 'Strengthening of Structures using Carbon Fibre/Epoxy Composites', in 'Construction and Building Materials', Vol 9, pp 431-351.

Moy, S S J, Barnes, F., Moriarty, J., Dier, A.F. Kenchington, A and Iverson, B. (2000), 'Structural Upgrade and Life Extension of Cast iron Struts using Carbon Fibre Reinforced Composites' Proceedings of the Conference on Composites and Plastics in Construction Building Research Establishment, UK.

Ladner, M., Pralong, J. and Weder, C. (1990) Geklebte Bewehrung: Bemessung und Erfahrung, EMPA Report No.116/5, EMPA, Dubendorf, CH-8600, Dubendorf, Switzerland, (in German).

Photiou, N K., Hollaway, L C and Chryssanthopoulos, M K. (2003) 'Characterisation of Adhesively Bonded Composite Plates for Upgrading Structural Steelwork' in 'Structural Faults and Repair – 2003' 10th International Conference on Extending the Life of Bridges, Concrete and Composites Buildings, Masonry and Civil Structures. 1st –3rd July 2003, London.

Photiou, N K., Hollaway, L C and Chryssanthopoulos, M K (2004), 'Selection of CFRP Systems for Steelwork Upgrading', to be delivered at 1st International Conference on "Innovative Materials and Technologies for Construction and Restoration – IMTCR 04", Lecce Italy.

Quantrill, R.J., Hollaway, L.C. and Thorne, A.M. (1996) Part 1. Experimental and Analytical Investigation of FRP Strengthened Beam Response, Mag. Concrete Research, Vol.48, No.177, pp.331-342, Dec. 1996.

Quantrill, R.J. and Hollaway, L.C. (1998) 'The flexural rehabilitation of Reinforced Concrete Beams using prestressed advanced composite plates', Composite Science and Technology, **58**(8).pp 1259-1275

Richmond, B. and Head, P.R.(1988) Alternative materials in long span bridge structures' Kerensky Memorial Conference, London. June 1988.

ROBUST (Strengthening of Bridges using Polymeric Composite Materials) UK Government's DTI-LINK Structural Composites Programme, 1995-1998.

Schwegler, G (1994), 'Masonry Construction Strengthened with Fiber Composites in Seismically Endangered Zones' Proc. 10th European Conference on Earthquake Engineering, Acapulco, Mexico.

Schwesinger, P. and Wittman, F. (2000) Present and Future Monitoring, Proceedings of th eSixth International Workshop on Material Properties and Design, Bauhaus University Weimar, Aedificatio Publishers, Freiburg.

Shahin, H., Hashim,Y., Shaaban, I. Abdelrahman, A. and El-Rakib, T. (2002) 'Behaviour of Concrete Columns Retrofitted by Fiber Reinforced Polymers under Repeated Loads' Proceedings of the 3rd Middle East Symposium for Infrastructure Applications, Dec. 17-20, 2002, Aswan, Egypt.

Shaw, M. (1993) Strengthening Bridges with Externally Bonded Reinforcement, in Bridge Management 2, (eds. J.E. Harding, G.A.R. Parke and M.J. Ryall), Thomas Telford, London, pp.651-659.

Taljsten B. (1997) 'Strengthening of concrete structures for shear with bonded CFRP fabrics' Proc. of US-Canada-Europe Workshop on Recent Advances in Bridge Engineering - Advanced rehabilitation, durable materials, non-destructive evaluation and Management., Ed U. Meier and R Betti, pub. EMPA Dubendorf Switzerland 1997.

Triantafillou, T.C. and Plevris, N. (1992) Strengthening of RC Beams with Epoxy-Bonded Fibre-Composite Materials, Materials and Structures, Vol.25,.pp 201-211.

Triantafillou, T.C., Deskovic, N. and Deuting, M. (1992), 'Strengthening of Concrete Structures with Prestressed Fiber Reinforced Plastic Sheets', ACI Struct J **89**(3), pp 222-235.

Triantafillou, T C and Fardis, M N (1997), 'Strengthening of Historic Masonry Structures with Composite Materials', Materials and Structures, RILEM. Vol. 30 pp 486-496.

Triantafillou, T C (1998), ' Strengthening Masonry Structures using Epoxy-bonded FRP

Laminates', ASCE Journal of Composites for Construction Vol.2 No. 2, pp 96-104.

Tumialan, J G, Micelli, F. and Nanni, A. (2001), 'Strengthening of Masonry Structures with FRP Composites' Structures 2001, Washington DC, May 21-23, 2001.

