FRP INTERNATIONAL

The Official Newsletter of the International Institute for FRP in Construction

Volume 1, Issue 2 ***August 2004***

Welcome to the second issue of IIFC. In this issue we continue with *"Reports from Around the World"* focusing on rehabilitation. The lead article is written by Prof. Urs Meier – one of the FRP community's pioneers in the application of FRP for the strengthening and repair of concrete structures. He provides an interesting perspective on how far we've progressed since 1967 and shares some thoughts on the future. We are also initiating a new section highlighting ongoing research activities at a University, Industrial Research Laboratory, or Government Research Laboratory. The first article in this series is from North Carolina State University.

As we move forward I'd like to invite our readers to submit material to the Newsletter on new applications of FRP in construction, forthcoming conferences/workshops, or even general items that may be of interest to the worldwide community. Material can be submitted directly to me at vkarbhari@ucsd.edu or to any of the members on the advisory or editorial boards.

Please also feel free to write to me or to the President of IIFC, Prof. J.G. Teng (cejgteng@polyu.edu.hk), with any ideas you may have for the newsletter and for IIFC itself.

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In this issue

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Reports From Around the World

In this issue we highlight applications related to the external of concrete structures using FRP composites.

External Strengthening and Rehabilitation: Where from – Where to?

By
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When do structures have to be post-strengthened? These measures are required when structures must take on new tasks involving increased loads. Furthermore, during the process of modernization of buildings, individual supports and walls may be removed, thus leading to a redistribution of forces and the need for local strengthening. In addition, strengthening may become necessary when, in course of time, damage occurs due to normal degradation or environmental factors; this is a particular problem with bridges. There are also cases where errors in the design or construction of a structure may put its safety in question. In such situations the method of externally bonded reinforcement may represent an attractive solution since it can be achieved with relatively small impact on structure. Furthermore, the existing clearance limits to bridges is not affected.

In 1967 L'Hermite and Bresson[1] proposed the external bonding of steel plates with epoxy resins for the post-strengthening of structures. Within the 1970's this method was going to be state-of-the-art in Europe and in few other parts of the world. However, long-term outdoor creep tests at the EMPA have indicated that problems concerning corrosion of the steel must be expected especially in bridge applications. Small traces of rust were found at the concrete crack tips at the interface adhesive/steel on not primed as well as on primed bonded steel plates even after only three years of exposure to weathering and creep loading. The rust became more extensive during the course of the test and after 15 years of exposure the areas have grown to 10 mm in diameter. These tests, started in 1970, are still continuing at EMPA and do indicate a weakness in the strengthening of structural systems using steel plates. Steel plates have also other disadvantages. During rehabilitation work, particularly on bridges, generally only a limited amount of mechanized lifting machines are available. In the interior of box girders, for example, the strengthening plate would have to be carried by hand to the point of installation. Consequently, due to handling limitations on site, the steel plates are rarely longer than 6-8 m; however, if the strengthening work involves greater plate lengths, a butt-joint system must be used. This type of joint cannot be welded since the welding temperatures would destroy the adhesive bond; consequently butt-jointed steel plates have to be formed from single shear lap joints.

The partial substitution of steel plates with carbon fiber reinforced polymer (CFRP) strips was discussed at EMPA in 1982 and in 1987 it was shown that this is feasible[2]. The Figure 1 illustrates the promise given in 1985 during a seminar at ETH in Zurich for a bright future for CFRP in post-strengthening. 94 kg of steel plates should be replaced by only 4.5 kg of CFRP for the very same task. However there was at that time a tremendous amount of doubt about these modern materials in the civil engineering community.

Since 1984, in static and fatigue loading tests at the EMPA laboratories, CFRP strips have successfully been employed for the post strengthening of flexural beams with a span up to 7 m. The results of this comprehensive research program showed that the calculation of flexure in reinforced concrete elements post strengthened with not tensioned or with tensioned CFRP strips could be performed analogous to conventional reinforced or pre-stressed concrete. In both cases long-time fatigue tests on 7 m girders illustrated the outstanding fatigue performance of this strengthening technique.

Only since 1991, for the first time real structures were post-strengthened with CFRP. The first bridge, the multispan box girder Ibachbruecke is located near Lucerne and the first building the City Hall of Gossau near St. Gallen. In addition, the historic wooden bridge near Sins (Canton of Aargau) was post-stiffened with 300 GPa high modulus strips for heavy trucks in 1992.

Figure 1: The promise given in 1985 during a seminar at ETH in Zurich for a bright future for CFRP in post-strengthening is reality today. The 94 kg of steel plates of Mr. Traditional are replaced for the very same task by only 4.5 kg or even less of CFRP of Miss Futura.

Another important method for rehabilitation is external post-tensioning. This very powerful method whereby the steel tendons are not embedded in the concrete, but are placed instead "externally" to the structural elements, offers the advantage that the tendons can be inspected and replaced. However, this normally rules out grouting of the steel tendons, thus making them susceptible to corrosion. Stress corrosion is another problem for the highly tensioned steel cables. With CFRP corrosion and stress-corrosion can be avoided.

Single FRP wires or strands have been used for external post-tensioning for some years. Larger units of parallel wire or strand bundles have been rarely used in the past, but three such applications were realized in 1998 and 1999.

This bicycle and pedestrian bridge over the river "Kleine Emme"[3] near Lucerne was externally post-tensioned with 2 CFRP cables in October 1998. The bridge is 3.8 m wide, 47 m long and is designed for the maximum load of emergency vehicles. The superstructure is a space truss of steel pipes in composite action with a steel rebar reinforced concrete deck. The bottom flange, a tube of 323-mm diameter, was post-tensioned with 2 CFRP cables inside the tube. Each cable was built up with 91 pultruded CFRP wires of 5-mm diameter. The post-tensioning force of each cable is 2.4 MN. Therefore the CFRP wires are loaded with a sustained stress of 1350 MPa. Each cable is equipped with 3 CFRP wires with an integrated optical fiber Bragg grating sensor. The sensors were integrated during the pultrusion process. In the post-tensioning phase it was possible to calculate the post-tensioning force at all times from the data of the wires with calibrated sensors. The "Verdasio" [3] bridge is a two-lane highway bridge and was built in the seventies. The length of the continuous two-span girder is 69 m. Internal post-tensioned steel cables positioned in a concrete web corroded as a result of the use of salt for de-icing. They were replaced in December 1998 by four external CFRP tendons arranged in a polygonal layout at the inner face of the affected web inside of the box. Each cable was made up of 19 pultruded CFRP wires with a diameter of 5 mm. The CFRP wires are loaded with a sustained high stress of 1610 MPa. Here too the cables are equipped with sensors to monitor the post-tensioning force. In October 1999 four post-tensioning cables have been installed on the Dintelhaven Bridge [4] in Rotterdam. Each cable was build up with the same cross-section as at the bridge over the river “Kleine Emme” however of 75 m length. In all three post-tensioning cases the EMPA/BBR system was used for the anchorage sockets [5].

Post-strengthening with FRP, including strips, wet-lay-up, near surface mounted reinforcement, shear angles, wrapping, etc. is meanwhile worldwide an overwhelming success. Figure 2 gives an illustration of the acceleration of the use of CFRP for post-strengthening in Switzerland since 1995. The situation is world-wide in many countries very similar. The global use of CFRP for post-strengthening purposes is today per annum approximately 3400 tons. Considering all the doubts and counter-argument the FRP pioneers were facing from the civil engineering community in the past this is outstanding. Success is a journey, not a destination. This is the key message for the next generation of FRP researchers within civil engineering.

