FRP INTERNATIONAL

The Official Newsletter of the International Institute for FRP in Construction

Volume 2, Issue 4 **December 2005**

Welcome to this issue of the IIFC newsletter. In this issue, two articles focus on crucial challenges facing the use of FRP composites in civil infrastructure – fire resistance and ductility. In the past there has been significant concern raised about both issues, and I'd like to invite discussion in the form of "letters to the editor" on these topics. There are significant advances being made in both areas and the community needs to hear all viewpoints.

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, Professor 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

FRP INTERNATIONAL

The Official Newsletter of the International Institute for FRP in Construction

Volume 2, Issue 4 **December 2005**

Reports From Around the World

In this issue we highlight articles on new developments and research from around the world.

New Applications of Fire Hard Composites

by
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INTRODUCTION

The ever-increasing use of composites in many new applications attests to the many advantages they provide. Weight reduction, corrosion resistance, design flexibility, part consolidation, low maintenance costs and the facile reproduction of complicated designs are the main reasons for choosing composites over metal, wood or concrete.

The most commonly used thermoset resins are Unsaturated Polyesters, Vinyl Esters and Epoxies. A major problem of using these composites in many applications is their propensity to burn, producing heavy smoke and toxic fumes, which debilitate those trying to escape in a fire.

Another thermoset resin, well known for its excellent Fire / Smoke / Smoke Toxicity (FST) properties is Phenolic. Recent developments in Phenolic resin chemistry that allow the use of commom fabrication techniques such as Hand Lay-up, Spray-up, Filament Winding, Vacuum Infusion, Resin Transfer molding (RTM), Pultrusion and Press Molding have resulted in the use of composites in heretofore unacceptable applications.

RESIN CHEMISTRY

Cellobond Phenolic resole resins are prepared by the reaction of phenol and formaldehyde under alkaline conditions. A molar excess of formaldehyde is used to produce a water-based polymer capable of cross-linking or curing merely with heat. For faster cure rates at lower temperatures, an acid catalyst is used.

Catalyzed Cellobond Phenolic resins will cure in the region of 60 - 80°C. A range of resins with varying viscosity (as low as 250 cps) and catalysts of different reactivities are available to suit each processing technique.

Phenolics are inherently fire retardant, without the use of fillers such as Alumina Trihydrate or additives. Thus, an unfilled Phenolic composite of just resin and glass or carbon reinforcement, would have a 20 – 30% lower density than a filled system.

When fully cured, the high strength of the bonds and high cross-link density confer to Phenolic matrices an exceptional level of fire performance and resistance to high temperatures. Phenolic matrices are rated for continuous use at 200°c, maintaining over 90% retention of their Flexural modulus at 200°C compared to ambient temperature.

APPLICATIONS

Transit

The excellent FST properties of Phenolic have been exploited by transit specifiers for the use of Phenolic composites in interiors and exteriors of trains and buses – specially in Europe, where the FST requirements are much more stringent than in the USA. Table 1 illustrates the current Passenger Rail Equipment Requirements in the USA and what can be achieved with Phenolics.

Table 1. Current Passenger Rail Equipment Requirements* Compared to Phenolic Capability

TEST	Requirement	Painted Phenolic (35% glass)
ASTM E 162		
Flame Spread Is	≤ 35	0.85
ASTM E 662		
Smoke Density Ds (1.5 minutes)	≤ 100	0.6
Ds (4.0 minutes)	≤ 200	15
Ds (Maximum)	-	51
Time to Maximum Ds (Minutes)	-	14
NBS Smoke Chamber Gas Analysis (ppm)		
CO	≤ 3500	100
HF	≤ 200	0
NO_2	≤ 100	0
HCl	≤ 500	0
HCN	≤ 150	0
SO_2	≤ 100	80

** Federal Register / Vol. 64, No. 91 (May 12, 1999) (also FTA/UMTA 1984 and 1993)*

Ideally suited for trains that travel underground, current applications in Europe include London Underground, Chunnel trains, Tilt trains in Norway and Light Rail trains in London and Germany. Applications in North America include People Movers at Dallas Airport (built in 1984), BART cars, Baltimore subway, Amtrak trains, SERTA trains and VIA Rail in Canada.

Phenolic flooring (with a Balsa wood core) replacing plymetal (plywood with a metal skin) for trains and buses are commonly used due to the 40 – 50% weight reduction, improved fire properties and increased durability.

Underground train station platforms, third rail covers, ceiling and wall panels are ideal applications.

Offshore / Marine

Cruise ship interiors are frequently made of Phenolic composites since they meet IMO Level 3 requirements. Vacuum infused Phenolic panels have met MIL-STD 2031 for submarine interiors. Phenolic pultruded grating that meet Coast Guard requirements are used on Offshore Platforms and Navy ships. Filament wound Pressure pipe for deluge systems on Offshore Platforms that withstand the Jet Fuel Fire Test (per UKOOA guidelines) are extensively used.

Construction

Phenolic fume and exhaust ducting approved per Factory Mutual Research protocol Class 4922 and 4910 are commonly used in Clean Rooms for the semiconductor industry. The low Heat Release Rate and Flame Spread of Phenolic allows the ducting to pass without the use of water sprinklers inside the duct. Table 2 depicts the FM protocol test results.

Table 2. Factory Mutual Research Protocol Class Number 4922

ASTM E-84		
	Flame Spread	5
	Smoke Density	10
Oxygen Bomb Calorimeter		235 Btu/lb (1.682 x 104 kJ/kg)
Autoignition Temperature		887°F (475°C)

The maximum thermocouple reading taken 1 ft (0.3 m) from the exhaust end of the duct was 639°F (337°C). Maximum allowable: 1000°F (538°C)

Polyester or Vinyl Ester composites have been used in exterior construction for many years and have proven their long-term durability. Phenolic composites should be able to meet most Building Codes for interior applications. Mechanical and thermal properties of Phenolic, polyester and metals are compared in Table 3.

Some exterior applications of Phenolic composites include the dome of the Law School at Quinnipiac College and the clock tower at City Hall in New York City. Both were built using Hand Lay-up with a Balsa wood core.

Phenolic composites meet various European Building Regulations (see Table 4). The interior panels of schools and walkways in hospitals in London were made of Phenolic composites as well as ceiling panels in London Underground. The interior panels in the recently built Rotterdam Shopping Mall in Netherlands are all Phenolic composites

Vacuum infused Phenolic laminates containing 65 – 70% fiberglass have been tested per ASTM E-136 and determined to be Non Combustible (see Table 5).

Table 3. Comparison of the Performance of Phenolics, Polyester and Metals

PROPERTY	PHENOLIC FRP	FR POLYESTER FRP		MILD STEEL (PAINTED)	ALUMINUM (PAINTED)
		UNFILLED	FILLED		
Density (g/ml)	1.4 – 1.5	1.4 – 1.5	1.6 – 2.3	7.8	2.7
Tensile Strength Mpa	100 – 140	100 – 140	30 – 75	410 – 480	80 – 430
Tensile Modulus (Gpa)	5.5 – 7.5	6 – 7.5	7 – 19	210	70
Elongation @ Break (%)	1.8 – 2.5	1.8 – 2.5	0.4 – 1.7	20 – 35	3 – 18
Flexural Strength (Mpa)	150 – 200	150 – 200	100 – 125	200 (yield)	65 – 220 (yield)
Flexural Modulus (Gpa)	6 – 8	6 – 8	6 – 15	210	70
Izod Impact Strength (KJ/m2)	65 – 75	50 – 75	20 – 50	-	-
Coefficient of Thermal Conductivity (W/m/K)	0.20 – 0.24	0.20 – 0.23	0.22 – 0.30	46	140 – 190
Coefficient of Thermal Expansion (°C x 10-6)	10 – 15	25 – 35	18 – 25	11 – 14	22 – 24
Temperature Index (BS 6853)	> 420°C	Fail	< 365°C	> 420°C	> 420°C
UK Building Regs. (BS 476 Parts 6 & 7)	Class 1/0	Class 2/3	Class 1/0	Class 1/0	Class 1/0
3 Meter Cube Smoke Test (BS 6853)	Category 1	Fail	Category 2	Category 1	Category 1

Table 4. European Building Regulations

COUNTRY	REGULATION	CLASS
Netherlands	NEN 6064, 6065 & 6066	Class 1
Germany	DIN 4102	Class B1
United Kingdom	BS476 Part 6 & 7	Class 1 / 0
US	Pittsburgh Toxicity Test	
	35% glass	61g
	65% glass	92 g

Table 5. Mechanical Properties of Vacuum Infused Phenolic (70-75% glass)

REQUIREMENT	RESULT
30 seconds into the test – No Flame	No Flame
Maximum Chamber Temperature Increase - 30°C	
Starting Temperature	750°C
Ending Temperature	774°C
Maximum Weight Loss - 50%	12%

Helipad

A new first for composites was the construction of a Helicopter Landing Pad on the roof of Cooper Hospital in Camden, NJ. Normally built of steel, it would have been too heavy and require reinforcing the roof. Aluminum was considered but rejected because if a helicopter crashed on the roof, aluminum would melt and burn quickly. Phenolic panels were selected because Phenolic has met the Jet Fuel Fire Test and ASTM E-136 Non Combustibility Test requirements.

The Helipad was rated for an Apache Helicopter. Measuring 3,140 ft2 and 8" thick with an isocyanurate foam core and 0.44" phenolic/glass face skins, the density was 20 lbs/ft2. The panels were vacuum infused, some measuring 16 ft x 26 ft.

Phenolic Helipads would be ideal for Offshore Platforms, where weight reduction and fire safety are paramount concerns.

CONCLUSIONS

It has been demonstrated that Phenolic composites can provide all the advantages of composites and eliminate concerns over Fire / Smoke / Smoke Toxicity safety. This should allow their use in many applications where fire concerns were a hindrance. The Cellobond User-Friendly Phenolic resins that are now available make all this possible.

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BIOGRAPHY

Aram Mekjian is President of Mektech Composites Inc. He is the exclusive Distributor (in North America) of Cellobond Phenolic resins (now owned by Hexion Specialty Chemicals), which he introduced to the US market in 1990 as Business Manager for BP Chemicals. Prior to that, Aram was the Technical Director and Product Manager for Aristech Polyesters for 13 years. He received a BS in Chemistry from Valdosta State College, a MS in Chemistry and MBA in Marketing from Fairleigh Dickinson University.

Development of New Ductile FRP Systems for Strengthening Concrete Beams

by

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INTRODUCTION

Fiber Reinforced Polymers (FRP) has become attractive materials for engineers in the construction field, especially for strengthening existing reinforced concrete structures. Several FRP systems are now commercially available, incorporating glass, aramid, and carbon fibers. They are available in many forms such as pultruded plates, fabrics, and sheets.