Varastehpour, H. and Hamelin, P. (1995) Structural Behaviour of Reinforced Concrete Beams Strengthened by Epoxy Bonded FRP Plates, in Non-Metallic (FRP) Reinforcement for Concrete Structures, (ed. L. Taerwe), E & FN Spon, London, pp.559-567.

Achievement of Mission Impossible by Advanced FRP Materials

Prof. Issam E. Harik
Department of Civil Engineering, University of Kentucky, U.S.A.

In Fall 2001, I was asked to give an address on "Achievement of Mission Impossible by Advanced FRP Materials" at the Japan Society of Civil Engineering annual meeting. Never before did "Mission" and "FRP Materials" cross my mind in the same sentence. Before I could even identify the key points in my presentation, I had to define the "Mission". It barely took a minute to look at FRP Composites as the second "new construction material" of the 20th century, the first being "Prestressed Concrete".

There are some parallels between prestressed concrete and FRP composites. According to David Billington, "*The idea of prestressing, a product of the 20th century, announced the single most significant new direction in structural engineering of any period in history.*" Looking back at the 20th century, FRP Composites can be added to the statement. Billington reports that around 1930, Eugène Freyssinet, the father of prestressing, speaking of his discovery of prestressed concrete to LeCorbusier, said: "*I reached my goal. So now I'm looking around to see what I can use this discovery of mine for. And in my opinion, modern society needs housing, parks and highways. The new material is entirely different from any other already in existence; it is five or six times more resistant than the cements and steels now in use.*" The same questions were raised by researchers about FRP composites in the 1970s and 1980s, and are still being raised today.

At first, prestressed concrete was not embraced by the engineering community, and Freysinet was even ridiculed. The first prestressed concrete bridge in the US was constructed in the early 1950s. In less than 25 years, more than 95% of the short to medium span bridges (less than 30 m spans) were built using prestressed concrete girders in some states in the US (e.g. Kentucky).

Recently, advanced materials have been increasingly used in civil engineering structures. They range from high strength steel, high performance concrete, stainless steel, fiber-reinforced polymer (FRP) composites, etc. I will focus the presentation on the use of FRP composites in the United States.

FRP construction components such as grating, tanks, rebars, small size structural shapes, automotive components, etc., have been used since the early 1950s by a number of industries in areas where corrosion, lightweight, magnetic interference, etc., were of primary concern (e.g., chemical, aerospace, and marine construction). The majority of these FRP components were subjected to light loading (or used as secondary structural components). During the past two decades, we have witnessed field applications where FRP members were the primary structural components in bridges, buildings, and other structures. Although the use of FRP composites in civil engineering structures has increased dramatically in the last decade, these achievements have been referred to by some as "Mission Impossible." The "Impossible" part comes from applications where other construction materials could not compete with FRP composites and from a number of obstacles facing any new construction material, such as testing standards, design and construction codes, acceptance by the public, cost, etc.

Committees in the American Concrete Institute (ACI), American Society for Testing and Materials (ASTM), American Society of Civil Engineers (ASCE), American Association of State Highways and Transportation Officials (AASHTO), and other organizations are currently preparing guidelines for testing of FRP specimens and components. Within the next couple of years, it is expected that published documents by a number of these committees will be available for distribution to the engineering community. These committees are have and are also preparing guidelines for analysis, design and construction of

FRP components and structures. ACI published the "Guide for the Design and Construction of Concrete Reinforced with FRP Bars" (ACI 440.1R-01), and the "Guide for the design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (ACI 440.2R-02).

Similar to prestressed concrete, public acceptance of FRP structures was quite hesitant at first. The lack of codes and standards, familiarity with material, and few field applications, limited the consideration and deployment of the material. This was also true in the aerospace industry when composites were first introduced in the early 1950s. In addition to familiarity, cost was and remains a major hurdle. With the exception of repair or strengthening with FRP fabric and laminates, and since the lowest bid remains the primary factor in awarding projects in the US, it is difficult for FRP material to compete with established construction material. The following sections present case studies that have introduced FRP composites to the U.S. civil engineering community.

The first major FRP composites structure in building construction is the three-story high pultruded FRP turret tower which houses antennas for police and fire communications on top of the Sun Bank building in Orlando, Florida. FRP components were chosen because of their electromagnetic transparency, low reflection level of radio waves, and lightweight. Other examples include buildings which house sensitive electronic equipment and require construction material possessing nonmagnetic properties. These and other structures were constructed with components produced by Strongwell (formerly Morrison Molded Fiber Glass, or MMFG) and other fabricators.