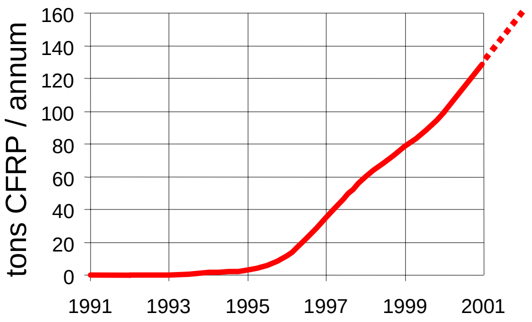

Figure 2: Annual use of CFRP for post-strengthening in Switzerland

Most of the objects described in the first section are monitored. To our best knowledge all the results are matching the high expectations. This is also the case for external post-tensioning from the technical performance point of view. From a commercial point of view external post-tensioning with CFRP is similar to CFRP suspension and stay cables up today a huge "flop". What are the reasons? Number one is in all cases the price. CFRP cables are at least four times more expensive than steel cables. If the owner of a structure is only considering the first investment steel will be the winner. CFRP will only have a chance within a serious life cycle costing. For such a serious costing we still have to prove all the promises about the outstanding long-term behaviour. The maximum of 10 to 15 years of proof being available nowadays with the pioneering objects is for most authorities not yet sufficient. That means we have to be patient for another 10 years, considering CFRP cables as applicable for external post-tensioning in rehabilitation.

If technical systems are not continuously improved they are within short time out of competition. We make a distinction between "daily" improvements and novelties. Novelties require in general large investments in R&D and in the certification of a product. Let's talk about possible future novelties.

Within the last ten years we have seen dramatically decreased costs for carbon fibers. This was much less the case for CFRP strips. The reason for that is the relative slow speed of pultrusion with an epoxy matrix system. The use of a thermoplastic matrix allows an at least ten times higher production rate. Today thermoplastic CFRP strip are not yet cheaper because the market does not yet play. The feasibility of application of thermoplastic CFRP strips has been proven [6] and they may replace the thermoset strips within the coming years.

Epoxy adhesives as they are used today are in most cases sufficient for northern hemispheres. Being closer to the equator the glass transition temperature is often not high enough. This can be solved with hot curing. However we expect new resins with higher glass transition temperatures and ambient temperature curing soon.

The state of application of adhesives seems no longer state-of-the-art. In aircraft industry the application of adhesive films is in use since decades. The development of similar relative thick films for applications in civil structures is an urgent need. This would help to reduce labor hours, simplify the quality assurance and improve the visual appearance.

The strengthening methods with pre-stressed CFRP strips are not so well established yet. It will take more development work before they are suitable for practical applications since the pre-stressing methods are still complicated to use and installation techniques, both manual and automatic, have yet to be perfected. These include surface preparation, pre-stressing, placing and bonding, forming end anchorages and vacuum bonding. Automatic application methods will offer advantages in hazardous areas, where there is danger from traffic and will reduce traffic management and traffic delay costs. It is a need to make in the future better use of the high strength of CFRP with pre-stressed applications.

Are non-laminated FRP straps [3] a future element for bridge repair? A pin-loaded strap element may provide a practical means of joining different components and transferring significant forces between them. This element consists of a unidirectional FRP lamina wound around endpins in a racetrack manner. Circular pins transfer the tensile load to the components being joined. However, both experimental and theoretical studies have revealed 'high' stress concentrations next to where the strap leaves the pin. The effect of these concentrations is to reduce the load at failure considerably compared to that of the straight solid laminate, as determined by a standard coupon test. One means of reducing these undesirable stress concentrations is to replace the solid laminate by the non-laminated equivalent. In the "new" strap there are a number of non-laminated layers formed from a single, continuous, thin, thermoplastic matrix tape reinforced with unidirectional carbon fibers. In the non-laminated system the tape is wound around the pins and only the end of the outside, final layer is fixed. A non-laminated strap system of this type enables the individual layers to move relative to each other. Apart from improving stress distribution, winding can easily be performed on site, so the system allows greater flexibility in terms of adjusting tendon length. This flexibility allows the system to compensate for the dimensional tolerances of the components to be connected. This system could have an excellent future in bridge repair for active shear strengthening, for the end anchorage systems of tensioned CFRP strips, for flexural strengthening and for external post-tensioning. "Non-laminated FRP straps" will be as strong as cables for external post-tensioning, and much cheaper.

From a global view the use of FRP materials in bridge repair is still in its infancy, but there are very clear indications that it will be an excellent choice for a multitude of rehabilitation methods on bridges.

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Externally Bonded FRP Systems for Structural Strengthening: Southeast Asian Region, China and India

By
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The Southeast Asian Region, together with China and India, has witnessed a rapid growth in the use of external FRP systems in strengthening works in recent years. In China, for example, it is estimated that about 600,000 m^2 of FRP sheets had been used in structural strengthening works in the year 2003.[1] The application of FRP systems in these regions has largely been confined to typical strengthening works such as flexural and shear strengthening, as well as seismic strengthening.[1,2,3]

Figure 1: Flexural strengthening of a highway RC bridge slab in China[1]

Figure 2: Seismic retrofit of supporting columns for a cryogenic tank in Gujarat, India[2]

As the material is still considered relatively new in this part of the world, most of the works had been carried out in accordance to available guidelines and published literature such as ACI 440 Guidelines[4], fib Bulletin[5], The Concrete Society Technical Report[6], JSCE Specifications[7] and ICBO AC125 Document[8], augmented by local codes for structural concrete. In countries like Singapore, the authority is receptive of such references as the move is towards a performance-based design philosophy. However, this is not so in China where foreign codes or standards are only used for the purpose of research.

Figure 3: Strengthening of slab in a shop house, to take heavy computer networking equipment, in Malaysia[3]

There are, expectedly, efforts to establish codes and guidelines for local use.[9, 10] The China Association for Engineering Construction Standardization in China has issued a document entitled "Technical Specification for Strengthening Concrete Structures with CFRP Laminates (CECS146:2003)". This document gives the method to calculate the flexural and shear capacities of RC beams, and the axial load and seismic capacities of RC columns strengthened with FRP laminates. In addition, construction measures for structural RC members strengthened with FRP laminates are given in details. In Shanghai, a local standard, "Technical Code for Strengthening Concrete Structures with FRP (DG/TJ08-012-2002)" was developed in 2002. The contents of this local code are almost the same as those of CECS146, except for some special specifications that are based on construction practices in Shanghai.

In India, the Department of Science and Technology, Government of India, in collaboration with the universities, is developing standards for FRP in construction. Focus is placed on the rate of degradation of glass FRP in view of the South Asian environment and the concrete mix typically used in India. The application is targeted at corrosion damaged structures and seismic retrofitting.

Elsewhere, in Singapore, the FRP Society (S), which was established in September 2002, is working with the universities and industrial partners to establish guidelines on design issues related to tropical climate and special structures typical of the local industry.[10]

In summary, the application of externally bonded FRP systems in strengthening works is experiencing an accelerated pace in the Southeast Asian region, China and India. However, the technology is still unfamiliar to many practicing engineers. There is a need to provide the proper information through general university education and continuing professional activities. In addition, there is a necessity for agencies and organizations to work towards the establishment of guidelines, standards, or codes of practices that are more suited to local economic, geographical and climatic conditions, as well as construction practices.