Unfortunately, there are several drawbacks associated with using commercially available FRP strengthening systems for flexural/shear strengthening of reinforced concrete beams. The objective of this article is to introduce two hybrid, pseudo-ductile FRP strengthening systems designed to avoid many of these drawbacks. The article also reviews some of the important findings of an experimental study[1-4] to evaluate the effectiveness of these new systems in flexural and/or shear strengthening.

CURRENT PROBLEMS

Although FRPs have high strengths, they are very brittle. When loaded in tension, they exhibit a linear stress-strain behavior up to failure without exhibiting any yield plateau. The strain response of these materials is also different from that of steel, which yields after elastically deforming to relatively small values of strain (0.2% for Grade 60 [410 MPa] and 0.14% for Grade 40 [280 MPa]); while FRP materials exhibit elastic deformation to relatively large strain values before rupture. So, when they are used for flexural strengthening of concrete beams reinforced with steel, the steel reinforcement may yield before the FRP contributes any additional capacity to the beam. Therefore, a significant improvement in beam yield load or stiffness can hardly be gained.[5-8] When an increase in beam yield load or stiffness is required, larger cross sections of these materials must be used, which generally increases the cost of strengthening. Although using some special low strain fibers such as ultra high modulus carbon fibers may appear to be a solution, they can result in brittle failures due to fiber rupture.

Taking advantage of high strength of FRPs during flexural strengthening is limited by the bond capacity between them and the concrete. In many cases, debonding occurs at stress levels that are small fractions of FRPs' strengths.

In beam shear strengthening, FRP materials usually stretch to strain values that are usually small fractions of their ultimate strains when the beam reaches its shear capacity.[9-11] Therefore, the benefits of the FRP are not fully realized. Furthermore, strengthening the beam in shear requires orienting the fibers perpendicular to the beam longitudinal axis.[11-12] Therefore, simultaneous flexural and shear strengthening of beams requires using more than one layer of FRP. Finally, carbon FRP systems, the most commonly used FRP strengthening systems, are relatively expensive.

DEVELOPMENT OF NEW DUCTILE SYSTEMS

A research program [1-4] conducted at Lawrence Technological University resulted in the development of two new hybrid FRP (HFRP) strengthening systems that differ from currently available CFRP systems. They were designed specifically for use in strengthening reinforced concrete beams for flexure and/or shear while potentially avoiding the drawbacks mentioned previously. Hybridization has also been utilized to compensate for the lack of ductility of FRP reinforcing.[13-15]

The first HFRP system [H-System] is a uniaxial fabric consisting of different types of carbon and glass fibers. The fabric was mainly designed for use in strengthening reinforced concrete beams for flexure by mimicking the behavior of steel in tension. Since the fabric, with relatively low yield-equivalent strain value (0.35%), is attached to the bottom of the beam, it can potentially contribute significantly to the beam load before the steel reinforcement yields. Therefore, significant increase in beam yield load and stiffness can be achieved.

The second HFRP system [THD- system] is a triaxially braided fabric (Figure 1 and 2) designed for strengthening reinforced concrete beams for flexure and/or shear. A hybrid of different types of carbon and glass fibers, the fabric is triaxially braided in three different directions: 0^o, $+45^o$, and $–45^o$. The fabric was designed to exhibit a linear stress-strain behavior followed by a yield plateau if loaded in tension in any of these directions. The 0^o direction (axial direction) acts mainly for flexural strengthening, while the $+45^o$ and $–45^o$ directions (diagonal directions) provide shear strengthening (Figure 1 to 3). Providing fibers perpendicular to potential shear cracks increases their effectiveness in strengthening the beam shear capacity. Moreover, the diagonal yarns work to self-anchor the fabric when bonded around the tension face and the sides of the beam, significantly reduces the potential of debonding or shear-tension failures.

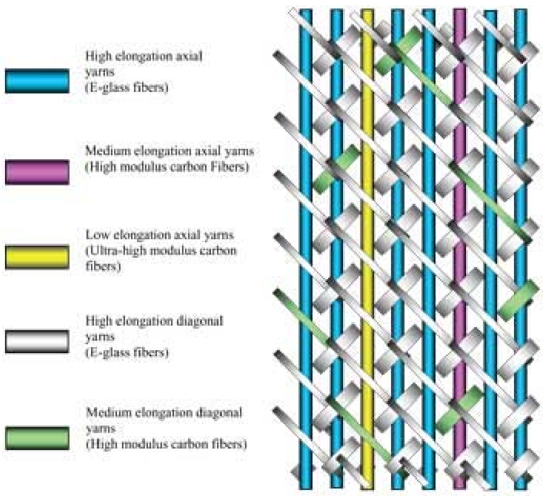

Figure 1: Details of the triaxially braided HFRP fabric (THD system)

Figure 2: Photo of the triaxially braided HFRP fabric (THD system)

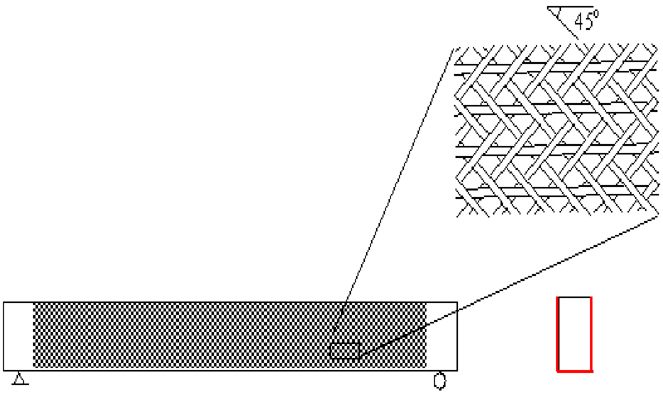

Figure 3. Lay-up of triaxially braided HFRP fabric for simultaneous flexural and shear strengthening

Figure 4 and Table 1 show a comparison between the tensile behavior of the developed systems and some commercially available FRP strengthening systems used in this experimental program.

Table 1. Comparison between the Tensile Behavior of the Developed Systems and Some Commercially Available FRP Strengthening Systems

Material		Yield-equivalent Load kN/mm (kips/in.)	Yield-equivalent Strain (%)	Ultimate Load kN/mm (kips/in.)	Ultimate Strain (%)	Thickness mm (in.)
THD-System	(0^o) Direction	0.19 (1.08)	0.35	0.33 (1.89)	2.10	1.0 (0.039)
	(45^o) Direction	0.115 (0.66)	0.47	0.20 (1.15)	2.05	
H-System		0.23 (1.30)	*0.35*	0.39 (2.24)	1.74	1.0 (0.039)
Carbon Fiber Sheet		-	-	0.34 (1.95)	1.2	0.13 (0.005)
Glass Fiber Fabric		-	-	0.42 (2.4)	2.00	1.0 (0.039)

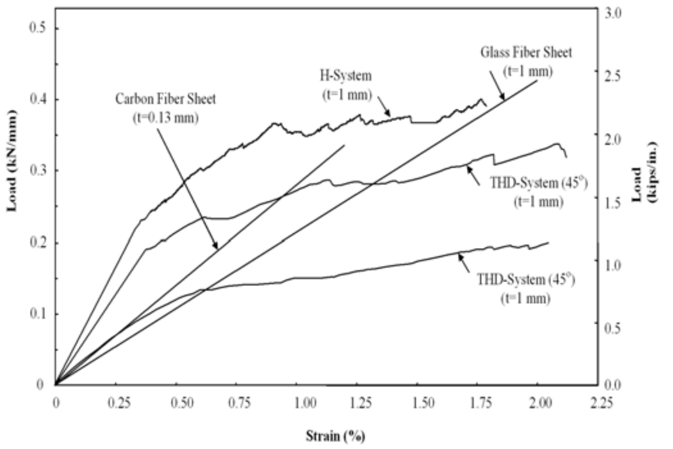

Figure 4. Comparison between the tensile behavior of the developed systems and some commercially available FRP strengthening systems

PROBLEMS SOLVED

Testing [1-4] was conducted at the Structural Test Center at Lawrence Technological University to evaluate the effectiveness of the HFRP systems in flexural/shear strengthening of reinforced concrete beams. Identical beams were strengthened using some commercially available carbon fiber systems in order to compare their behavior with those strengthened with the new systems (Figure 5). Advantages of the new systems are as follows:

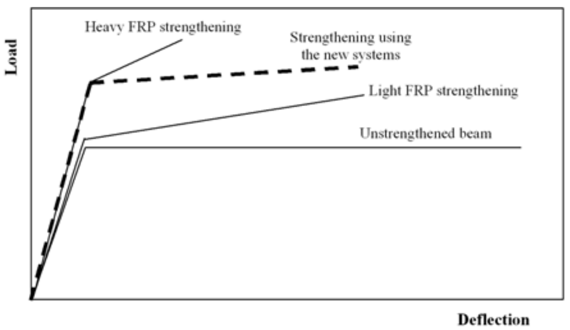

Figure 5. Schematic diagrams of load-deflection relationships experienced by reinforced concrete beams strengthened in flexure using commercially available FRP and the hybrid systems

YIELD LOAD INCREASE

Because HFRP systems have a relatively small yield-equivalent strain value (0.35% [Figure 4]), they have the potential to contribute with most of their strength when the steel reinforcement of the beam yields, which may significantly increase the beam's yield capacity. Experimental investigations [1-3] showed that the beams strengthened with HFRP systems generally showed similar increase in beam yield load to that of identical beams strengthened with carbon fiber sections of similar rigidity. The ultimate strains of HFRP strengthened beams were several times greater than those of CFRP strengthened beams.

DUCTILITY LOSS AND BRITTLE FAILURES

Test results for reinforced concrete beams strengthened in flexure using HFRP systems showed that those beams were less vulnerable to experience significant loss in beam ductility compared to identical beams strengthened with carbon fiber sections of similar rigidity.[1-3] Table 2 compares the ductility and the failure modes of the tested beams.

Table 2. Comparison between Ductility and Failure Mode of Simple Beams Strengthened in Flexure

Group	Beam Designation	Strengthening System*	Ductility Index†	Mode of Final Failure
1**	F-B-2	THD-System	1.95	Steel & fabric yield followed by concrete failure
	F-CB-1	Carbon fiber sheet	1.61	Steel yield followed by sheet debonding
2**	F-U-2	THD-System	2.18	Steel & fabric yield followed by concrete failure
	F-CU-1	Carbon fiber sheet	1.61	Steel yield followed by concrete failure
3**	F3-B-1	THD-System	2.92	Steel & fabric yield followed by fabric debonding
	F3-CB-1	Carbon fiber sheet	1.5	Steel yield followed by sheet debonding
4**	F3-U-1	THD-System	3.75	Steel & fabric yield followed by fabric rupture
	F3-CU-1	Carbon fiber sheet	2.27	Steel yield followed by sheet debonding
5	F-U65-1	THD-System	1.95	Steel & fabric yield followed by concrete failure
	F-CU65	Carbon fiber sheet	1.33	Steel yield followed by shear-tension failure at sheet end

* *The sections of the strengthening systems in each group are similar in rigidity.*
** *Grace, Ragheb, and Abdel-Sayed* [2]
† *The ratio between the deflection at failure and the deflection at first yield.*

The beams strengthened using the THD-system were greater in ductility index by 21-95% than those strengthened with the carbon fiber sheets. Because the HFRP systems behave like steel in tension, they play a role in two different ways. First, the reduction in stiffness of the HFRP systems past the yield-equivalent point limits the force in them and hence it becomes less likely to exceed its anchorable limit, which significantly reduces the potential of a brittle debonding failure. Second, the reduction in stiffness of the HFRP systems past the yield-equivalent point reduces beam's stiffness, which generates higher deformations before failure and thus more ductility.