Pedestrian bridges, mainly truss bridges, constructed with pultruded FRP channels and tubular sections were first to attract the attention of the civil engineering community in the U.S. These bridges were built using FRP components because they were less expensive to construct than bridges with conventional material (steel, concrete, or wood). The bridges are located in remote areas where structural components are delivered by hand, on mules, or by air, and construction is carried out without any mechanical equipment. The design firm of E.T. Techtonics in Pennsylvania, designed the bridges, and Creative Pultrusion as well as Strongwell produced the FRP components.

In the early 1990s, and in an effort to transfer aerospace FRP technology to civil infrastructure, the U.S. Department of Defense Advanced Research Projects Administration-Technology Reinvestment Project funded a number of projects to deploy advanced composites in bridges. One example is the Clear Creek bridge which was constructed in 1996 in the Daniel Boone National Forest in Kentucky. where hybrid carbon/glass FRP I-beams were used. Since the late 1990s, deployment of FRP composites in highway bridges has increased considerably due to funding from FHWA through the Transportation Equity Act 21 - Innovative Bridge Construction Program (IBRC). More than fifty field applications on bridges have been or are being carried out.

Strengthening with FRP fabric or laminates has become the method of choice for repairing and/or strengthening structural elements in bridges and buildings. FRP has proven to be economical and effective material for such applications.

What does the future hold? Well, FRP composites in civil engineering infrastructure are here to stay. FRP will be one of the construction materials in the future, but not the only one. It has already proven itself in a number of applications as the material of choice. Although gigantic hurdles have been overcome, even larger hurdles remain. Reduced cost, and codes and standards remain as the challenges to meet. Ongoing research in the international engineering communities is addressing a number of the issues that will pave the way for wider acceptance and field applications of FRP composites.

Silver Springs Equestrian Bridge, Maryland, USA (courtesy of E.T. Techtonics)

Sun Bank Building, Florida, USA (courtesy Strongwell)

Clear Creek Bridge, Kentucky, USA (courtesy of the University of Kentucky)

A Perspective From Industry

In each issue the newsletter will highlight a perspective from industry. In this issue we are fortunate to have a brief article by Mr. Doug Gremel of Hughes Brothers, Inc., one of the pioneers in the development and use of FRP rebar.

An Industry Perspective

Doug Gremel
Hughes Brothers, Inc.

It's an honor to be able to write you with an industry perspective on the state of the FRP industry in this edition of the IIFC newsletter.

Simple ideas can have enormous consequences. The notion that FRP materials can make buildings and structures last longer is a powerful one. Academics wish to make a name for them selves with this new technology, businessmen hope to profit and government agencies throughout the world can see the potential benefits. It's a noble cause to free billions of dollars of public money that could be directed to higher uses.

The FRP community has grown to be a large one. In many ways this can be bad if we become self-delusional. I see the same people at different venues around the world. We have become our own choir, but we need to evangelize outside ourselves.

I've attended conferences where academics have asked, "Is anybody using this stuff?" The answer is an emphatic, YES!! From our factory anyway, shipments of FRP materials are a daily occurrence. An industry is being born. Competition is heating up and projects are being won and lost around the globe. This applies to new construction and strengthening.

Academics are always asking, what kinds of projects are happening? As a member of industry, we are as anxious to tell you about our revenue streams, as you are to tell us about yours. Rest assured, its not very sexy or worth publishing a paper about a simple transformer pad or MRI project or the negative moment strengthening of the second floor slab of a hot dog factory. The published design guidelines and standards we collaboratively work on are having an impact. Real businesses are being built furnishing FRP materials and design and installation services.

Being asked to author a newsletter piece such as this is an invitation to challenge the FRP community. At the risk of being too simplistic, I offer the following challenges to Academia, Industry and Government.

Academia
- Be practical in your research endeavors.
- Don't duplicate your colleague's research; expand on it.
- Foster partnerships between Industry and practitioners. This will help your research be grounded in practicality.

Industry
- Cooperate and participate in International standards for design and test methodologies.
- Be open about your process, quality assurance methods and constituent materials.
- Collaborate with a research institution or University.

Government
- Keep funding research and practical implementation of FRP technologies.
- Keep a neutral bias, but talk with Industry.
- Correlate with practitioners to ensure a payoff.

