FRP INTERNATIONAL

The Official Newsletter of the International Institute for FRP in Construction

Volume 2, Issue 3 ***August 2005***

In this issue we continue with *"Reports from Around the World"* focusing on developments in materials and their application to structural systems. Articles in this issue have been contributed BY IIFC members from Australia, Canada, Europe, Japan, The United Kingdom, and the United States, emphasizing the international nature of the institute. Steve Loud, an internationally recognized member of the international materials community provides his view-point in the current issue, highlighting developments, needs, and the future.

Our members are continuously being honored for their expertise and their contributions to the community. In this issue we highlight the recognition of Professor Antonio Nanni. We'd like to similarly congratulate and acknowledge the achievements of our members worldwide. Please send your news to the editor at vkarbhari@ucsd.edu or to any of the members on the advisory or editorial boards.

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.

Vistasp M. Karbhari, Editor-in-Chief
Email: vkarbhari@ucsd.edu

In this issue

FRP INTERNATIONAL

The Official Newsletter of the International Institute for FRP in Construction

Volume 2, Issue 3 **August 2005**

Reports From Around the World

In this issue we highlight applications related to the development of new materials and the integration of developments in materials and structures from around the world.

Vinylester/Cenosphere Composite Materials for Civil and Structural Engineering

By
Scott W. Davey, Tim J. Heldt, Gerard M. Van Earp and Stephen R. Ayers
Polymer Testing Laboratory
Fibre Composites Design and Development
University of Southern Queensland, Australia

With the increasing use of fibre reinforced polymer (FRP) composites in civil engineering structures, there is a growing realisation of the need to develop new structural systems which can utilise the unique characteristics of these materials in a more efficient and economical manner. In many instances this will require the development of new materials tailored to address the unique performance and economic parameters of mainstream civil construction.

One approach to increase the performance and minimise the costs of FRP composite structures is the use of sandwich construction. In this technique typically a low cost core material is reinforced with FRP laminates. However, many of the more traditional core material options lack the functional performance required for civil engineering applications. This stems from the fact that many of these traditional core materials were historically designed for use in the aerospace or marine industries which have a different priority of performance parameters compared to civil engineering.

Over recent years, researchers at the University of Southern Queensland have pioneered the use of a new type of particulate reinforced polymer composite material which is composed of small hollow spherical fillers (microspheres) in a thermosetting polymer matrix. Initial research has shown these materials to have significant potential for widespread use in FRP composite structural elements, improving their performance and cost-effectiveness.

One of the most promising classes of these materials investigated to date are vinyl ester / cenosphere composites, which utilise a ceramic microsphere derived from fly ash (cenospheres) in a vinyl ester matrix. Vinyl ester / cenosphere composites may offer considerable flexibility in design and application to civil engineering structures with a range of constituent material options available to optimise performance.

This vinyl ester / cenosphere composite technology was adapted to manufacture composite structural elements for the centrepiece of Brisbane City Council River Walk initiative, an 850m long floating walkway extending from the Story Bridge to New Farm (Figure 1).

Figure 1: River Walk on the Brisbane River

The walkway consists of 288 5m wide and 3m long floating concrete pontoons with the connectivity between adjacent pontoons provided by composite “walers”. The walers are beams (see Figure 2) which are located on either side of the pontoons and are bolted together by stainless-steel rods which pass through pontoons and the walers. With the walkway located in an aggressive marine environment and the demanding loading scenario, the durability and performance advantages of a composite structural solution over more traditional timber or steel options was recognized.

Figure 2: Composite Waler

A vinyl ester based composite system was a predominant component of each of the more than 500 standard configuration walers, consuming well over 100 tonnes of composite materials. Significant developments were required in this technology to enable the successful completion of this innovative demonstrator project. The project highlighted the need to develop a more comprehensive understanding of material behaviour, from perspectives of both processing and end product performance. In particular, there was a need to improve the understanding of constituent influences on the performance of a resulting composite material to properly develop the technology for the mainstream civil engineering industry.

An in-depth investigation of vinyl ester/cenosphere composites was recently conducted under two broad performance categories [1]:

1. Processing Performance including: Cure, Viscosity Behaviour and Shrinkage, and
2. Product Performance including: Mechanical Properties and Temperature Performance

Through completing over 500 individual tests, this strategic investigation defined critical relationships and highlighted additional areas for further examination. Notably thermal analysis techniques, which are typically utilised by polymer chemists, were applied to examine material behaviour.