HFRP systems exhibited very limited permanent strains. However, unlike steel, they did exhibit a permanent loss in stiffness when loaded and reloaded past the yield-equivalent point. Despite this fact, the beams strengthened with HFRP systems still exhibited a considerable permanent deformation after unloading and reloading. This is attributed to the steel reinforcement existing in the beam before strengthening. The reduction in stiffness of the HFRP systems after the yield-equivalent point allows the steel reinforcement to exhibit an increase in strain. After unloading the beam, the steel reinforcement helps to maintain a permanent deformation in the beam.

The test results of beam F-U65-1 (Figure 6) indicated that the beam exhibited a permanent deflection after unloading and reloading. The beam had a cross- sectional area of 152 mm - 254 mm (6 in. 10 in.), length of 2740 mm (108 in.) and contained two No. 5 (16 mm) tension bars near the bottom and two No. 3 (10 mm) compression bars near the top. The compressive strength of the concrete at the time the beam was tested was 41.5 MPa (6,000 psi) and the steel reinforcement used had a yield stress of 490 MPa (71,000 psi). Beam F-U65-1 was strengthened with one layer of the THD-system 1594 mm (62 in.) long, centered along the beam span that was U-wrapped along the bottom face, extending 152 mm (6 in.) on both sides. The beam was tested as a simple beam in four-point bending at a shear span of 838 mm (33 in.). The THD-system contains bundles of fibers in the $\pm 45^{o}$ directions that anchor it when bonded around the tension face and the vertical sides of the beam along its length. Therefore, it is generally less vulnerable to debonding or shear-tension failures (Figure 7, Beam F-CU65). This coincided with the findings of Bencardino, Spadea, and Swamy[8] in case of biaxial fabrics.

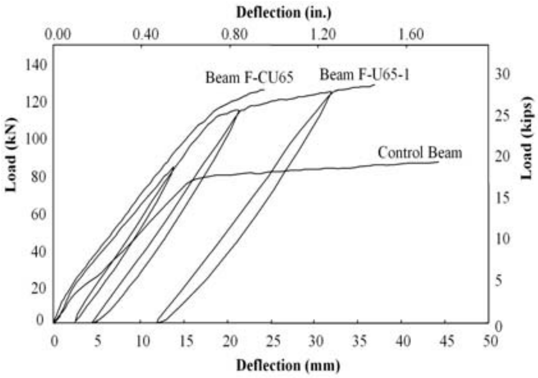

Figure 6. Load-midspan deflection relations of Beam F-U65-1, strengthened with HFRP, and Beam F-CU65, strengthened with CFRP

(a) Carbon fiber sheet strengthening (Beam F-CU65)

(b) Triaxially braided fabric strengthening (Beam F-U65-1)

Figure 7: Failure of two identical beams strengthened in flexure using two strengthening systems

Ductility is very important for statically indeterminate structures, such as continuous beams, as it allows for moment redistribution through the rotations of plastic hinges. The effectiveness of the THD-system in strengthening two-span continuous beams strengthened in flexure has been experimentally investigated.[3] Test results for Beams F-CT and F-CTC that were strengthened in flexure with the THD-system and a commercially available carbon fiber sheet, respectively showed that the ductile behavior of the THD-system resulted in a reasonable ductility in the plastic hinge of Beam F-CT, which in turn allowed for the redistribution of moment between positive and negative moment zones. Beam F-CT exhibited also a load-deflection response that was similar to that of the unstrengthened beam (Figure 8) and failed after exhibiting a reasonable ductility.

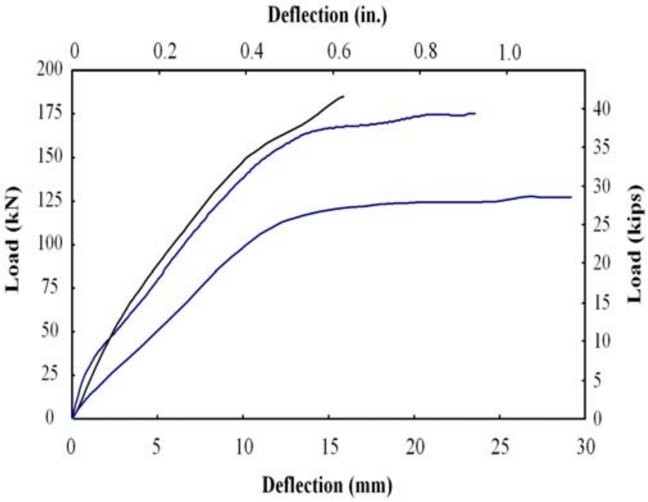

Figure 8. Load-midspan deflection curves of two-span continuous beams strengthened in flexure with CFRP and HFRP, respectively[3]

DISTINGUISHED AUDIBLE WARNINGS BEFORE FAILURE

Yielding of the new systems is always accompanied by audible sounds. The generation of ductility by these systems is based on allowing the fibers to rupture successively, which causes loud, audible sounds. Therefore, these signs can be considered as an indication of a potential failure. That is critically important as it adds a failure warning sign in addition to the visual sign of a potential failure revealed by the ductile behavior of the beam.

Cost and Material Exploitation

Despite the desirable characteristics of the HFRP systems, their cost is relatively low when compared to CFRP systems. That is because more than 75% of the fibers used are glass fibers that are relatively inexpensive. The new systems were designed to allow the fibers to fail successively starting with the most expensive ones (the carbon fibers), which start to fail after exceeding the yield-equivalent strain. Therefore, they have the potential to fully exploit their components, especially the most expensive ones. This was verified by the test results[1-4] for reinforced concrete beams strengthened using the HFRP systems, which showed that the maximum recorded strains of these systems before beam failure were much more than their yield-equivalent strain, and also more than the failure strain of the carbon fiber yarns in the system. In contrast, the maximum recorded strains of the carbon fiber systems used to strengthen identical beams were noticeably less than their ultimate strains, which indicated that their strength was underutilized.

The behavior of the THD-fabric in the 45^o directions allows optimum fabric contribution to beam shear strength. In other words, the fabric yield-equivalent strength was designed to be equal to the maximum possible usable fabric stress in beam shear strength.[4] Moreover, the THD-fabric was designed to have the diagonal yarns at 45^o to the beam longitudinal axis in order to increase the effectiveness of these yarns in the shear strength of the beam. At the same time, the existence of the axial yarns at the same layer with the diagonal yarns makes the fabric capable of strengthening the beam for flexure and shear, simultaneously.

APPLICATIONS

The HFRP systems were designed to be installed using the "wet lay-up" technique, which is the same technique currently used to install most of commercially available FRP systems.

Both pseudo-ductile FRP systems show promise of optimizing FRP properties without the drawbacks associated with currently available FRP strengthening systems.

ACKNOWLEDGEMENTS

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First Composite Material Trailer Developed in the United States Currently Being Evaluated by NC State University

by
Sami Rizkalla

Testing is currently underway at the Constructed Facilities Laboratory (CFL) at NC State University to evaluate the performance of a 48 foot platform trailer made almost entirely of Fiber Reinforced Composite material. The testing is taking place in the Large Scale Structural Systems Laboratory which is part of the Constructed Facilities Laboratory on the Centennial Campus. The trailer is a prototype which was developed by Martin Marietta Composites, a Raleigh, North Carolina based company.

In developing the platform trailer, Martin Marietta Composite integrated two patented composite technologies as well as its own composite engineering expertise and improvements to build a trailer that is light weight and corrosion resistant . This trailer is 30 percent lighter than equivalent conventional aluminum or steel trailers which could result in a 5 to 15 percent savings in operating costs. The base composite chassis concept was licensed to Martin Marietta Composites by Compositrailer n.v. of Belgium. Martin Marietta Composites adds the body which is made of Transonite®, a fiberglass sandwich panel, produced at their new 185,000 square foot production facility in Sparta, North Carolina. The trailers are also manufactured at the Sparta facility. Composite trailer technology is the result of many years of research. Prototypes trailers (shown in Figure 1) have been track tested and have logged over 800,000 miles to date.

Figure 1. Martin Marietta Composite Prototype Trailer

Martin Marietta Composites is an industrial member of the National Science Foundation (NSF) Industry University Cooperative Research Center on the Repair of Buildings and Bridges with Composites (RB^2C) which is based at the Constructed Facilities Laboratory (CFL) and directed by Dr. Sami Rizkalla. Martin Marietta Composites collaborates with the research team at the CFL to further develop the material for a wide variety of applications. Much of the initial testing of the Transonite® product has taken place at the Constructed Facilities Laboratory since 2000. Figure 2 provides two views of the trailer inside the Constructed Facilities Laboratory (CFL). Testing is currently in progress using the unique testing equipment at the CFL.

Figure 2(a). Overview of the CFL and Martin Marietta Composite Trailer

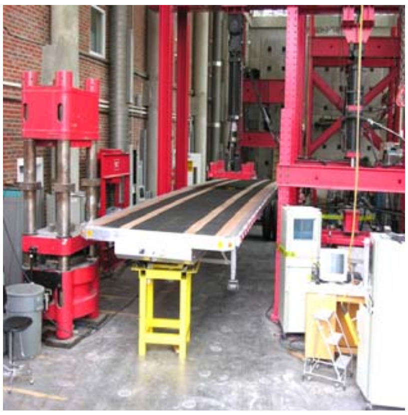


Figure 2(b). Current Testing of the Trailer at CFL

Developments in Codes, Standards and Guidelines

In this issue we highlight developments being made in Australia on the establishment of a comprehensive guideline for FRP and steel plating.

Philosophy behind the Generic Australian FRP and Steel Plating Guideline

by
Deric John Oehlers,
The University of Adelaide, Australia

ABSTRACT

A reinforced concrete retrofitting guideline is being developed in Australia under the auspices of Standards Australia that covers all forms of plating for all forms of materials. The aim of this guideline, as with established generic national standards such as those for reinforced concrete, is to provide engineers with comprehensive and, in particular, generic design tools that will allow them to find their own best solutions and to develop their own plating techniques.