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Design Guidelines for External Strengthening of Concrete Structures

By
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The structures may have to carry larger loads at a later date or fulfil new standards. In extreme cases, a structure may need repair due to an accident, or due to errors made during the design or construction phase, such that the structure needs to be strengthened before it can be used. Over the past decade, the issue of deteriorating infrastructure has become a topic of critical importance in Europe, and to an equal extent in North America and Japan.

The advantages of FRP-strengthening have been shown time and again during the last decade. All over the world several thousand structures retrofitted with FRPs exist. There are various reasons why the retrofit is needed, but since buildings and civil structures usually have a very long life, it is not uncommon that the demands on the structure change with time. There are several reasons for this; a structure may have to carry larger loads in the future or to comply with new standards than it was designed for. In extreme cases, a structure may have to be repaired or strengthened due to accidents. There are several methods for repairing or strengthening a concrete structure with FRPs: wrapping columns with sheets, bonding laminates to the outer face of a structure or even to place it in sawed grooves in the concrete cover as Near Surface Bonded Reinforcement. Mostly do the strengthening systems use epoxy as the bond medium, but also systems with cementitious bonding agents exist. If the technique is to be used effectively, it requires a sound understanding of both the short-term and long-term behaviour of the bonding system and the materials used. The execution of the bonding work is also of great importance in order to achieve a composite action between the adherents. Of the utmost importance is the knowledge within what limits the strengthening method can be used. Maybe the most important factor is a proper understanding of the design process. In this overview a short summary of the some guidelines developed in Europe will be discussed.

In this brief report only guidelines that can be considered national or European documents will be covered. Work with guidelines for external strengthening of structures in Europe has been going on for quite a time. In 1996 a collaboration work within the framework of FIB (Fédération Internationale du Béton) started. The aim with this work was to compile a guideline in various fields for FRP in construction. In March 2001 the guideline [1] "Externally bonded FRP reinforcement for RC structures" was printed. The aim with the guideline was to present a general description of materials and techniques related to the application of composites as external reinforcement of concrete elements. The guideline contains several chapters with each of them devoted to one particular aspect of strengthening, for example strengthening for flexural, shear, torsion and confinement as well as practical execution and quality control.

In Sweden a guideline for external strengthening was first made for steel plate bonding in the end of the 80-ties and during the end of the 90-ties a design guideline for FRP plate bonding was written and incorporated in the Swedish Bridge Code: BRO 94. However, this guideline has since then been extended and improved. The guideline covers flexural, shear, torsion, fatigue, confinement and execution and quality control. The guideline also gives design examples [2]. A large part of this guideline has also been incorporated into the Norwegian guideline [3] for external strengthening, with FRPs, which will be published soon, however, an adjustment to the national concrete code has been done.

Also in the UK a design guideline for external strengthening exists [4]. This guideline covers design in flexural, shear and for confinement. It also discusses installation procedures and workmanship. However, this guideline is not as detailed as [1] and [2], but gives a good understanding of external strengthening of concrete structures. In addition to this guideline a guideline for external strengthening of steel members using FRPs exists in the UK [5]. This guideline is very comprehensive and deals with many aspects regarding strengthening of steel structures.

There also exists other national design guidelines of codes for external strengthening with FRPs in Europe, for example the Swiss [6], which partly covers strengthening with FRPs, but covers the use of structural adhesive extensively.

In addition to the above mentioned guidelines, there also exists several company specific design guidelines, such as for SIKA, M.Brace and Sto. However, they are not considered as national guidelines and are consequently not covered by this overview.

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FRP Strengthening in Canada – Recent Code Developments

By

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Since 2000, the Canadian Standards Association (CSA) has published two approved national standards containing provisions regarding the use of FRPs in civil engineering structures. The first – CSA S6-00: Canadian Highway Bridge Design Code – released in 2000, represents the first design code in North America (and perhaps, worldwide) that considers the use of FRPs in bridge structures. In this edition of the bridge code, there is a chapter (Section 16) that deals specifically with “fibre-reinforced structures”. The provisions of the code apply to the following bridge components containing fibre reinforcement: fully or partially prestressed concrete beams and slabs; non-prestressed concrete beams, slabs, and deck slabs; FRC deck slabs of slab-on-girder bridges; stressed wood decks; and barrier walls. The current edition of CSA S6 does not address FRP strengthening. However, as discussed below, an Addendum to the code to be published in 2005 is currently under preparation. Work has also commenced on the next full edition of CSA S6, scheduled for completion within the next five years.

The second approved national standard – CSA S806-02: Design and Construction of Building

Components with Fibre-Reinforced Polymers – was published in 2002. This code covers the design of concrete components with FRP reinforcement, the design of concrete components prestressed with FRPs, as well as the strengthening of concrete and masonry components with surface-bonded FRPs. Also included are provisions for seismic design, and the design of FRC/FRP claddings. In the chapter on FRP strengthening with surface-bonded FRPs, the following topics are considered: concrete beam strengthening; concrete column strengthening; concrete and masonry wall strengthening; and seismic requirements for shear wall retrofit and rehabilitation. Provisions are given for the flexural and shear strength enhancements of various structural components such as: concrete beams, concrete columns, concrete walls, and masonry walls. The axial load capacity and ductility enhancements of concrete columns are also addressed. The chapter on seismic design contains provisions for the retrofit and rehabilitation of columns and shear walls. This chapter of the code deals with issues such as: shear strength enhancement, concrete confinement, lap splice clamping, and detailing requirements for strengthening and repairing with FRP sheets.

As mentioned above, an Addendum to the chapter on "fibre reinforcement" of the Canadian Highway Bridge Design Code (CSA S6-00) is being prepared. The primary purpose of the revision is to include provisions for FRP rehabilitation. In the Canadian bridge code, "rehabilitation" is defined as "a modification, alteration, or improvement to the existing condition of a structure or bridge subsystem that is designed to correct deficiencies for a particular design life and load level". With regard to FRP rehabilitation, the scope of the Addendum will include existing concrete elements with externally bonded FRP systems and near-surface mounted reinforcement (NSMR), as well as existing timber elements with surface-bonded FRP systems and NSMR. Design provisions will be given for the flexural and shear strengthening of concrete beams, concrete columns and timber beams, as well as for the axial capacity enhancement of concrete columns. Of special concern are issues related to the installation and quality control of FRP strengthening systems. As a result, the Addendum will provide detailed instructions on various aspects such as: shipping, storage and handling; installation procedures; climatic conditions; concrete preparation; curing conditions; staff qualifications; and inspection during all phases of the construction work.

A technical committee has been struck to draft the proposed revisions to Section 16 of the Canadian Highway Bridge Design Code. Dr. A.A. Mufti, President of the ISIS Canada Network Centres of Excellence, chairs this committee. Committee members include representatives from the Departments of Transportation of the Provinces of Manitoba, Ontario and Quebec, from the City of Calgary, as well as structural engineers from academia and private practice. To ensure that the code will reflect the state-of-the-art worldwide in FRP rehabilitation technologies, three foreign experts in the field – V.M. Karbhari (U.S.A.), A. Machida (Japan) and B. Taljsten (Sweden) – have been appointed to this committee, and are actively involved in the code development work.