Processing Performance

Processing performance of the composite materials includes those characteristics which influence the fabrication of a composite product. The composite material systems utilised to produce walers were designed to provide sufficient working time to complete the production process and be of a consistency to facilitate the casting process with moulds fabricated to produce a waler of the required dimensions. The cure characteristics, viscosity behaviour and shrinkage behaviour of the composite system all influence these processing activities.

Cure Characteristics

Differential scanning calorimetry (DSC) is a thermal analysis technique which evaluates the heat capacity characteristics of a material under specific thermal conditions. This technique was used as a relatively simple and quick method of examining the cure behaviour and development of network properties of vinyl ester matrix systems. In DSC a test specimen and reference specimen are simultaneously subjected to a controlled temperature programme within a high precision furnace. The differences in temperature of the reference and sample are used to determine endothermic and exothermic events in the sample material.

The relative influences of the cure system components and resin attributes were isolated by comparing the characteristics of the DSC curves of alternative samples. This is demonstrated in Figure 3 which shows selected DSC curves of samples cured with varying initiator concentrations. These tests were used towards establishing operating limits for initiator concentration to produce stable cure behaviour and good network properties. The inconsistent cure behaviour for initiator concentrations below 1.5% is clearly evident.

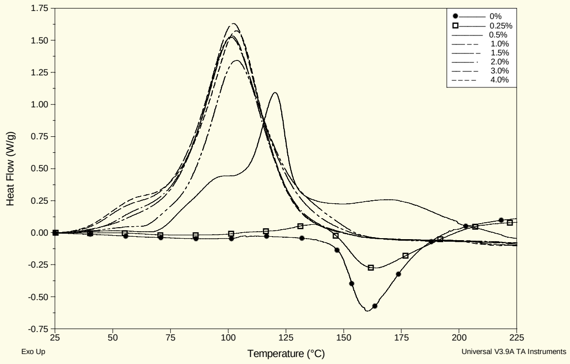


Figure 3: First DSC Heat Run With Varying Initiator Levels

The study highlighted the considerable flexibility available to cure vinyl ester matrix systems and composites by tailoring the cure system to meet specific working conditions and processing requirements.

Viscosity Behavior

Approximate relationships between filler volume fraction and the physical characteristics were also established. The viscosity of vinyl ester / cenosphere composites was measured using a Brookfield viscometer. The viscosity behaviour was observed to increase non-linearly with the filler content of the composite (see Figure 4).

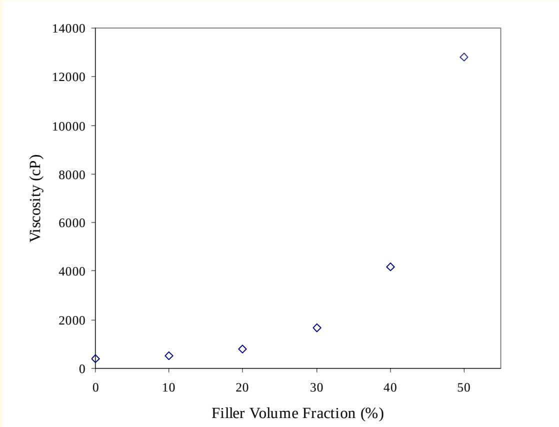


Figure 4: Influence of Filler Volume Fraction on Viscosity

At high filler levels the behaviour appeared dominated by particle interaction, characterised by significant increases in viscosity for only small increases in filler content. The experiments also highlighted the sensitivity of the viscosity behaviour to styrene concentration with only small additions of styrene producing large decreases in viscosity, particularly at high filler levels.

Shrinkage Behaviour

Linear shrinkage measurements were used as an indicator of general shrinkage behaviour. In general the total shrinkage of composites decreased with increasing filler content but the overall behaviour proved complex. The variation of initial shrinkage values after an ambient temperature cure was attributed to different degrees of conversion of the network achieved in the samples of each filler volume fraction. The more uniform total shrinkage behaviour was attributed to the post-cure progressing the degree of conversion such that each sample was cured to a similar extent and exposing each sample to an equivalent thermal cycle.

The geometry of the specimen also appeared to have a significant effect on measured shrinkage values particularly as the sample volume increased which suggested that the measured shrinkage values may only be an indicator of the overall shrinkage behaviour of a product. This highlights the need for prototype manufacturing trials as part of the development process.