FORMAT OF GUIDELINE

The technique of retrofitting reinforced concrete (RC) beams or slabs by bonding plates to their surfaces is advancing very rapidly and has reached the stage where the serviceability and ultimate behaviours of plated RC beams or slabs are understood. This behaviour, which encompasses flexure, vertical shear, shear connection and ductility, is described in the Guideline. It is described in generic terms so that the Guideline can be applied to all current forms of plating and, as the behaviours described are generic, they should assist in the application of new forms of plating. It is this fundamental and generic behaviour described in the Guideline that needs to be designed for. The Guideline uses the output from research on steel and FRP plated structures. However, the Guideline has been specifically written in generic terms so that it can, in theory, apply to plates of any material so as not to restrict but to encourage current and future developments in this rapidly developing retrofitting technique.

Plated RC structures are a new and unique form of structure which have similar failure mechanisms or behaviours as in both RC structures and composite steel and concrete structures. However, plated structures also have many new failure mechanisms that are not covered in RC and composite steel and concrete design manuals. As with all new forms of structures and because plating is a very efficient retrofitting technique, plating is being applied concurrently with the development of design rules. Hence, it is not possible at this stage of development of this new and unique technique to formulate prescriptive design rules that cover all situations. This should not hinder the application of plating but it does require a deep understanding of the behaviour of plated structures to ensure a safe design which, consequently, requires an understanding of the behaviour of both RC structures and composite steel and concrete structures.

The Australian guideline consists of a Guideline and a Commentary that are written in parallel. The Guideline covers the generic and fundamental behaviours of both plated beams and plated slabs and it is these behaviours that have to be understood and designed for. The more advanced design rules that quantify the generic fundamental behaviours in the Guideline are given in the Commentary. Hence, the designer needs to be aware of and design for the generic behaviours described in the Guideline. However, the Commentary is only meant to assist in the design and the designer is free to use any other approach that has been proven to be correct and safe, and which satisfies the generic and fundamental principles outlined in the Guideline.

It is recognised that design rules are improving and developing rapidly. In the long run, it is the intention to gradually transfer information from the Commentary to the Guideline as design rules become established.

GUIDELINE COVERAGE

The Australian guideline at present covers the retrofitting of both RC beams and RC slabs using bolted plates as in Figure 1 and adhesively bonded plates as in Figure 2. It is the intension to eventually expand the document to include columns, joints and frames.

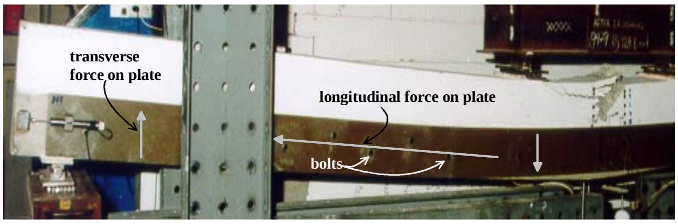


Figure 1. Bolted glass/carbon FRP plate

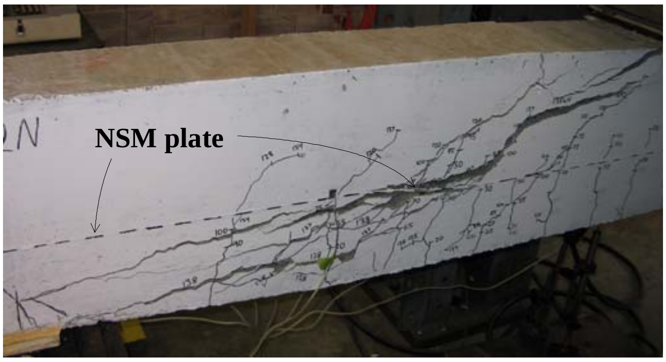


Figure 2. Adhesively bonded FRP NSM plate

Examples of the coverage of this Guideline specific to adhesively bonded plates are shown in Figure 3. The plating technique can be applied to any type of plate material such as any metal or fibre reinforced polymer (FRP) plate, and any cross-sectional shape of plate such as flat plates or angle sections.

The plates can be attached to any surface of an RC beam or slab as in Figure 3. Tension face plates in Figure 3(a) provide the greatest increase in the flexural capacity. However, tension face plates may interact with the stress concentrations induced by the adjacent reinforcing bars and, furthermore, they reduce the beam ductility by increasing the neutral axis depth. Compression face plates as in Figure 3(b) may be required where the tension face plate is extended into the compression face to reduce the possibility of debonding, or where a plate is added to the compression face to improve the ductility. Side plates as in Figure 3(c) may not be as efficient in increasing the flexural capacity as tension face plates but side plated do: allow a greater cross-sectional area of plate to be used; are placed away from the tension reinforcing bar stress concentrations; may provide a more ductile section when the plate is extended transversely into the compression zone; and can increase the shear capacity. Finally, combinations of plates can be used as in Figure 3(d).

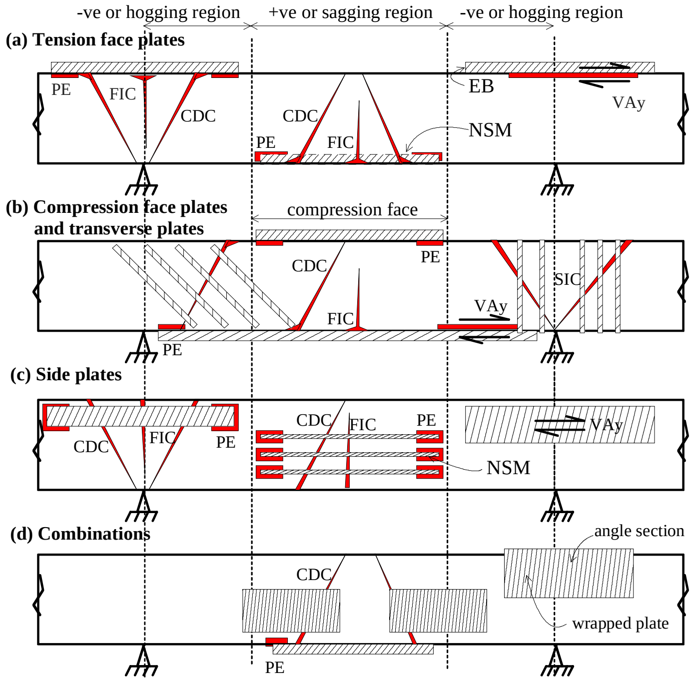


Figure 3. Range of adhesively bonded plates

The guideline covers all forms of debonding for both adhesively bonded and bolted plates. The debonding mechanisms for adhesively bonded plates are shown in Figure 3 where it can be seen that the same debonding mechanisms apply to all positions of plates. These debonding mechanisms include debonding due to stress concentrations which are: plate-end (PE) debonding through peeling due to curvature in the beam in the vicinity of the plate-end; flexural intermediate crack (FIC) debonding due to axial forces in the plate that are induced by flexure; critical diagonal crack (CDC) debonding due to rigid body shear deformations in the beam; and shear intermediate crack debonding (SIC) due to axial forces in the transverse plates due to rigid body shear deformations across a critical diagonal crack. Debonding between stress concentrations, VAy, is also considered.

The plates can be externally bonded (EB), near surface mounted (NSM) as in Figure 3, or bolted as in Figure 1. They can be used in both RC and prestressed RC beams to increase their flexural capacity or ductility, their stirrup vertical shear capacity as well as the concrete component of the shear capacity. The guideline caters for longitudinal and transverse plates as well as inclined plates as in Figure 3(b).

The wide coverage given in the guideline for all forms of adhesively bonded plates as well as for bolted plates and for all debonding mechanisms, will provide structural engineers with the flexibility to find their own best solutions for a particular retrofitting problem and to eventually develop their own retrofitting approaches. This wide and flexible coverage should expand and promote the technique of retrofitting by plating.

GUIDELINE CONTENTS

The Guideline and the parallel Commentary have the following major sections.

1. Stress resultants and material capacities often describes what my be considered by structural engineers to be the obvious, such as the resulting forces and stresses within a member. However, this section also describes behaviours unique to plated structures such as partial-interaction between transverse plates and between transverse plates and internal stirrups.
2. Debonding mechanisms in adhesively bonded plates identifies and covers all major debonding mechanisms for all positions of the plate and for all plate materials.
3. Debonding mechanisms in bolted plates describes the behaviour and design of the bolt shear connections for bolting any type of plate to beams. This section uses research on the design of stud shear connectors in composite steel and concrete beams to provide comprehensive design rules for the dowel resistance of the bolt as well as the resistance of the beam to the bolt forces.
4. Longitudinal concrete shear plane capacities ensures that all possible failure planes within the concrete medium can resist the additional longitudinal shear forces that are induced by the plates, whether they are adhesively bonded or bolted.
5. Design philosophies for strength identifies different strength design approaches that can be used and which are based on the fundamental behaviour of plated beams and their connections.
6. Generic ductility principles identifies different approaches that are required to deal with both ductile and brittle plate behaviour.
7. Plate buckling resistances explains plate buckling for both adhesively bonded and bolted plates of any material.

The generic approaches used for stress resultants and material capacities and the debonding mechanisms in adhesively bonded plates are described in the following sections, to provide examples of the generic approaches used in this guideline.

FLEXURAL STRESS RESULTANTS

As an example of the generic nature of the guideline, the section on the flexural stress resultants and capacities considers the flexural response of a plated beam as shown in Figure 4 for a side plated beam.

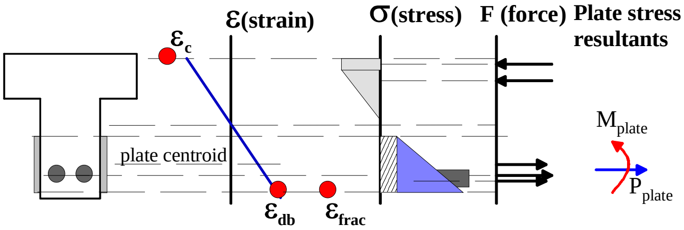


Figure 4. Generic flexural responses

Much of the analysis shown in Figure 4 is obvious to structural engineers but there are subtleties that are peculiar to plated structures. For example, in the design of unplated beams with ductile reinforcing bars, the beam is usually assumed to fail by concrete crushing at a fixed strain εc such that the strain profile pivots about this strain and which also allows the shape of the stress profile to be simplified often to a rectangular shape. However when the plate has a limited strain due to fracturing at εfrac or debonding at εdb, then these strains may cause failure before concrete crushing at εc as shown in the strain profile in Figure 4. Furthermore, when failure occurs before concrete crushing at εc then allowance needs to be made for the fact that some or all of the concrete may remain linear elastic as shown in the stress profile in Figure 4.

From the stress distribution in Figure 4, it can be seen that the plate may be subjected to a non-uniform stress distribution. Hence there is not only an axial force in the plate Pplate, which is well understood, but also a moment Mplate. The moment can only be resisted by the inducement of transverse forces, such as those shown in Figure 1, and subsequently stresses across the plate interface which should, therefore, be considered in design even in tension face plates.