Each of us has a responsibility to evangelize about FRP in our sphere of influence. IIFC has an important role in the dissemination and networking of this kind of information. I urge you to become more involved in this important effort.

An Owner's Perspective

In each issue the newsletter will highlight a perspective from the "owner/user" community. In this issue we are fortunate to have a brief article by Dr. Charles Sikorsky of the California Department of Transportation (Caltrans). It is interesting that the perspective is one of monitoring – a concern common to all structures, perhaps indicating a transition that has already made by FRP materials.

Validating the Performance of a Bridge In-Service Strengthened Using FRP Composites
By

Charles Sikorsky, California Department of Transportation

Initially, fibre-reinforced polymer or FRP composite materials were introduced to the bridge community as an effective material for strengthening structures subjected to seismic events. Since then these materials have also been investigated as a possible means of bridge rehabilitation to increase live-load capacity. They provide significant structural advantages due to their lightweight, high strength-to-weight ratio, high stiffness-to-weight ratio and corrosion resistance. They also provide opportunities to the bridge community that are not possible with conventional materials. While there are benefits to the use of these advanced materials, there are limitations as well. One such limitation is the lack of data to evaluate the long-term performance of bridges rehabilitated with these materials. Performance is taken here to include requirements important to a bridge manager or owner such as serviceability, durability and reliability. For example, the long-term durability of carbon composites subjected to environmental effects, as well as heavy truck traffic, is relatively unknown [Karbhari et al., 2000]. Durability in this work is defined as the ability of the material to resist cracking, oxidation, chemical degradation, wear, delamination, and/or the effects of foreign object damage for a specified period of time, under the appropriate load conditions, under specified environmental conditions. More simply, durability is measured as the period of time, these components can be expected to resist the original design loads. The serviceability of the bridge is defined by the load carrying capacity of the bridge. Reliability describes the probability these elements will survive the specified loading condition(s).

While experimental work in the laboratory is necessary and has largely been proven successfully, more emphasis needs to be placed on validation of laboratory results with experimental work in the field. It is difficult to realistically quantify strength in the laboratory, since deterioration, as a minimum, is a result of the interaction between the manufacturing process, environment and stress due to load. For example, the British Concrete Society (2000) acknowledges manufacturing processes and environmental conditions need to be considered in establishing design properties.

With the increasing use of fiber reinforced polymer (FRP) composites for rehabilitation of bridge decks and girders, a methodology to evaluate the rehabilitated structure's performance is necessary. Structural Health Monitoring, an emerging area of research has the potential to provide such information. An efficient structural health monitoring system must be capable of determining and evaluating the serviceability of the structure, the reliability, and the remaining functionality of the structure in terms of durability (Sikorsky 1999). Therefore, a structural health monitoring approach requires an integration of disciplines, which provides a means of combining assessment, rehabilitation, and prediction of remaining service life of a structure.

This article discussed preliminary results from on-going work to evaluate the effectiveness of monitoring the durability of a rehabilitated bridge superstructure using global non-destructive damage evaluation (NDE) algorithm incorporated into a structural health monitoring system.

Due to quality control in the aerospace industry, a sector where high material quality is a necessity, local NDE methods have become a common tool for characterization of composite materials in many fields (Kaiser et al., 2001). While local techniques are excellent for locating and sizing defects, they are inappropriate for evaluation of an entire structure.

During the past two decades, significant research efforts have focused on developing damage detection schemes and health monitoring methods to monitor the global integrity of civil structures. All the non-destructive damage evaluation (NDE) methods developed to-date can be classified into one of four levels according to their performance (Rytter, 1993). For example, a Level I NDE method can only identify if damage has occurred. On the other hand, a Level IV method can identify if damage has occurred, determine the location and estimate the severity of damage, and evaluate the impact of damage on the structure. One such technique is the Damage Index Method developed by Stubbs et al. (2000). In that work, damage was defined in terms of a loss of element or global stiffness. While this technique can locate and quantify damage severity, some means is required to relate this damage information to either structural demand or capacity. Relying on previous work in the area of continuum damage mechanics (Kachanov, 1986) work continues to investigate the theoretical link between damage indicators and structural capacity.

The following work describes the application of structural health monitoring on two reinforced concrete T-girder bridges in California. SHM was utilized to determine the bridge performance before and after the rehabilitation.