Product Performance

Product performance refers to the material characteristics which are of significance to a design engineer, specifically the material's mechanical properties and the maintenance of these properties at service temperatures.

Mechanical Properties

The basic mechanical properties of these materials were characterised by assessing their behaviour in tension, compression and flexure to determine the material properties of strain at failure, various moduli, stress at failure and Poisson's ratio. Overall an increase in the filler content resulted in an increase in stiffness (see Figure 5), a decrease in strength and decrease in the Poisson's ratio of the composite material. (Figure 5) also shows the close relationships of the tension and flexure moduli suggesting the flexure stiffness behaviour is highly influenced by the tension properties.

Whereas the moduli relationships with increasing filler content are linear, the viscosity behaviour exhibited an approximate bi-linear relationship. This highlights the complex relationships between the constituent materials and the behaviour of the resulting composite through the processing and into the final product form.

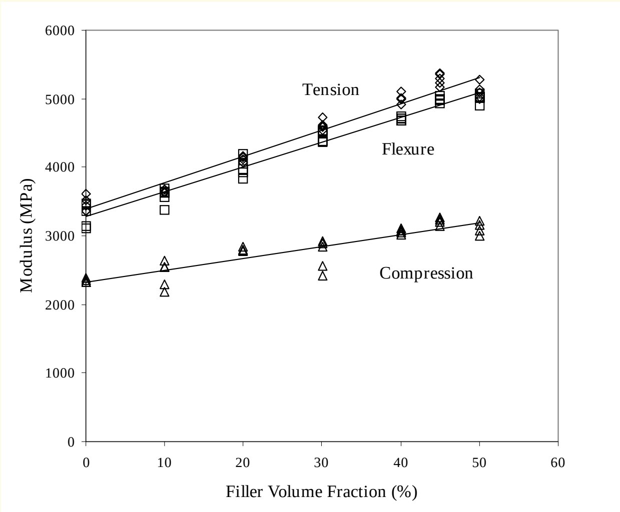


Figure 5: Relationship of modulus with filler volume fraction of vinyl ester / cenosphere composites in tension, compression and flexure

Temperature Performance

In dynamic mechanical analysis (DMA) a test sample is mechanically deformed at alternative rates and the response of the sample measured as a function of temperature or time [7]. DMA provides information regarding the actual changes in mechanical properties of materials when exposed to elevated temperatures. From an engineering perspective, this information is of greater value than the traditional measure of the glass transition temperature to gauge the elevated temperature performance. The glass transition temperature is a single temperature whereas the changes in material properties occur over a temperature range. Even when using DMA there are alternative interpretations of the glass transition temperature (see Figure 6) that yield different values which suggests T_g values determined using DMA techniques should be accompanied by a qualifying statement providing the utilised interpretation.

The changes in storage modulus and the rate of change of a vinyl ester matrix material versus temperature are shown in Figure 7.

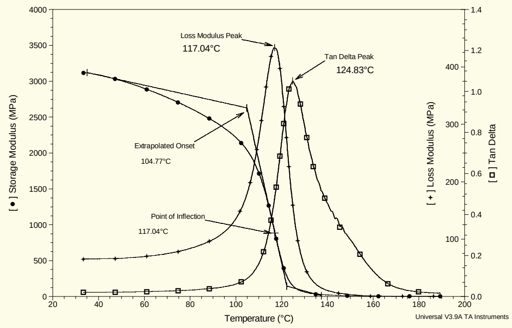


Figure 6: DMA results of a vinyl ester matrix showing alternative interpretations of the glass transition temperature.

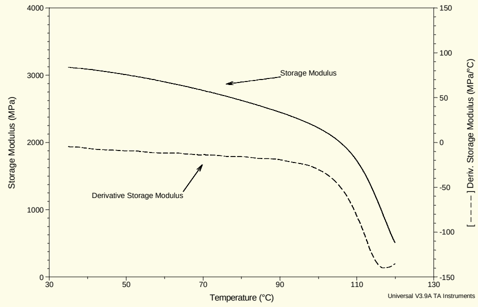


Figure 7: Storage modulus loss and rate of storage modulus loss of a vinyl ester matrix material.