Individuals interested in more information on CSA codes and in procuring copies of the various codes and documents are referred to the website www.csa.ca.

Guide Specifications from the American Concrete Institute

By

John Busel, Chair ACI-440

The American Concrete Institute (ACI) has published several important documents through its Emerging Technology Series to provide engineers and designers with information and direction regarding new technologies not covered in ACI 318. Established in 1990, Committee 440 is recognized as a leader in developing FRP composite specifications for concrete structures. With a growing membership of 190+ worldwide experts in the field of concrete and FRP composites technology, Committee 440 carries out its mission to develop and report information on fiber-reinforced polymer for internal and external reinforcement of concrete.

In 1996, Committee 440 prepared the first of several industry documents with ACI 440 440R-96, State-of-the-Art Report on Fiber Reinforced Plastic (FRP) Reinforcement for Concrete Structures. Since 1996, Committee 440 has focused on development of guideline documents. These guidelines are based on the knowledge gained from worldwide experimental research, analytical work, and field applications of FRP reinforcement. Four guide documents are available including concrete members reinforced internally with FRP rebars, externally bonded FRP systems for strengthening concrete structures, test methods for FRP bars and laminates, and prestressing with FRP tendons.

The first of the guideline documents was published in 2001. ACI 440.1R-03 - Guide for the Design and Construction of Concrete Reinforced with FRP Bars covers FRP material requirements and construction practices for reinforcing bars for concrete structures. The guide document provides general information on the history and use of FRP reinforcement, a description of the unique material properties of FRP, and committee recommendations on the engineering and construction of concrete reinforced with FRP bars. Due to other differences in the physical and mechanical behavior of FRP materials versus steel, the guide addresses design recommendations for flexure, serviceability, creep rupture and fatigue, in addition to shear and detailing for stirrups. The guide also addresses temperature and shrinkage as well as provides several design examples. Recently, this ACI was translated into Italian. Currently, the guide is being updated by the Committee based on new research.

In 2002, the second of the guides was published ACI 440.2R-02 - Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures. The guide covers FRP systems for strengthening concrete structures as an alternative to traditional strengthening techniques, such as steel plate bonding, section enlargement, and external post-tensioning. FRP systems offer advantages over traditional strengthening techniques such as lightweight, relatively easy to install, and non-corrosive. The guide provides general information on the history and use of FRP strengthening systems, a description of the unique material properties of FRP, and committee recommendations on the engineering, construction, and inspection of FRP systems used to strengthen concrete structures. Due to the characteristics of FRP materials, the behavior of FRP strengthened members, and various issues regarding the use of externally bonded reinforcement, the guide provides design recommendations for flexural and shear strengthening and axial compression. The guide also provides design examples for various applications. Currently, the Committee is reviewing several updates for the guide to add sections for Near Surface Mounting technique for strengthening, design recommendations for strengthening existing prestressed/post-tensioned concrete members, and suggested practice for various protective coatings.

In Fall 2004, a new guide ACI 440.3R-04 – Guide Test Methods for Fiber Reinforced Polymers (FRP) for Reinforcing or Strengthening Concrete Structures will be published. It is expected to be available in Fall 2004. This document provides model test methods for the short-term and long-term mechanical, thermo-mechanical, and durability testing of FRP bars concrete and laminates used for concrete and masonry. It is anticipated that these model test methods may be used or adopted, either in whole or in part, standards writing agency such as ASTM. The publication of these test methods is an effort to aid in this adoption. The recommended test methods are based on the knowledge gained from research results and literature worldwide. Many of the proposed test methods for reinforcing rods are based on those found in guidelines developed by the Japan Society for Civil Engineers (JSCE). The JSCE test methods have been modified extensively to add details and to adapt the test methods to U.S. practice. The test methods are as follows:

- Cross-Sectional Properties of FRP Bars
- Longitudinal Tensile Properties of FRP Bars
- Bond Strength of FRP Bars by Pullout Testing
- Transverse Shear Strength of FRP Bars
- Strength of FRP Bent Bars and Stirrups at Bend Locations
- Accelerated Test Method for Alkali Resistance of FRP Bars
- Tensile Fatigue of FRP Bars
- Creep Rupture of FRP Bars
- Long-term Relaxation of FRP Bars
- Performance of Anchorages of FRP Bars
- Tensile Properties of Deflected FRP Bars
- Determining the Effect of Corner Radius on Tensile Strength of FRP Bars
- Direct Tension Pull-Off Test for FRP Laminates Bonded to Concrete Masonry

- Tension Test of Flat Specimen
- Overlap Splice Tension Test

In late 2004, early 2005, Committee 440 newest document, ACI 440-YR - Prestressing Concrete Structures with FRP Tendons is expected. FRP have been proposed for use in lieu of steel prestressing tendons in concrete structures. The guide provides general information on the history and use of FRP for prestressing applications and a description of the unique material properties of FRP. The guide focuses on the current state of design, development, and research needed to characterize and ensure the performance of FRP prestressed concrete structures. The guidelines are based on the knowledge gained from worldwide experimental research, analytical work, and field applications of FRPs used as prestressed reinforcement. The guide includes a basic understanding of flexure and compression prestressed members, FRP shear reinforcement, bond of FRP tendons, unbonded or external FRP tendons for prestressing applications, and serviceability. The document concludes with a description of research needs.

Several Committee 440 Subcommittees are busy working to develop new guides, reports, and state-of-the art documents, to be published in the next 2-5 years. The following is a brief summary:
Committee 440 is steadfastly working on the update of the report published in 1996 and reauthorized in 2001 on the application of FRP in concrete structures. The State-of-the-Art report will present the many new applications of FRP materials and emerging market opportunities providing the reader with a comprehensive overview of the impact FRP composites have made in concrete.

A document focusing on FRP Durability in Concrete Structuresintends to address durability of FRP composites when used in conjunction with concrete. Environments that are considered critical to the long-term efficacy of FRP composite reinforcement are outlined in the initial chapters. These environments include moisture, chemical solutions, alkaline environment, extreme temperatures, creep and relaxation, and ultraviolet light. The effect of each of these environments on FRP composites at the fiber and matrix level is covered. The areas where knowledge is lacking are covered as well as chapters devoted to each general class of FRP composite reinforcement including internal reinforcement (bars and tendons), external reinforcement, and structural stay-in-place forms. The document reviews environments that are critical for each class of reinforcement and the effects that these environments have on the structural design of the particular reinforcement.

Committee 440 is collaborating with The Masonry Society to develop a guide document that addresses upgrading of existing unreinforced masonry with FRP systems to improve strength and displacement capacity under in-plane and out-of-plane loading. The research community has developed various methodologies of FRP strengthening that make use of externally bonded laminates or NSM bars. The common drive of these solutions is to address and resolve structural masonry problems by working on exposed surfaces with minimum disruption and aesthetic alterations. The guide document intends to cover material characterization, design procedures, construction practice, and inspection techniques, as well as economics and specifications. It is envisioned that in the near future the use of FRP systems for masonry strengthening will become more common in the construction industry as engineers and contractors become aware of the value of knowledge available in this field.