The first bridge rehabilitated was built in 1964 and strengthened using FRP composites in 2000. The structure is a 103.6m long, 5 span, two-lane highway bridge spanning a canal that is part of the California Aqueduct System. The bridge superstructure consists of five, cast in-place, continuous, reinforced concrete T-girders, monolithically connected to the bents. The 5 spans have lengths of 17.68, 22.86, 22.86, 22.86, and 17.68 meters, respectively. The 158 mm thick, reinforced concrete deck spans transversely between the girders spaced center-to-center at 2.21 meters.

Modal tests of the bridge were performed between December 1999 and November 2001. Both frequencies and mode shapes were extracted from the test data. The Damage Index Method was used to investigate changes in structural stiffness of the deck spans.

The second bridge is part of California Interstate 40 in the Mojave Desert. The bridge, constructed in 1968 is a skewed, two lane interstate bridge 225.9 m long. The superstructure consists of a cast-in-place reinforced concrete deck and girder structural system with sixteen 12.8 m central spans and two shorter spans of 10.52 m at each abutment. The 15.56 cm thick deck spans transversely across six girders placed at 2.13 m centers. Shear transfer hinges separate the bridge into five frames (denoted Frame S-1 to Frame S-5). The primary frame of interest is Frame S-3, consisting of spans 8, 9, 10, and 11, with a hinge-to-hinge length of 56.1 m. The decks of spans 8 and 9 are rehabilitated using carbon fiber reinforced polymer (CFRP) composites for additional capacity and prevention of punching shear failures occurring on the bridge deck.

Modal tests of the bridge were performed between May 1999 and June 2003 and again damage indices were determined. As with the first bridge it was seen that the application of FRp composites served as an efficient means of rehabilitation and life-extension.

Lastly, the demand-capacity ratios for the deck of the first bridge were computed using design values as defined by ACI-440, TR 55 and following Karbhari (2000), as well as the results arrived at through the use of the damage index method. While these indicate the D/C ratios were within the acceptable limit of less than one, there was little room for error. Comparing the demand-capacity ratio obtained using the ACI design characteristic, it is apparent that the manufacturing process does affect the strength of the wet lay-up material. Unlike the methods proposed by Karbhari (2000) and TR 55, the ACI design guidelines do not consider the effects of the manufacturing process. The existence of voids, defects, and an uneven bond line potentially contribute to a lower reliability of the structural performance relative to the intended level prescribed by the design. It is critical that such aspects are considered and their effects determined.

While FRP composites provide an efficient and valuable means of external rehabilitation for life-extension, especially over the 1-10 year time frame, their efficacy will not be realized till a comprehensive evaluation of durability is completed, and an "effect-of-defects" methodology is implemented. In the interim it is essential that a global nondestructive testing technique is used to provide a measure of the effectiveness of the rehabilitation in terms of change to the system level of the structure.

References

Concrete Society, "Design Guidance for Strengthening Concrete Structures Using Fibre Composite Materials," Concrete Society Technical Report No. 55, 2000.

Karbhari, V.M. "Determination of Materials Design Values for the use of fibre-reinforced Polymer Composites in Civil Infrastructure," Proceedings, Institution of Mechanical Engineers. Vol 214, Part L, 2000 pp. 163-171.

Karbhari, V.M., Chin, J. W., and D. Reynaud. "Critical Gaps in Durability Data for FRP Composites in Civil Infrastructure." *Proceedings, 45th International SAMPE Symposium,* SAMPE, Long Beach, California, May 21-25, 2000.

Rytter, A. *Vibration Based Inspection of Civil Engineering Structures*. Ph.D. Thesis, University of Aalborg, Aalborg, Denmark, 1993.

Stubbs, N., Park, S., Sikorsky, C., and S. Choi. "A Global Non-destructive Damage Assessment Methodology for Civil Engineering Structures." *International Journal of Systems Science*, Vol 31 (11) (2000), pp. 1361-1373.

Kachanov, L.M. *Introduction to Continuum Damage Mechanics*, Martinus Nijhoff Publishers, Dordrecht, The Netherlands, 1986.