SHEAR STRESS RESULTANTS

Vertical shear also needs special consideration as transverse plates act in a brittle fashion compared with the ductile behaviour of steel stirrups. The vertical shear capacity of plated RC beams is often written in the following form

$$V_{cap} = V_c + \Delta V_c + k_s V_s + k_{tp} V_{tp} \qquad (1)$$

where Vc is the concrete component of the shear capacity of the unplated RC beam and Vs the contribution from vertical steel stirrups. Hence longitudinal plates enhance the concrete component by ΔVc and transverse plates act as additional stirrups contributing Vtp. This approach allows the contribution of inclined plates to be deduced from both their horizontal and vertical force components as shown in Figure 5.

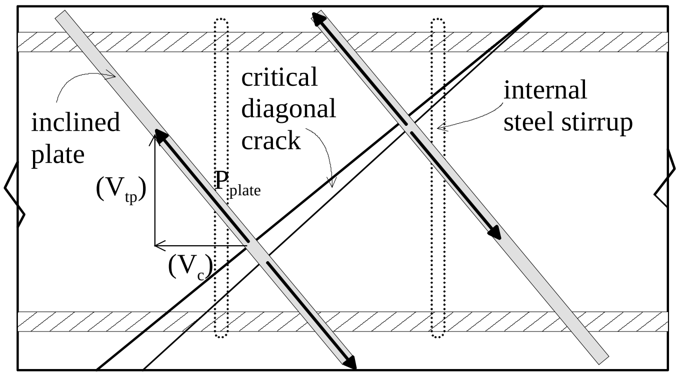


Figure 5. Inclined plates

The form of Eq.1 used in RC standards is based on the use of ductile stirrups. However, transverse plates often behave through their material or debonding characteristics, in a brittle fashion. Hence, the transverse plates may debond before their individual peak strengths are achieved, in which case the partial-interaction factor ktp < 1 in Eq.1. Furthermore, the plates may debond before the stirrups are fully yielded in which case the partial-interaction factor ks < 1.

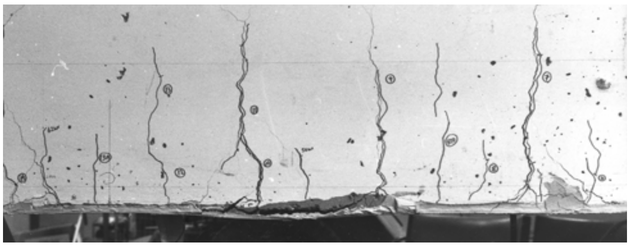
INTERMEDIATE CRACK DEBONDING

An example of intermediate crack (IC) debonding of an externally bonded (EB) tension face plate is shown in Figure 6(a). The same IC debonding mechanism also occurs in near surface mounted (NSM) tension face plates in Figure 6(b) and NSM side face plates in Figure 6(c). This form of debonding is caused by axial forces in the plates that are induced by flexure such as Pplate in Figure 4.

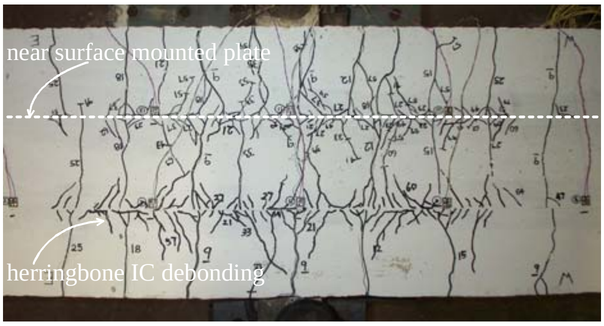
Generic design procedures for the form of debonding shown in Figure 6 have been derived from the fundamental behaviour of the partial-interaction interface bond characteristics shown in Figure 7, where τ is the interface shear stress and δ is the interface slip. From the partial-interaction interface characteristics in Figure 7, the maximum axial force in a plate is given by

$$P_{AIC} = 0.78\sqrt[3]{\left(\frac{d_f}{b_f}\right) f_c}\sqrt{L_{per}(EA)_p} \tag{2}$$

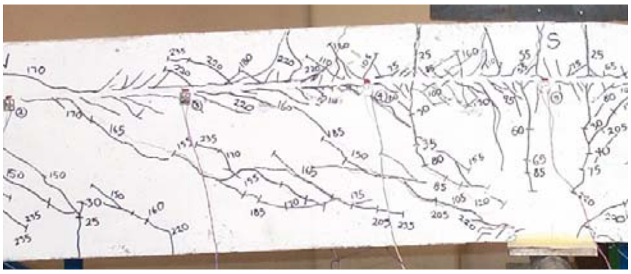
where PAIC is the maximum IC debonding resistance in a pull-test that is known to be equal to or a lower bound to the IC debonding resistance in a beam, df and bf are the depth and width of the failure plane within the concrete medium, Lper is the perimeter length of the failure plane, fc is the compressive strength of the concrete and (EA)p is the axial rigidity of the plate.



(a) EB tension face plate



(b) NSM tension face plates



(c) NSM side face plate

Figure 6. Intermediate crack debonding

The IC debonding resistance of Eq.2 is generic as it can be used for EB pultruded and wet lay-up plates, as well as NSM plates. It can be seen that it depends on the axial rigidity of the adhesively bonded plate (EA)p and as such it is independent of the plate thickness, applies to all plate materials and can include the adhesive stiffness if so required.

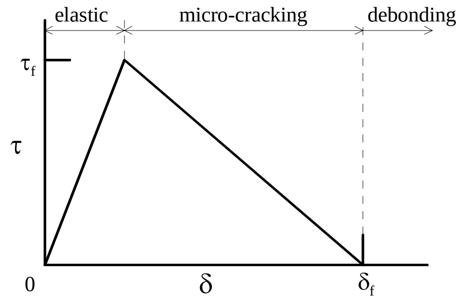
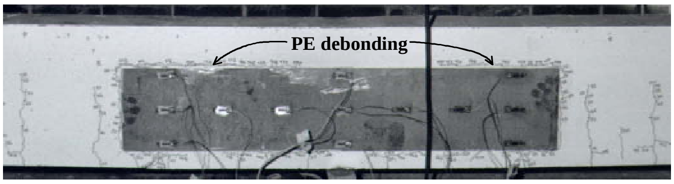


Figure 7. Generic interface characteristics

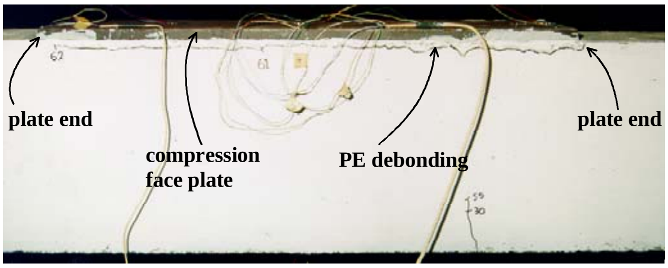
PLATE END DEBONDING

Examples of the generic nature of plate end (PE) debonding are shown in Figure 8 for an EB tension face plate in Figure 8(a), an EB side face plate in Figure 8(b), an EB compression face plate in Figure 8(c) and for a NSM tension face plate in Figure 8(d). This form of debonding is induced by transverse forces across the plates due to Mplate in Figure 4.

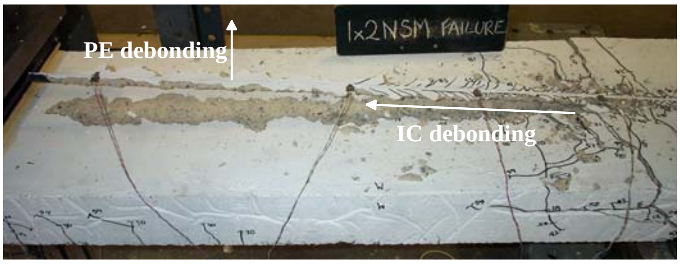
(a) EB tension face plate



(b) EB side face plate



(c) EB compression face plate



(d) NSM tension face plate

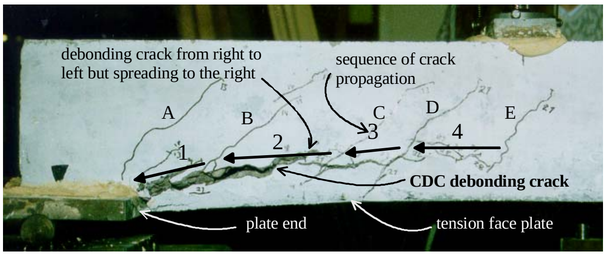
Figure 8. Plate end debonding

It can be seen in Figure 8 that PE debonding is generic and this has allowed the development of generic design rules such as in the following equation which gives the moment at the plate-end to cause PE debonding.

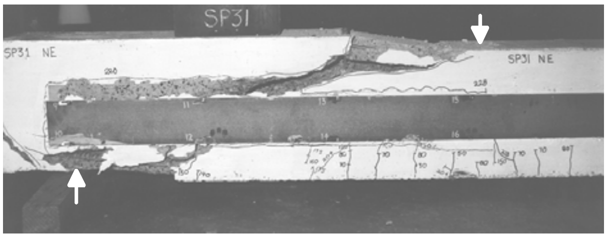
$$M_{PE} = \frac{k_1(EI)f_t}{E_p(k_2 t + 0.0185d)} \tag{3}$$

where EI is the flexural rigidity of the plated section, ft the tensile strength of the concrete, Ep the Young's modulus of the plate, and the remaining variables are either sectional dimensions or constants that depend on the position of the plate. Equation 3 is generic as it applies to any RC cross-section and any plate. It is simply the curvature in the vicinity of the plate-end, MPE/EI from Eq.3, that causes PE debonding.

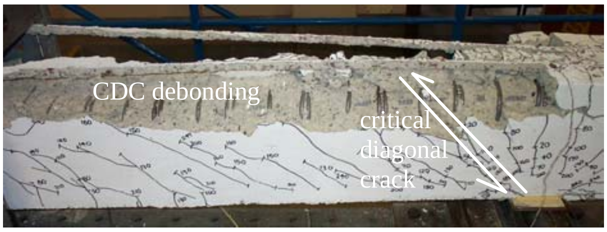
CRITICAL DIAGONAL CRACK DEBONDING



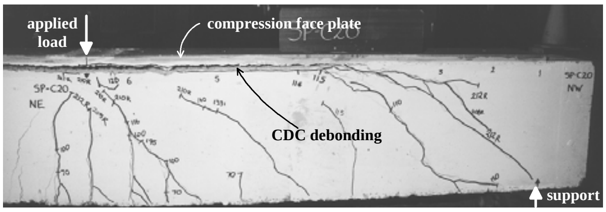
(a) EB tension face plate



(b) EB side face plate



(c) NSM tension face plates



(d) EB compression face plates

Figure 9. Critical diagonal crack debonding

Critical diagonal crack (CDC) debonding can occur for any plate position such as for an EB tension face plate in Figure 9(a), an EB side face plates in Figure 9(b), a NSM tension face plates in Figure 9(c) and an EB compression face plates in Figure 9(d). This form of debonding is caused by rigid body shear deformations across a critical diagonal crack as in Figure 5.