A Perspective From Industry

In each issue the newsletter will highlight a perspective from industry. In this issue Sarah Witt provides a perspective on behalf of Fyfe Co. LLC, one of the first companies in the US to get involved in the rehabilitation of structures using FRP materials.

An Industry Perspective
Strengthening of Structure Using Externally Bonded Fiber Reinforced Polymers

By
Sarah Witt
Fyfe Company LLC

Externally bonded fiber reinforced polymers are increasingly being used throughout the world as an alternative to more traditional building materials. This type of strengthening is a well established technique for seismic retrofit and is also becoming a popular choice for general strengthening and upgrading of structures. This includes adding additional capacity for an increase in loading, adding additional strength to existing structural members due to a change in the configuration of a building, preservation of historical structures, and repair and protection of structures against corrosion. Fyfe Company has been involved in this strengthening market since the late 1980's, with the Tyfo® Fibrwrap® System being used on a variety of these types of strengthening projects here in the United States and throughout the world.

After many years of use, an existing structure often needs to be upgraded to meet heavier loading requirements or individual members need to be upgraded to accommodate changes in the original structural design. Fiber Reinforced Polymers ("FRP") offer an ideal way to achieve these new design loads because of their high strength to weight ratio, minimal impact on the existing structure and speed of installation.

During renovations of an existing building, architectural changes may require the addition of new openings in existing structural members. This might be for new doors, escalators or even elevators. One example is the Clinica Las Condes Building in Santiago, Chile. A new doorway needed to be placed in an existing shear wall, cutting much of the critical steel. This new opening required additional reinforcement to prevent diagonal cracking and to stabilize the surrounding masonry. The Tyfo® SEH Glass Composite System was used on each side of the opening in both the vertical and horizontal direction to add the strength lost due to cutting of the steel (Figure 1). The retrofit with FRP allowed a very quick fix and eliminated the need for additional demolition, complicated steel reinforcement or space consuming concrete casting.

Figure 1: Rehabilitation in the Clinica Las Condes Building

Often times during the course of a buildings service life, additional equipment is needed, resulting in increased dead and live loading. At the King Abdul Aziz University in Jeddah, Saudi Arabia, new HVAC equipment was being placed on the roof of the structure. The existing beam that supported this equipment was flexurally deficient in its ability to support the additional weight of the new unit. The Tyfo® SCH Carbon Composite System installed on the bottom of the beam was used to provide additional flexural capacity, with U-shaped wraps placed to provide anchorage (Figure 2).

Figure 2: Rehabilitation of Beam at the King Abdul Aziz University

A similar project was completed in Athens this past spring. A former school was being converted into the Hotel "Kaningos 21" for use by television and media personnel during the Olympic Games. New HVAC equipment as well as a swimming pool were installed on the existing roof. The slab was strengthened to carry these new loads using the Tyfo® UC Pre-Cured Strip System. In addition, the Tyfo® AFP System was used to protect the composite strengthening from damage during a fire. This AFP System is UL approved with a 4-hour rating. Individual design requirements determine the necessity of this type of fire protection.

Change of use of a structure often necessitates structural strengthening and FRP can often be a quick, easily installed structural solution. On the site of the former Athens International Airport, several venues were constructed for use during the 2004 Summer Olympic Games. One of the most dramatic undertakings was the conversion of the former customs building into the home of the canoe slalom competition (Figure 3).

Figure 3: Canoe Slalom Course in Athens

The conversion of this building had to accommodate the additional weight of the water, storage area for the boats and initial part of the competition course. The Tyfo® Glass Composite System was used on both the beams and columns to provide additional strength. The project was completed in a very short time frame and allowed the building to be reopened on time.

A structure may need to be strengthened without a change of use. Initial design errors or deterioration over time may necessitate structural repairs. The Pengrowth Saddle Dome in Calgary, Canada was originally constructed for the 1988 Winter Olympics and is now home to the Calgary Flames and a major entertainment venue for the City of Calgary (Figure 4). During an inspection, flexural cracking was identified in the main girders of the precast roof panels. For this strengthening, pre-cured laminates were chosen because of their ease of installation. A wet lay up system was used to anchor the laminates at the ½ point and end points of the girders (Figure 5). The composite retrofit solution provided a strengthening solution that was completed well ahead of schedule and in between scheduled events, with minimal impact on the owner.

Figure 4: Saddle Dome in Calgary

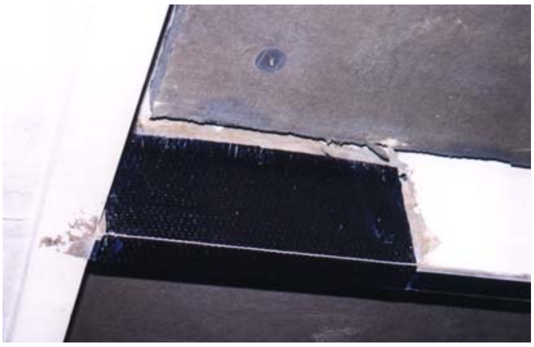

Figure 5: Wet Layup System Used to Anchor Adhesively Bonded Prefabricated Strips in the Saddle Dome

Fiber Reinforced Polymers are an ideal strengthening technique for historical buildings and bridges. On these structures, it is often not allowed to change the shape or appearance of the existing members. Any retrofit technique needs to have minimal architectural impact on the structure.

In Singapore, the Chinese Heritage Building at The River House was ear marked by the Urban Redevelopment Authority of Singapore for conservation as a National Landmark in 1993. The River House Building consists of a Unique Chinese Tile Roof supported by timber trusses and beams. During a structural inspection in 2003, many of the timber beams were found to be seriously damaged by termites. A pest control specialist was hired to clear the termites and the extent of the damage to these timber beams was assessed. A total of 53 timber beams were found with cracks and voids, among them 12 were seriously damaged with more than 50% hollowness in their internal core.

The first thought was to replace the seriously damaged beams with new timber beams. However, due to a shortage of time and concern over damage to the Chinese architectural roof during replacement, both the owner and consultant were anxiously looking for a better alternative. A solution was proposed using Tyfo® Epoxy to grout the voids and seal the cracks and using the Tyfo® Fibrwrap® System to provide additional strength to the most seriously damaged beams. The retrofitted timber beams were then repainted to the original wooden color and the architectural beauty of this Chinese Heritage Structure was preserved.

Another example of strengthening a historical structure with FRP is the Wellington Town Hall Restoration Project in Wellington, New Zealand. On this historical structure, the concrete ceiling was cracking and falling. A solution was needed to stabilize the roof that would have minimal impact on the structure. The Tyfo® Glass Composite System was installed in bands across the ceiling and Tyfo® Anchors were installed at discrete locations for anchorage. After installation of the FRP, the ceiling was refinished to the original appearance. This FRP strengthening option provided a lightweight solution to the problem, without impacting the historical appearance.

Fiber Reinforced Polymers offer an excellent strengthening solution for corrosion damaged structures as well as a method of protecting structures against future deterioration. The Johnson Manufacturing facility in Port Alegre, Portugal had corrosion damage of the concrete beams supporting the roof, caused by water leaking through the corrugated steel roof. In addition, the existing roof was to be replaced with heavier panels, increasing the load on the already damaged beams. After extensive concrete repair, the Tyfo® SCH Carbon Composite System was used to provide the additional capacity necessary to meet the design requirements. Tyfo® Fibrwrap® Anchors were installed at the terminating ends of each segment to help with long-term bond durability. This upgrade of 6 beams took place in 4 days without any disruption to the operation of the facility. By allowing this manufacturing plant to remain in operation during the repair, the owner saved a considerable amount of money over some the more traditional, invasive repair methods.