International Conference on Advanced Polymer Composites for Structural Applications in Construction (ACIC 2004)

The Second International Conference on Advanced Polymer Composites for Structural Applications in Construction (ACIC 2004) was held at the University of Surrey from 20th – 22nd April 2004. The Conference was organised by the Centre for Advanced Composites in Construction (CACIC), which comprises the Universities of Surrey and Southampton and the Building Research Establishment Garston. Innovation, safety, durability, cost-effectiveness and sustainability are key issues in which the expanding composites community in construction has made significant strides in recent years. These topics were the themes of some 74 technical and 9 keynote papers presented over the three days of the conference by engineers and scientists representing 16 countries throughout the world. On the first evening of the conference a workshop was held to discuss the design and site construction techniques for the rehabilitation of reinforced and pre-stressed concrete and metallic bridge structures. Three short presentations were given and a lively discussion followed on the problems faced by engineers during and after the rehabilitation process. During the conference a small exhibition was held for delegates to visit.

This successful and informative conference attended by many engineers throughout the world has demonstrated the importance to the construction industry of this unique material. As illustrated during the conference, there are problems and unknowns associated with the material; these are gradually being overcome and understood and engineers are showing more confidence to its use in construction. Only by holding conferences dealing with all aspects of this constructional material will engineers eventually solve the engineering problems. If a complete solution cannot be found steps must be taken to reduce the effect of the problems to a minimum.

The conference proceedings are published by Woodhead Publishing, Ltd, Abington Hall, Cambridge, England. (ISBN 1 85573 736 1).)
(Submitted by Professor L.C. Hollaway; Email: l.hollaway@surrey.ac.uk)

International Institute for FRP in Construction

COUNCIL

AUSTRALIA

Dr. D.J. Oehlers	University of Adelaide
Professor G.M. Van Erp	University of Southern Queensland

BELGIUM

Prof. L. Taerwe	Ghent University

CANADA

Dr. Baidar Bakht	JMBT Structures Research Inc.
Prof. N. Banthia	University of British Columbia
Professor P. Labossiere	University of Sherbrooke
Professor A. Mufti	University of Manitoba
Professor K.W. Neale	University of Sherbrooke

CHINA

Professor Z.T. Lu	Southeast University
Professor J.G. Teng	The Hong Kong Polytechnic University
Professor Q.R. Yue	National Diagnosis and Rehabilitation of Industrial Building Research Centre
Professor L.P. Ye	Tsinghua Univerrsity

FRANCE

Professor P. Hamelin	University of Lyon I

GREECE

Professor T.C. Triantafillou	University of Patras

ITALY

Professor E. Cosenza	University of Naples Federico II

JAPAN

Professor K. Maruyama	Nagaoka University of Technology
Dr. T. Ueda	Hokkaido University
Professor Z.S. Wu	Ibaraki University
Dr. H. Fukuyama	Building Research Institute

SINGAPORE

Dr. K.H. Tan	National University of Singapore

SWEDEN

Professor B. Taljsten	Lulea University of Technology

SWITZERLAND

Professor T. Keller	Swiss Federal Institute of Technology
Professor U. Meier	Swiss Federal Laboratories for Materials Research (EMPA)

USA

Professor L.C. Bank	University of Wisconsin–Madison
Professor V.M. Karbhari	University of California at San Diego
Professor A. Mirmiran	North Carolina State University
Professor A. Nanni	University of Missouri-Rolla
Professor S.H. Rizkalla	North Carolina State University
Professor F. Seible	University of California at San Diego
Professor I.E. Harik	University of Kentucky

UK

Dr. J.F. Chen	University of Edinburgh
Professor L.C. Hollaway	University of Surrey
Professor P. Waldron	University of Sheffield

ADVISORY COMMITTEE

L.C. Hollaway	University of Surrey, UK
A. Machida	Saitama University, Japan
U. Meier	EMPA, Switzerland
A.A. Mufti	University of Manitoba, Canada
A. Nanni	University of Missouri-Rolla, USA
S.H. Rizkalla	North Carolina State University, USA

EXECUTIVE COMMITTEE

President

Professor J.G. Teng	The Hong Kong Polytechnic University, China

Vice-Presidents

Dr. B. Bakht	JMBT Structures Research Inc., Canada
Professor L.C. Bank	University of Wisconsin–Madison, USA
Professor T. Keller	Swiss Federal Institute of Technology, Switzerland
Dr. T. Ueda	Hokkaido University, Japan

Newsletter Editor

Professor V.M. Karbhari	University of California at San Diego, USA

Treasurer

Professor N. Banthia	University of British Columbia, Canada

Secretary

Dr. J.F. Chen,	University of Edinburgh, UK

Conference Coordinator

Dr. R. Seracino	University of Adelaide, Australia

Members-at-Large

Professor Z.S. Wu	Ibaraki University, Japan
Dr. J.T. Mottram	University of Warwick, UK