Generic design rules for CDC debonding are given in the guideline to cover all the forms of plating in Figure 9. Some of these rules are complex but do allow the position of the critical diagonal crack to be determined and, hence, the extent of plating required to be determined. Others are much easier to use, such as in the following equation for the vertical shear to cause CDC debonding, but require the whole shear span to be plated.

$$V_{CDC} = V_c + 0.15\sum(P_{AIC}) \tag{4}$$

where ∑PAIC is the sum of the axial forces in the longitudinal plates to cause IC debonding as in Eq.2 which has also been shown to be generic. Equation 4 was derived from the analogy with the vertical shear capacity of prestressed beams.

SUMMARY

The first step in developing a generic code, on par with generic established codes such as those for reinforced concrete and composite steel and concrete, is in identifying the generic failure mechanisms, which includes the generic debonding mechanisms as well as the generic interface material failure mechanisms. The problem is extremely complex. There are all the deformation problems associated with RC structures, all the partial-interaction problems associated with composite steel and concrete structures, plus the additional complexity of plate debonding. We are in effect dealing with a brand new form of structure which is more complex than any existing form of structure and much good research has and is being done.

The very rapid advances over the last two years, through some excellent research in understanding the failure mechanisms and in developing the structural mechanics of these failure mechanisms, has allowed a generic Australian plating design guideline to be written. This guideline covers a very wide range of adhesively bonded plates as well as the additional technique of bolting plates which, together, should allow structural engineers to find plating solutions for most of their retrofitting problems and, furthermore, help to extend the use of plating.

New and Ongoing Projects

From this issue forward we hope to highlight new and ongoing projects worldwide with short descriptions. The current sets were collected by Professor Issam Harik.

SUPER-SIZED DOUBLE-LAYER PULTRUDED GRATINGS

As part of the construction of the 151 bypass around Fond Du Lac, Wisconsin, Double-layer pultruded FRP grids were used in an experimental bridge as the reinforcing for a concrete bridge deck. The grids were pre-fabricated in 8' x 43'x 5.5" sections. A crane and four workers completed the placement in a little more than a day. This project was funded by the Federal Highway Administration Innovative Bridge and Construction Program.

For more information, please contact Dr. Bank, at bank@engr.wisc.edu

Super-Sized Double-Layer Pultruded Grid Being Lifted into Position

THE HISTORY CHANNEL HIGHLIGHTS RETROFIT WITH FRP

The History Channel's Back to the Blueprint program that aired on March 26, 2005 featured the retrofit of a historic theatre in Arizona. Among the unique features of this project are the strengthening of a number of unreinforced masonry walls with a system developed by Professor M. Ehsani and his associates (U.S. Patent No. 5640825). Host of the show, Marty Dunham demonstrates how easily a portion of the old walls can be retrofitted using QuakeWrap's carbon fabric and resins. The portion of the video dealing with FRP is 5 minutes long and can be viewed by clicking on the following link: http://www.quakewrap.com/news.htm

The project is currently in progress. The original contract was for QuakeWrap, Inc. to strengthen the masonry walls only. However, due to the efficiency of strengthening with FRPs, the scope of work has been tripled. The other elements in this building that are now being retrofitted with FRPs include the entrance lobby, several reinforced concrete beams and walls in the basement, the parapets and five large in-fill panels that are a part of the proscenium.

For more information, please contact Dr. Ehsani, at Ehsani@Arizona.edu

Some of the 60-ft high wall panels that will be strengthened with FRP.

Carbon fiber fabric adhered to under-designed bridge girder in Delta region, Egypt.

FRP-GLULAM-CONCRETE DEMONSTRATION BRIDGE

As a partnership between the town of Fairfield, Maine, the Maine Biotechnology Incubator and the Advanced Engineered Wood Composites Center at the University of Maine, the 21.3m Fairfield Biotech Bridge with seven single span FRP-glulam-concrete beams was designed and constructed to evaluate the potential for the application of FRP-glulam-concrete bridge construction.

To dramatically increase stiffness and strength in glulam bridge girders, this bridge design develops composite action between the bridge's concrete slab and the supporting girders using dowel-type shear connectors. The bridge design indicates stiffness increases of over 200% and strength gains of over 60% relative to noncomposite girders.

For further information, please contact Dr. Habib Dagher, at hd@umit.maine.edu

FRP-glulam-concrete bridge under construction in Fairfield, Maine

TIMBER BRIDGE STRENGTHENING

Glass FRP rebars were used to strengthen stringers in two timber bridges in rural Manitoba, Canada. The stringers were strengthened for both bending and shear. For bending, GFRP rebars were inserted horizontally in epoxy filled grooves routed in the bottom of the stringers. The shear strengthening was achieved by inserting GFRP rebars in vertically drilled holes and injecting epoxy resin around the rebars. Manitoba

Highways and Transportation, the owner of the project, saved taxpayers from paying for a new bridge.

Shear strengthening completed and flexural GFRP rebars partially installed.

For further information, please contact Garth Fallis, at GarthF@vectorgroup.com

USE OF FRP COMPOSITES IN GLULAM TIMBER STRUCTURES

A research program conducted at the University of Lecce (ITALY) allowed to investigate the possibility of using Carbon FRP (CFRP) rods in glulam structures. FRP rods were used as glued-in reinforcement of beams and as glued-in connectors for joints that should transfer flexural moment and shear between two adjacent beams. FRP rods and laminates were also studied as cross bracing systems to carry wind loads in glulam timber structures.

Bond properties between FRP and glulam timber were studied in a preliminary phase. Half scale specimen were tested in laboratory, a real scale application was carried out using these emerging technologies. Funding for this project was provided by COFIN 2002 project, STRATEX spa (Sutrio –UD) and MAPEI spa (Milan).

For further information, please contact Francesco Micelli, at francesco.micelli@unile.it

FRP laminates as cross bracing in glulam timber structures

BRIDGE DECK CONSTRUCTION WITH INTERNAL FRP REINFORCEMENT

A research project was undertaken to evaluate the use of post-tensioned FRP for bridge-deck construction.
The type of structure selected for this project is a four-span continuous concrete slab having GFRP bars for top and bottom mats and CFRP reinforcement for internal post-tensioning of the bridge deck. This bridge is located in Rolla, Missouri (Southview Drive on Carter Creek).

The combination of prestressed and non-prestressed FRP reinforcement resulted in an economical solution for a deck system with low deflection and high shear strength at a minimum deck thickness.

For further information, please contact Ing. Raffaello Fico, at ficor@umr.edu

Poured Bridge Deck Before Post-tensioning

STRENGTHENING OF STEEL BRIDGES WITH HIGH MODULUS CFRP

An experimental program is underway at North Carolina State University to study the strengthening of steel bridges with high modulus CFRP. The research is funded by the NSF Center “Repair of Buildings and Bridges with Composites” (RB2C). The study includes testing large-scale steel-concrete composite beams strengthened with post-tensioned and un-stressed high and intermediate modulus CFRP. Smaller-scale beams are also being tested to examine shear-lag, overloading and fatigue behavior.

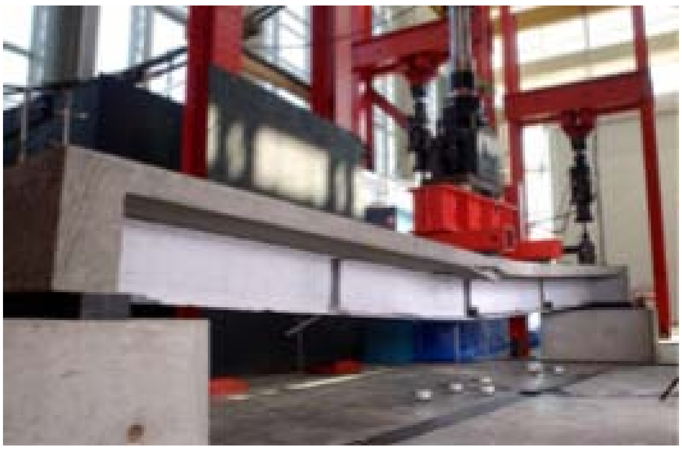
Large-scale (20 ft) beams were strengthened using high modulus and intermediate modulus CFRP and tested. The measured strength increases ranged from 16 percent to 45 percent using the intermediate and high modulus CFRP respectively. Stiffness increases ranged from 10 percent to 36 percent for intermediate and high modulus CFRP respectively. Post-tensioning was studied to improve serviceability and the system ductility. The post-tensioned beam exhibited a stiffness increase of 31 percent in comparison to the un-strengthened beam using half the amount of CFRP as the unstressed beam and maintaining the same ductility of the un-strengthened system.

Failure of large-scale beam

Once the effectiveness of the system was established, a series of smaller-scale (10 ft.) beams were tested to determine the extent of shear-lag between the steel and the CFRP and the effect of overloading conditions. The results demonstrate that the shear-lag between the steel and the CFRP is minimal. Furthermore, the strengthening system can substantially reduce the damage after an overloading event by significantly reducing residual deflections, particularly after yielding of the steel flange.

Fatigue testing of the small-scale beams is underway. To simulate the actual behavior of strengthened bridges, dead load is being applied to the small-scale beams prior to bonding of the CFRP strips. The beams will then be subjected to 3 million cycles with stresses ranging from 30 to 60 percent of the yield strength. Results will be compared to the results of an un-strengthened beam.

For further information, please contact Sami Rizkalla, at sami_rizkalla@ncsu.edu



Testing of small-scale beams

INDIANA EVALUATES FIRST BRIDGE DECK WITH FIBER GLASS REBAR

Indiana DOT, assisted by Purdue University, recently completed their first installation of FRP (fiber reinforced polymer) rebar in a bridge deck application. The bridge, a three-span structure utilizing steel I beams on concrete piers, is located on Thayer Road crossing I-65 in Newton County. It is 191’ long, 34.5’ wide, and designed for speeds of 40 mph by car and truck traffic estimated at 3600 vehicles/day. Fiberglass rebar is used in the top mat. It is instrumented with optical fiber sensors for ongoing evaluation via remote connection to the Purdue campus.

For further information, please contact Sam Steere, at: sam@fiberglassrebar.com

Deck ready for concrete pour at Thayer Bridge

A Perspective From a Leader of Industry

Mr. Fred Isley was one of the drivers behind early R&D efforts in the US associated with the use of FRP in construction. In the article below he provides a perspective on the current issues related to data. He is currently the global business manager of Civil Engineering and Construction Systems for Hexcel Corporation. He has over 30 years of experience in the fibers and composites industry. Mr. Isley holds numerous patents including some of the first applications of FRP composites for rehabilitation of civil infrastructure.

How Much is Enough?

by
Fred Isley
Hexcel Corporation

“It must be considered that there is nothing more difficult to carry out nor more doubtful of success nor more dangerous to handle than to initiate a new order of things; for the reformer has enemies in all those who profit by the old order, and only lukewarm defenders in all those who would profit by the new order; this lukewarmness arising partly from the incredulity of mankind who does not truly believe in anything new until they actually have experience of it.”.