Externally bonded Fiber Reinforced Polymers can also be used to prevent future corrosion on both existing and new structures. This was the design goal of the Shekpou Port Project in China. This was a new construction project in which composites were considered during the design stage as a method of providing long term corrosion protection to the proposed steel piles. The design called for a suitable method for corrosion protection of the exposed portions of the steel piles in the splash zone, which would not only be subjected to intermittent wetting and drying cycles of the sea water, but also the abrasive wave forces. The Tyfo® Glass Composite System met the requirements of a non-corrosive, non-conductive, watertight and abrasion resistant material. In total, 482 steel piles were wrapped with this system prior to insertion into the sea. Through this preventative approach, the steel is protected from corrosion causing agents from the beginning. In this case, the FRP provided a long term and cost effective solution to the corrosion of the steel piles in adverse environmental conditions.

These projects highlight the many uses for structural strengthening with Fiber Reinforced Polymers. Engineers throughout the world have used this technology to solve their structural problems in an efficient and economical manner. FRP's are extremely versatile and can be designed for a wide variety of projects, and may be the ideal solution for a number of structural problems that cannot be efficiently solved using conventional means.

An Owner's Perspective

In each issue the newsletter will highlight a perspective from the "owner/user" community. In this issue Ruth Eden of the Department of Bridges and Structures, Manitoba Transportation and Government Services, Canada, co-authors a paper on the efficiency of FRP rehabilitation for a critical life-line structure. The coauthors on the paper are from industry and academia, emphasizing the value of government-industry-academia partnerships.

Damaged bridge girder repaired using prestressed CFRP sheets

By

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Many Canadian jurisdictions are faced with the challenge of managing an aging and deteriorating highway infrastructure with limited funding. As a means of providing the best possible level of service for the user, not only in the present but also in the future, many are investigating the potential use of new and innovative designs and technologies. The Province of Manitoba has partnered with ISIS Canada, Intelligent Sensing for Innovative Structures – A Canadian Network of Centers of Excellence, to develop and take advantage of this emerging technology for various applications in bridges and structures. The Manitoba Department of Transportation (Department) has been actively involved with ISIS Canada through the sponsorship of research and several demonstration projects.

The Department owns a large number of major river bridges and interchange structures, typically 30 – 40 years old, that require strengthening, major rehabilitation, or replacement. Because of high traffic volumes and/or the large cost for detour structures, the Department is investigating options that extend the service life of these structures by an additional 50 years with minimal maintenance or repair/rehabilitation. A number of upcoming rehabilitation projects include FRP reinforcement in superstructure concrete and FRP materials to strengthen substructure units.

One area of particular interest to the Department is the application of carbon fibre reinforced polymer (CFRP) sheets to strengthen and rehabilitate existing structures. This innovative technology has proven to be viable and cost-effective when compared with conventional methods. Specifically, the Department is investigating the application of CFRP sheets bonded to the tensile face of structural members to increase flexural capacity. Typically, the application of CFRP sheets: a) can be completed relatively easily on site due to the material’s light weight, b) requires a small number of workers, and c) requires minimal traffic control measures when compared with conventional repair techniques. In addition, FRP materials provide virtually corrosion-free, long-term performance.

The Department was approached by members and network partners of ISIS Canada to undertake a demonstration project utilizing state-of–the-art technology - prestressed CFRP sheets. Research at Queen's University and the Royal Military College of Canada was focusing on the use of prestressed CFRP sheets for rehabilitating structures damaged by impact loads. By applying prestress to the FRP sheets directly, the efficiency of an FRP repair can be greatly enhanced. The research had shown improved structural performance when compared with non-prestressed applications in terms of load carrying capacity, durability, and serviceability [1]. In addition, the anchorages of the prestressed CFRP system (i.e. mechanical anchors) prevent premature peeling failure of the sheets in high shear stress zones. Despite the benefits of prestressing FRP sheets, few field applications have been reported. The PTH 9 and PTH 101 Overpass (PTH 9 Overpass) in Winnipeg, Manitoba, Canada, was an appropriate structure to apply this strengthening technology (Figure 1); and, in fact, this project was the first North American field application of prestressed CFRP sheets.

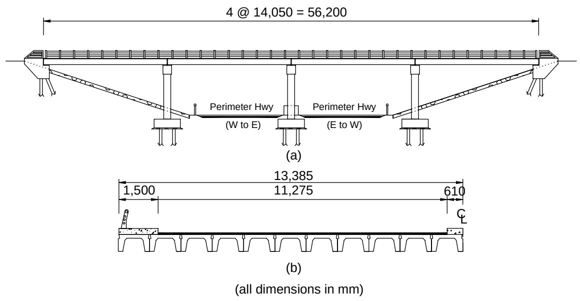
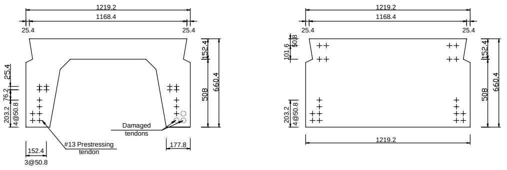


Figure 1 – Schematics of PTH 9 Overpass

A number of the girders on this overpass had been struck repeatedly by overheight vehicles, and three prestressing strands out of twenty in one girder were broken due to the impact loads. This resulted in a decrease in flexural strength. A strengthening method utilizing prestressed CFRP sheets was chosen to repair the damaged girder and replace some of the lost prestressing force within the girder.

The PTH 9 Overpass was constructed in 1963 and is located in Winnipeg, Manitoba, Canada. It is a 4 span prestressed concrete channel girder structure that is 56.2 m (4 spans of 14.05 m) long, and 26.8 m (6 traffic lanes) wide. This overpass consists of twenty-two prestressed concrete channel girders spaced at 1220 mm centre to centre. The main reinforcement for these channel girders is #13 prestressing strands as shown in Figure 2. The in-situ strength of the concrete and the prestressing strands was not available at the design stage; therefore, the design strengths were estimated based on the

Evaluation Chapter of the Canadian Highway Bridge Design Code [2] as 25 MPa for the concrete and 1,725 MPa for the prestressing strand. Even though there was a possibility of reduced tendon areas due to long-term exposure to the environment, nominal areas were used for the design.



(All dimensions in mm)

Figure 2 – Sectional Views of the PTH 9 Overpass Channel Girders

An analysis of the load carrying capacity for this structure was completed in accordance with the AASHTTO LRFD Bridge Design Specification. The Department officially uses the AASHTO LRFD Bridge Design Code [3]. The following deficiencies were calculated: a) flexural capacity of the damaged channel girder (Figure 3) was not adequate to carry the current design loading, and b) the serviceability (i.e. crack control) did not meet code requirements.

Figure 3(a) –Severely damaged girder

Figure 3(b) – Significant Loss of Concrete and Damage to Steel Reinforcement

The design for the repair consisted of three layers of CFRP sheets, prestressed to 21% of ultimate fibre strain, bonded to the bottom flange of the girder. The prestressed CFRP sheets were designed to be effective not only in recovering the flexural strength, but also improving serviceability and durability (i.e. crack closure). The material properties for the CFRP materials and epoxy resin used are shown in Table 1.