Niccolo Machiavelli – The Prince circa 1514 AD

So said Machiavelli 500 years ago and he was right. The Prince is a very pragmatic look at management and it is obvious that Machiavelli had no great love for change because of the difficulties it presents, but he recognized that it was an inevitable, if unenviable, part of leadership. His counsel was to approach it carefully, for “*there is nothing more difficult* “ to institute, but change we must.

The area of concern is fiber reinforced composite materials (FRP) use in the civil engineering arena. The topic is leadership regarding the use of these materials in the construction industry.

We have FRP materials for application now. We have successfully used them on literally thousands of projects around the world over the past 15 years. Yet they have not been accepted into general use by civil engineers and regulators. The question is why and for that answer an analysis of the epigraph by Machiavelli is required.

In the litigious and finger-pointing atmosphere of today's society avoiding mistakes, particularly visible ones, is paramount to success, maybe even survival. One must be sure, know all and have relevant, on point answers to all questions, comments or criticisms that may be directed in their general direction. Initiating a *"new order of things"* places the initiator squarely in the cross hairs of the critics and nay sayers. For if you are wrong…..

All well and good, do nothing and you need fear nothing, right? Well, maybe not, the sins of omission, though harder to recognize, are just as deadly to those who commit them. Look to Kofi Anan, Bernie Ebbers or Ken Lay for examples of the results of allegedly allowing others to mismanage your affairs. In the current events column, the mayor of New Orleans, the governor of Louisiana, the President of the United States and all the President's men have, per the critics, thoroughly mismanaged a crisis of epic proportions by simply not doing enough fast enough. Regardless of the action or inaction there will always be disagreement.

Critics, like the poor, will always be with us.

Leaders by definition set the pace. Someone in long forgotten prehistory first sought shelter inside a cave. There might have been bears or tigers or some other misbegotten beast that would have eaten this intrepid soul, but he went anyway. The uncertainty of being eaten may have lost out to the certainty of freezing; maybe it was simple curiosity; maybe it was just the right thing to do, but that choice changed the way we live today. Today's leaders make changes like yesteryear's first spelunker either because they believe in what needs to be done or they feel they have no choice. With the mounting pressures of decaying infrastructure, increased risk from natural disasters, terrorist attacks or limited funding, limiting ourselves to the traditional way of making retrofits and repairs to our structures needs to change now.

Historically the use of composites in construction goes back to straw reinforced, sun baked bricks and has continued with FRP wrapped columns for seismic upgrades; retrofitted wall patches to stand in for missing rebar and overlays to strengthen cracked beams. Without composites the air age may not have happened. Shellac and cotton fabric is not much of a composite by today's reckoning, but it proved a light weight, strong and very conformable material that allowed the Wright Brothers to achieve powered flight at Kitty Hawk, NC. Modern aircraft, space craft and marine vessels are heavily dependent on composite materials to function. The strength to weight ratios and durability of FRP has been verified by decades of use. None of the traditional building materials can approach the mechanical properties offered by FRP because these materials were designed to be better, more economical, to carry more load, to be impervious to the environment and to last. Still the critics say we need to know more. And we do, but the time has come to proceed concurrently rather than consecutively.

Are these materials perfect? No, of course not. They have weaknesses just like any other material. Among the areas of concern are the following:

- Durability
- Fire resistance
- Creep
- Stress rupture
- Ductility
- Joining to other materials
- UV sensitivity
- Useable temperature range
- Cost
- Lack of knowledge.

Of these the lack of knowledge by the engineer of record or the approving authority is perhaps the most problematic. If you don't know what it is, you will have a hard time designing with it or approving its use. ACI, ICC and *fib* (Federation Internationale du Beton, European Construction Design Bureau) have issued design codes for composites. While the critics may grumble about their thoroughness, they are workable. Most manufacturers will provide not only design guides, but also installation and testing instruction.

As to costs, composites are generally less expensive to install on a job to job basis than traditional materials. My experience has shown a 25 -50% overall project cost reduction vs. traditionals. Even though the materials themselves are more expensive than steel, concrete or wood, lowered labor, equipment costs and time on site plus lower waste factors all result in a less expensive completion.

As to the other areas of concern, I will cite a few studies that have been done. References are available from Dr. Karbhari.

- Durability- 10,000 hour exposures to a variety of climatic conditions and chemicals showed life expectancies in excess of 25 years for properly prepared composites. Some studies have extrapolated life expectancy values of 50 to 100 years.
- Fire Resistance - The organic component of most composites will burn, however protective coatings allow up to 4 hours under loaded ASTM E119 testing. These coatings are generally intumescents that insulate the flammable component of the composite from heat. Further, composites exposed to heat will regain their full strength upon cooling so long as chain scission temperatures for the resin component are not exceeded. For most epoxies this temperature is in excess of 550 F.
- Creep – generally this is not a factor in composites once the resin component has been fully extended. The thermoset resins will creep under sustained loads, but the glass and carbon fibers have much less creep than steel and they restrain the resin system from elongating.
- Stress Rupture – Phi factors for glass and carbon have been set at 25% and 45% of ultimate tensile strength. While these numbers are quite conservative, they are the accepted industry standard.
- Ductility – In the civil engineering arena composites are considered non ductile. They have for the most part fairly linear stress-strain curves. When incorporated into a design with ductile materials a quasi-ductile structure can be obtained.

- Joining – The use of adhesive and mechanical joining systems has been well documented by the marine, automotive and aircraft industries.
- Ultraviolet Sensitivity - Most thermoset resins have a cyclic or aromatic chemical component. This component is sensitive to UV radiation and will degrade over time. Protection with paints or gel coats is more than sufficient to protect the resin from this exposure for decades.
- Useable Temperature Range – Most composite resin systems are characterized by T_g, glass transition temperature. This is the temperature at which the resin viscosity begins to sharply lower thus decreasing the strength of the composite. The T_g for well designed ambient cure resin systems is in excess of 180F making them useful for most civil structures. Higher transition temperatures can be obtained by selecting resins that cure with elevated temperatures

Hexcel has installed composites on 100's of columns, walls, beams, pilings and tanks. Our competitors have 1000's of installed structures. I am aware of just two failures and both could be traced to faulty installation, not material defects. Just as insufficient rebar will allow a beam to fail under load, insufficient FRP will allow the same result. Lack of water, cement or rebar can be equated to insufficient fiber or resin. Improperly placed reinforcement in either case introduces a flaw into the structure. These are not the faults of the material, but rather improper use. This is not, unfortunately, an uncommon occurrence with any material. That is why we provide simple, easy to use, field tested materials, equipment lists, installation manuals and field training. We bring a system to the table, not just materials and it works

FRP, like steel, concrete or wood, is simply another material with all the foibles inherent in any material. It is not perfect and we do not, nor will we, in our lifetime, know all there is to know about it. Even though we still research the effects of X on Y for traditional construction materials, we do not halt their use while we await the outcome of the research. This is not the case with FRP. All too many critics await that "perfect knowledge" preferring not to commit the sin of commission, but rather the sin of omission.
In this case the sin of omission is failed structures and wasted funds, neither of which can we nor should we tolerate. The question has moved from the technical realm to that of the political.

It's time for the leaders to step forward, we have enough.

University Research Activities

In this issue we highlight the research activities at University of Central Florida.

FRP Research at the University of Central Florida
by
Lei Zhao

Research on FRP at the University of Central Florida (UCF) is led by Dr. Lei Zhao, Assistant Professor, who joined UCF in 2002 after completing his Ph.D. in 1999 and a 3-year appointment as an assistant project scientist at the University of California at San Diego. Dr. Zhao's recent FRP-related research projects include the following:

1. Thermomechanical durability of FRP-strengthened reinforced concrete beams

This project studies the combined effects of humidity, cyclic thermal variation, and fatigue loads on the CFRP and its interface with the concrete substrate through accelerated large-scale laboratory testing. A total of fourteen 16-ft-long RC beams with various CFRP-strengthening designs will be subjected to various environmental and fatigue loading conditions in the laboratory for 18 months before being tested to failure. These tests will help the Florida Department of Transportation (FDOT), who sponsored the project, decide if the CFRP-strengthening technology shall be considered a long-term repair or a temporary fix. Load tests will also be performed on a number of Florida highway bridges that were strengthened with CFRP in the early 1990's.

2. Effects of anchorage strips on the ductility and failure modes of CFRP-strengthened RC beams

In CFRP-strengthened RC beams, interfacial behavior between the CFRP strengthening sheets and the concrete substrate—although an important issue that could significantly affect the behavior of the beams—has not been sufficiently characterized. This project investigated the interface and the effects of lateral anchorage strips on the flexural behavior of CFRP-strengthened RC beams, using a three-dimensional non-linear finite element model. The model used experimental data to calibrate properties such as the interface shear strength and stiffness, which can not be easily obtained through other means. Then, these calibrated properties were used to predict behavior of other beams. It was concluded that (1) lateral anchorage strips had a significant impact on the flexural behavior of CFRP-strengthened RC beams, and (2) various anchorage designs led to different load-deflection behavior and failure modes. Good agreement between the results from the analysis and experimental tests was obtained. The same model is being used in another on-going project to further test its applicability.

Figure 1. Casting specimens at FDOT's Structures Laboratory

Figure 2. CFRP-strengthened RC beams with transverse anchorage strips

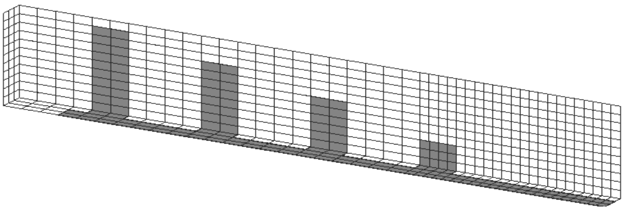


Figure 3. FE model used to calibrate the FRP-to-concrete interface behavior

3. CFRP wrapping repair of leakage of pressurized underground sewage pipe joints

Underground sewage pipe leakage, which typically occurs at the spigot-to-bell joint, causes contamination and soil erosion, which can further lead to road and structural settlement. Internal lining is difficult to implement for small-diameter pipes due to lack of access space, nor is it feasible for large diameter pipes due to the high content of toxic fumes. This project developed a technique that allows for quick repair of leaking joints. It included the following steps:

(a) Use ground-penetrating radar (GPR) to identify the leakage location
(b) Locally excavate to expose the leaking joint
(c) Use a quick-setting plaster material to cast a sleeve with an octagonal (or circular) cross-section outside the joint
(d) Wrap the plaster sleeve with CFRP

The prototype successfully demonstrated the ease of application and the wrapped specimens had sufficient strength when tested per ASTM C 497 – 03a.

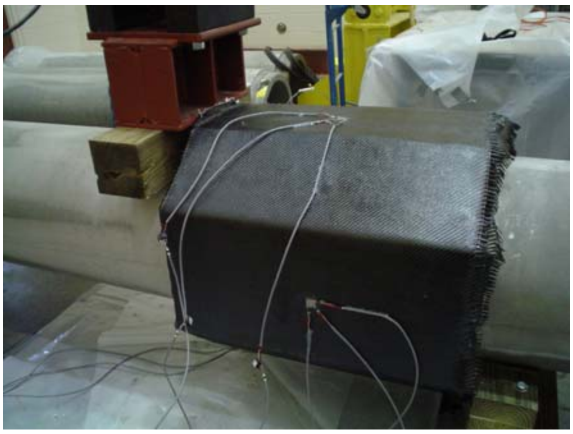


Figure 4. CFRP wrapped outside a plaster sleeve cast at the spigot-to-bell joint

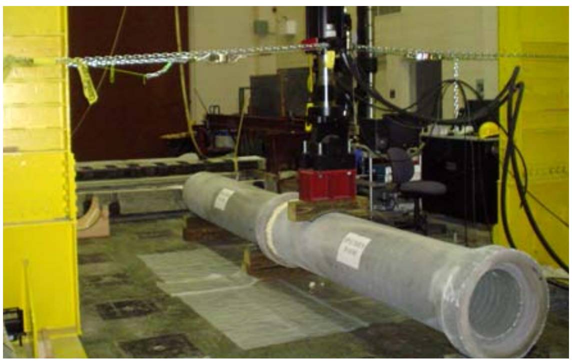


Figure 5. Pipe joint test per ASTM C 497 – 03a

(e) GFRP composite decks

Most lift bridges in Florida use steel open-grid decks, which are noisy to drive on, slippery when wet, prone to damage, and costly to maintain. GFRP composite deck panel is an excellent potential candidate to replace steel open grid decks because of its lightweight and solid riding surface. In this project, a new low-cost GFRP deck system will be analyzed and tested by UCF, FDOT and the material supplier. If the deck system successfully passes the tests, it will be used to replace the steel grid deck of an existing Florida bridge.

Figure 6. Repair patches on a steel open-grid deck.

The Structures Laboratory at UCF was completed in 2001. It has a 1,600-ft^2 testing area, which include a 50 ft × 25 ft strong floor in a high-bay area supported by a 20-ton overhead crane. Loading can be applied by a steel reaction frame and two 110-kip MTS servo-controlled hydraulic actuators. Other equipment includes a 200-kip Instron/Satec and a 60-kip Satec Universal Test Machines. More information about UCF's FRP research can be found at http://people.cecs.ucf.edu/zhao/.

Highlights of ConMat '05

From this issue onwards we will be accept submissions providing brief reports on conferences that may be of interest to readers. The current report was submitted by Professor Lei Zhao and Professor Jin-Guang Teng, and the photographs were provided by Tony Nardella.

CONMAT '05 Held in Vancouver

The 3rd International Conference on Construction Materials (ConMat '05), hosted by Professor Nemy Banthia and his colleagues at the University of British Columbia, was held in Vancouver, Canada, on 22-24 August 2005. Professor Banthia is the Treasurer of the IIFC Executive Committee.

Under the general theme "performance, innovations and structural implications", the conference featured a wide spectrum of topics including high performance and fiber-reinforced concrete, FRP composites, long-term performance of materials and structures, structural health monitoring and NDE, and design methods and codes. The conference included the Mindess Symposium as a tribute to

Professor Sidney Mindess who has made outstanding contributions to the area of construction materials.

Among the 370 technical papers presented at the conference, approximately 40 were dedicated to work on FRP composites (under Themes 1.01 Microstructure and Interface, 1.13 Fiber Reinforced Polymer, 3.2 Strengthening, Repair Methods, and Retrofitting for Seismic Loads, and 3.6 Additional ISIS Canada Papers). Issues addressed by these FRP papers include:

- FRP-to-concrete bond behavior: modeling and test verifications
- Durability of FRP composites
- Shear strengthening of beams
- Strengthening of slabs for punching shear resistance
- All-FRP and hybrid FRP bridge deck systems
- Wall and column retrofit/strengthening
- Prestressed FRP sheets and anchorage systems

Many IIFC members attended and presented papers at the conference. Professor Aftab A. Mufti, a founding Fellow of IIFC and a member of the Council and the Advisory Committee of IIFC, delivered one of the only two keynote lectures on the innovative work of ISIS Canada on FRPs and Fiber Optic Sensors (FOSs). Professor K. Maruyama, who is also a member of the Council of IIFC, delivered the other keynote lecture on a new JSCE standard for the seismic performance verification of structures.

The conference proceedings (ISBN 0-88865-810-9) include a print volume of all abstracts and a CD containing the full-length papers, edited by Professors N. Banthia, T. Uomoto, A. Bentur and S.P. Shah. More information about the conference can be found at its official conference web site at http://www.civil.ubc.ca/conmat05/.


Professor Banthia


Professor Maruyama


Professor Mufti

Honors and Member News

Dr. Aftab Mufti, President of the ISIS Canada Research Network (ISIS) and Professor of Civil Engineering at the University of Manitoba, recently received the extraordinary honour of being given the Mirko Roš Award from EMPA, the Swiss Federal Laboratories for Materials Testing and Research. The Award is a gold medal and bears the bust of Dr. Mirko Roš, an outstanding researcher and distinguished academic who was the Director of EMPA from 1924 to 1949. Dr. Mufti, who is credited with coining the term " Civionics " to define the need to bring together the brightest minds in the fields of electrical engineering, electronics, and photonics to expand the envelope of civil engineering in the future design of civil infrastructure, was presented with the Mirko Roš Award for his outstanding life's work in research and education.

FRP Photo Competition '05 - Competition Result

The Winners have been chosen!

It was not easy to select 2 winners from the large number of impressive, high-quality submissions for the photo competition. The panel of judges had a difficult task.

The winner in each category will receive an award of US$ 200 and have his/her photograph appear on the cover of the Journal of Composites for Construction published by the American Society of Civil Engineers (ASCE). The winner and the five runners-up in each category will have their photographs made into posters and displayed (with due acknowledgement) at international conferences and events where the IIFC exhibits.

A. Application Category

Winner

Ref. No.: PC05-010
Caption: Lay'n Out the Deck
Photographer: Doug Gremel
Description: Laying out the Aslan 100 GFRP Rebar in the Sierrita de la Cruz Creek Bridge near Amarillo Texas USA.

Runner-up

Ref. No.: PC05-005
Caption: Strengthening the Gasconade River Bridge in Missouri, USA
Photographer: Paolo Casadei
Description: One of the girders was impacted immediately after construction jeopardizing the entire structural performance of the new bridge. CFRP strengthening was chosen by MODOT as the most cost/time efficient solution.

Ref. No.: PC05-147
Caption: CFRP Cable-Stayed Bridge
Photographer: Jiwen Zhang
Description: CFRP cable stayed bridge in China.

Ref. No.: PC05-070
Caption: Phillips Campus Bridge across the River Dommel
Photographer: Jaap Ketel
Description: Total span approx. 32 meters. Width 4 meters. Cladding is double curved 4 meter wide, 1 meter high section length 3 meters, made with hand lay-up special fire resistant resins. Owner: Phillips Electronics Netherlands BV, Architects: Juurlink and Geluk Engineers; DHV Contractor: Ballast Nedam – Polyproducts Consultants: CLC-TNO

Ref. No.: PC05-071
Caption: Loading by Ourselves
Photographer: Yu Bai
Description: The Pontresina bridge is an all FRP composite pedestrian bridge which was built in 1997. Dynamic tests by human-induced vibration were conducted after eight years' service.

Ref. No.: PC05-068
Caption: A Softeye for the Dome
Photographer: Karl Huck
Description: Lifting of a ComBAR GFRP-reinforcement cage for the North-South Metroline in Cologne. Modern reinforcement and classical buildings on one photo.

B. Research Category

<u>Winner</u>

Ref. No.: PC05-138
Caption: FRP Bars
Photographer: Steve Preston
Description: FRP bars waiting to be tested at the University of Wisconsin.

<u>Runner-up</u>

Ref. No.: PC05-062
Caption: Fatigue Behavior of Full-Scale CFRP Repairs on CRC Deck-Girders
Photographer: Grahme Williams
Description: Specimens 26 ft long, 4 ft tall, 36 in wide decks, and 14 in wide stems were cracked, repaired, fatigued 1,000,000 cycles and tested to failure to study fatigue behavior of CFRP U-wrap repairs.

Ref. No.: PC05-075
Caption: Innovative Strengthening Technique for RC Beam
Photographers: Francesco Focacci and Alessandra Barbieri
Description: Debonding of carbon fibers embedded in cementitious matrix used as flexural reinforcement of RC beams, in the maximum bending moment zone.

Ref. No.: PC05-123
Caption: Composite Materials for the Structural Strengthening of Reinforced Masonry Shells
Photographers: Joaquim A. O. Barros, Juliana T. Oliveira and Everaldo Bonaldo
Description: Effective strengthening technique using carbon fiber reinforced polymer (CFRP) materials, developed to significantly increase ultimate load of damaged reinforced

masonry shell structures. This strengthening system is composed of strips of wet lay-up CFRP sheet at the extrados and prefabricated laminate strips of CFRP at the intrados.

Ref. No.: PC05-036
Caption: Giant Wye 3-D FRP Sandwich Panel Under Tire Load
Photographer: Engin Murat Reis
Description: Testing of a 3-D FRP Sandwich panel under simulated truck tire load.

Ref. No.: PC05-133
Caption: Fiber-Tear Failure of an Adhesive Connection
Photographer: Martin Schollmayer
Description: The photo was taken at the Swiss Institute of Technology within a research project, developing a bridge system with FRP bridge decks adhesively bonded to structural steel girders. The photo shows a failed adhesive connection after being tested with rest of glass fibers teared out of the FRP material.

International Symposium on Bond Behaviour of FRP in Structures

The International Symposium on Bond Behaviour of FRP in Structures (BBFS 2005) organized by the IIFC Working Group on Bond between FRP and Concrete in conjunction with the Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, was successfully held in Hong Kong on 7-9 December. More information on BBFS 2005 will be provided in the next issue of *FRP International.*

Delegates of BBFS 2005

Announcement

Third International Conference on FRP Composites in Civil Engineering, (CICE 2006) 13 – 15 December 2006, Miami, Florida

Applications of fiber reinforced polymer (FRP) in civil engineering have increased significantly in recent years, both for the strengthening of existing structures and for new construction. The aim of this conference is to provide an international forum for all concerned with the application of FRP composites in civil engineering to exchange recent advances in both research and practice.

The three-day conference (December 13-15, 2006) will be filled with a variety of session formats, with a balance of technical advancement and practicality to permit the widest possible participation, including researchers and engineers. A number of world-renowned scholars will be invited to present keynote lectures. A concurrent FRP product exhibition session will also be held. A pre-conference workshop on FRP repair applications and a post-conference cruise from Port of Miami are being planned.

For enquiries about this conference, please contact Dr. Amir Mirmiran at:

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INTERNATIONAL INSTITUTE FOR FRP IN CONSTRUCTION