Table 1 – Material Properties of the Repairing Material

Property	Carbon Fibre Fabric (Wabo ® Mbrace CF-160)†	Adhesive (Wabo ® MBrace Saturant) ††
Ultimate tensile strength	3,800 MPa	55.2 MPa
Yield strength	N/A	54 MPa
Tensile modulus	227 GPa	3,034 MPa
Ultimate rupture strain	1.67 %	3.5 %
Yield strain	N/A	2.5 %
Nominal Thickness	0.33 mm / ply	N/A

†: Fibre directional properties

††: Mixed by the ratio 3 to 1 (Part A to Part B)

The success of a post-tensioned strengthening method using CFRP sheets is dependent upon the bond strength between the CFRP sheets and the anchors. Therefore, anchor tests were undertaken to confirm the ultimate strength of the design. Five specimens (2 - 650 mm long x 100 mm wide x 12 mm thick steel flat anchor plates per specimen) were fabricated and tested to failure [4]. The CFRP sheets were bonded to the steel anchors using an epoxy adhesive. Mathematical derivations and a finite element analysis were also completed as a means of independently verifying the test results. Based upon the test results, a prestressing force of 800 MPa was specificed and one week of epoxy curing time was required to guarantee the bond performance.

Considering the harsh weather conditions in the province of Manitoba, the effectiveness of prestressed CFRP applications under low temperatures also had to be investigated. El-Hacha et al. (2004) [5] tested T beams (flange width of 535 mm, a web width of 60 mm and height of 375 mm, and a span length of 4,000 mm) strengthened with prestressed CFRP sheets under low temperatures (i.e. -28°C). They investigated flexural behaviour, crack patterns and failure modes. The test results showed that: a) the low temperature did not affect the beams' structural behaviour, b) the adhesive strength did not appear to be affected by the low temperature, c) the prestressed CFRP sheets significantly enhanced serviceability, and d) the sheets contributed to stress re-distribution in the beams.

Fatigue behaviour is also an important factor to be considered in the rehabilitation of an existing structure because it has been already undergone millions of loading cycles and is expected to continue to carry millions more loading cycles. Shi (2003) [6] conducted tests using rectangular beams (160 mm wide, 280 mm high, and a span length of 3,300 mm) strengthened with a prestressed CFRP sheet. In order to simulate a damaged condition (i.e. loss of prestressing tendons), steel reinforcement areas were decreased from 153.5 mm^2 (undamaged) to 99 mm^2 (damaged) and the damaged beams were then strengthened. After 2 million cycles of loading, the strengthened beams demonstrated satisfactory behaviour and the average ultimate strength was 63% higher than the damaged beams.

The damaged portions of the channel girder were repaired using conventional repair techniques and materials prior to the application of the FRP strengthening system. Because FRP strengthening systems are sensitive to environmental conditions (i.e. temperature, humidity, and dew point), extreme care had to be taken throughout the entire process. All materials were stored, handled and mixed in accordance with the manufacturer's recommendations.

In order to improve the bond between the CFRP sheets and the legs of the concrete channel girders, a putty and primer, compatible with the epoxy resin, were applied to the bottom surface of the girder legs and levelled prior to the application of the epoxy resin (Figure 4).

Figure 4: Completed Girder

After completing the surface preparation, 22 mm diameter holes for the anchor system were drilled into the sides of the girder, and shear plates, measuring 750 mm long x 350 mm high x 12 mm thick, were fastened to the girder using 20 mm diameter high strength bolts (Figure 5). The anchorage system was pre-fabricated one week prior to the on-site work. The CFRP sheets, previously bonded to the attached anchor plates, were then mounted on the shear plates. The epoxy resin was applied in between the sheets and on the prepared surface of the girder. Care was taken to control the epoxy thickness to ensure full saturation of the CFRP sheets without a build-up of the epoxy resin. This is extremely important for the effective transfer of bond strength from the concrete girder to the CFRP sheets. The CFRP sheets were supported by temporary support devices (i.e. light cables with turnbuckles looped around the web of the beam) during this process.

Figure 5: Mounting of Shear Plates

The temporary support devices were useful not only in holding the long sheets during the application of the epoxy resin, but also in avoiding debonding of the sheets from the surface due to camber effects after prestressing of the sheets (Figure 6).

Figure 6 – Placing the CFRP Sheets

The prestressing operation was conducted using 30 ton capacity hydraulic jacks. The specified prestress force in the CFRP sheets was 140 kN (31,400 lbs), and thus each jack was loaded to 70 kN (15,700 lbs). As a separate, independent check of the applied prestress in the CFRP sheets, the elongation of the sheets was measured. Once the desired prestressing force had been reached, the prestressed CFRP sheets were bonded carefully to the legs of the girders using nap rollers to remove any air bubbles that could negatively affect the bond performance. The prestressing operation created a slight gap between the FRP sheets and the bottom face of the girder legs due to camber effects. In order to provide full contact between the sheets and the concrete, plywood was placed on the bottom of the girder and then cables were fastened to remove the gap. The plywood and cables were left in place throughout the curing time of the epoxy. From laboratory tests, the epoxy adhesive was expected to be fully cured after one week; however, the repair was undertaken in October 2003 and the temperatures during this time were relatively low (i.e. below 15 °C). Thus, the plywood and cables were left in place for three weeks to allow for increased curing time at low temperatures.

To avoid any unexpected damages, the repaired areas were covered with plastic (Figure 7). During the repair work, traffic was restricted to one lane (Figure 8).

Figure 7 – Plastic Sheets to Maintain the Curing Conditions

Fig. 8 – Traffic Flow during the Repair Work

From the Department's perspective, this project was completed successfully with minimal disruption to the traveling public. It was obvious that the researchers and the Contractor (Vector Construction Ltd.) had spent a considerable amount of time planning and designing the installation. Because this project was the first North American field application using prestressed CFRP sheets, a number of variables had to be anticipated, considered and taken into account in the design and installation. The overall cost of this project was comparable with other projects using conventional repair techniques, and the Department will definitely consider using this innovative technique again in the future.

Acknowledgements: The authors are members and network partners of the Intelligent Sensing for Innovative Structures Network (ISIS Canada) and wish to acknowledge the contribution of Leo Mancs, Haixue Liao, John Ford, and Jamie Escobar-Valeria.

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Research Activities

Starting from this issue, each newsletter will highlight ongoing research – at a University, an Industrial Research Center, or a Government Laboratory. In this issue we highlight the research activities at North Carolina State University.

FRP Research Activities at North Carolina State University

By
Prof. Sami Rizkalla and Prof. Amir Mirmiran

FRP research projects at the Civil Engineering Department of North Carolina State University are sponsored by the National Science Foundation (NSF) and North Carolina Department of Transportation (NCDOT). Currently, NSF sponsors the Industry/University Collaboration Research Center (I/UCRC) "Repair of Buildings and Bridges with Composites (RB^2C) where the research is focused on:

- Innovative 3-D FRP sandwich panels; and
- Development of new adhesives for repair of steel pipes; and
- Use of high modulus carbon fiber reinforced polymers (CFRP) materials for strengthening steel structures and bridges.

NSF sponsors also development of new innovative 3-D woven FRP bridge decks. NCDOT sponsors a research study to examine the value engineering and cost effectiveness of various FRP repair systems using 40 years old bridge girders. In collaboration with the University of Cambridge, UK, special study is currently in progress to evaluate the durability of prestressing concrete structures with CFRP bars. The following is a brief description of each project:

1. Innovative 3-D FRP Sandwich Panels for Transportation and Infrastructure

The development of a new generation of 3-D FRP sandwich panels is currently in progress under the auspices of National Science Foundation (NSF) Industry / University Collaborated Research Center (I/UCRC) and incorporated with Martin Marietta Composites. The research includes development of innovative system for transportation and civil infrastructure. The primary objective of the research is to study and examine the structural performance of innovative 3-D FRP sandwich panels produced by Martin Marietta Composites, USA. The panels consist of GFRP laminates and foam core sandwich where top and bottom skin GFRP layers are connected together with through-thickness fibers. An extensive experimental program has been conducted. The test program consists of two phases to examine the material characteristics as well as the behavior of the panel.

Fundamental material properties in tension, shear, flexure and compression were evaluated. The variables in this study include the thickness of the panel, number of GFRP plies in the top and bottom skins, core configuration and density of through-thickness fibers. Overall panel behavior of 3D-FRP sandwich panels having different thicknesses was investigated under various loading conditions. Research is currently underway to develop an analytical model to predict the behavior of the panels using rational analysis and finite element analysis.

Figure 1: Test Setup for FRP Sandwich Panels Using a Concentrated Tuck Tire Loading at Mid-Span

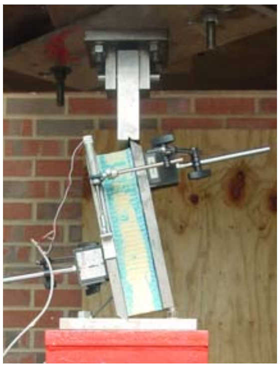

Figure 2: Setup for Shear Test

Figure 3: Setup for Tension Test

Figure 4: Setup for Flexural Test

2. Flexural Strengthening of Steel Monopole Towers Using High Modulus CFRP Materials

Increasing number of cellular phone users and their requirement for improved service has required cellular phone companies to increase the number of antennas on monopole towers. Addition of new antennas increases the wind load acting on the monopole; therefore strengthening is required to match this demand. Research has recently been conducted at NC State University under the auspices of the I/UCRC Center dealing with the strengthening of steel structures using new high modulus carbon fiber produced by Mitsubishi Chemical America, Inc. Research work commenced two years ago identifying suitable resins for wet lay-up of high modulus carbon fiber sheets and to identify adhesives suitable for bonding pultruded CFRP strips using the high modulus fiber. Further work examined the bond performance using small-scale flexural specimens. Three 6.1 m long scaled steel monopoles were fabricated with similar proportions to monopoles that are typically used as cellular phone towers. Each pole was strengthened with a different strengthening configuration, one by wet lay-up and two by adhesively bonded CFRP laminate strips, as shown in Figure 5.

Figure 5: Application of the High Modulus FRP Strips to the Monopole

The research also includes structural details provided by AeroSolutions, LLC to optimize the use of these materials. Substantial stiffness increases up to 39 percent at the tip have been shown for the three strengthened monopoles. Figure 6 shows the test of the monopole using the high modulus CFRP laminate strips.

Figure 6: Strengthened Monopole Near its Ultimate Capacity

3. Bond Characteristics and Qualifications of Adhesives for Marine Applications and Steel Pipe Repair

Industrial adhesives have become an important component of the structural elements with the developing technology of new materials. Adhesives that bond metals, plastics, FRP and other materials have been used in transportation, industrial and marine applications. Fundamental understanding of the bond behavior and load transfer mechanisms of different adhesives is essential prior to their use in civil infrastructure. The objective of this research is to evaluate the engineering properties of SB03-17400 adhesive, produced by IPS Corporation, USA. Mainly, the bond characteristics between composite-to-composite and composite-to-steel materials are investigated. As a control product, Plexus MA-440 adhesive is used and tested using the same testing scheme as that for SB03-17400 adhesive. A comprehensive experimental program is designed using single lap-joint specimens. A total of 76 specimens submerged in de-ionized water with different PH values and different temperatures are tested. The influence of high temperature and creep on the bond characteristics is examined as shown in Figure 7. Strength properties in cleavage peel by tension loading are determined.

Figure 7: Environmental Exposure Tests

4. 3-D Woven FRP Bridge Decks

The primary goal of this research project is to utilize the advancements in the three-dimensional weaving technology in developing an innovative glass fiber reinforced polymeric (GFRP) deck system that will meet AASHTO HS-20 performance requirements. A leader in 3D braided and woven composite materials, 3TEX, Inc. located in Cary, N.C. maintains a machine capable of utilizing the innovative 3Weaving^{TM} technique in fabricating a completely woven continuous glass fiber bridge deck preform. This preform will "puff out" into a modular three inch bridge deck panel with V-shaped (truss-like) cell orientation. The cells will be packed with triangular cut shafts of lightweight Balsa wood, and the deck will be vacuum resin infused. The new weaving technique introduces continuous fibers in both the top and bottom skins as well as between the outer skin and the inner core. This research will encompass experimentally characterizing the new bridge deck along with the material properties of the components comprising the specimen. The deck will be tested in three-point bending. Particular attention will be given to the connection points of the structural components of the truss-like bridge deck.

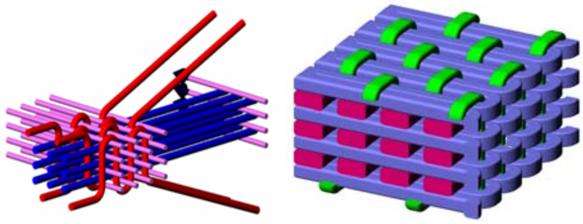

Figure 8: Weaving Process and Resulting Fiber Architecture

Figure 9: GFRP Truss Bridge Deck with Concrete Layer

5. Value Engineering and Cost Effectiveness of Various FRP Repair Systems

This research project is sponsored by the North Carolina Department of Transportation. The prime objective of the research program is to study and evaluate the value engineering and cost effectiveness of various FRP repair/strengthening systems. Test specimens are tested under static and fatigue loading. The specimens are full size prestressed concrete girders taken from a bridge erected in 1961 in NC, USA. Strengthening systems used in the research include externally bonded CFRP sheets and strips and near surface mounted CFRP bars and strips. Installation was done under field conditions using experienced FRP contractors. Preliminary results for the static tests show that FRP strengthening can achieve increases in the ultimate load capacity of up to 60% over unstrengthened specimens.

6. Durability of Concrete Beams Prestressed with CFRP Strands

This project investigates the durability of concrete beams prestressed with CFRP tendons in collaboration with Cambridge University and NC State University. A total of 15 beams have been constructed and precracked for this purpose. The main parameters are the sustained stress in the tendon (either $0.55f_{pu}$ or $0.70f_{pu}$ of strand), the environmental exposure condition (either in or outside the chamber), the length of time under loading (either 9 months or 18 months) and the type of testing to failure (either under static or cyclic loading). Similar beams prestressed with steel strands are also tested as control specimens. The test configuration in the chamber is shown in Figure 10.

Figure 10: Beams in the Environmental Chamber

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