The material displays a relatively uniform rate of storage modulus loss up to around 90°C. Above this temperature there is a rapid increase in the rate of modulus loss as the material passes through its glass transition. In structural applications a material would typically be utilised at a temperature below its glass transition, therefore it is important to understand the changes in modulus through this pre-transition zone. Given that the glass transition occurs over a relatively narrow temperature band and that the net modulus loss can be over 90% [6], the behavioural changes of the material through this temperature range are of great significance to the engineer.

The temperature performance of vinyl ester matrix systems and vinyl ester / cenosphere composites was assessed by examining the changes and rates of change in modulus through the pre-transition and glass transition as performance indicators. A trend was evident through the results where many samples possessed similar T_g values but exhibited significantly different mechanical performances. Only by examining the actual mechanical performance were the changes in material behaviour due to the elevated temperatures detected. This investigation also highlighted the requirement of an elevated temperature post-cure above the glass transition temperature to develop optimal network properties and subsequent superior elevated temperature performance (see Figure 8).

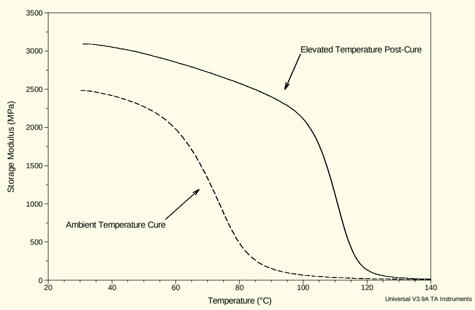


Figure 8: Elevated temperature performance of an ambient temperature cured and elevated temperature post-cured vinyl ester matrix material.

Discussion

This investigation of vinyl ester / cenosphere composites showed how particulate composite systems can offer improved performances when compared to neat resin matrices in a range of areas. Overall the main advantages of particulate composite systems when compared to neat resins are:

- Lower cost
- Reduced cure reaction temperatures
- Reduced total shrinkage
- Increased stiffness characteristics
- Improved temperature performance

However this improved performance also has associated detrimental side effects including:

- Increased viscosity
- Reduced strength

Four key parameters were found to influence the end product performance and processing characteristics of vinyl ester / cenosphere composites, namely:

- Filler volume fraction
- Molecular weight of the vinyl ester oligomer
- Styrene concentration
- Processing and curing temperatures

Other important parameters which primarily influence the processing performance of vinyl ester / cenosphere composites are:

- Initiator concentration
- Initiator type
- Accelerator level

The relationships between the behaviour of these materials are significant demonstrating the necessity to collectively consider the relative influences of parameters on the behaviours. From an engineering perspective, the systems must meet the requirements of the desired application implying the consideration of the end product performance then adapting the processing performance to meet these requirements.

Approaches currently used to quantify polymer behaviour are often inconsistent with the requirements of civil engineering applications. Meeting these requirements requires simple and consistent experimental techniques that relate to the properties of interest to structural and production engineers. This may require adjustments to materials characterisation paradigms commonly available. Techniques such as DSC and DMA may be readily applied to assess material performance relating to the cure behaviour and mechanical performance of polymer matrices and composite systems. The techniques are not only rapid but provide detailed information relevant to the engineer.

Conclusions

The use of composite structural solutions in civil engineering applications is increasing however this continued growth requires the further development of these materials and an understanding of their behaviour. Particulate reinforced polymer composite systems, in particular vinyl ester / cenosphere composites appear to have significant potential to meet the requirements of civil engineering structures.

The application of this technology to the design of products has highlighted the need to develop a more comprehensive understanding of material behaviour, identifying both the processing performance and end product performance as critical.

Key constituent material parameters were found to influence both the processing and end product performance with significant interrelationships existing between these parameters and the composite material behaviours. This requires the consideration of the end product performance then the processing performance to meet the requirements of civil engineering applications.
Existing material characterisation methods appear limited which requires the adoption of new techniques, such as DSC or DMA, to quantify material behaviour for the engineer.

The findings of the investigation, which were summarised in this paper, significantly improved the understanding of the constituent influences on the behaviour of vinyl ester / cenosphere composite systems. This improved understanding instils more confidence in the material performance and may facilitate the continued integration of composite structural solutions into civil engineering applications.

References

[1] Van Erp, G.M., 1999, A New Fibre Composite Beam for Civil Engineering Applications. *International Journal of Advanced Composite Letters*, Vol 8, No 5, pp. 219-225.

[2] Van Erp, G.M., Simpson, P.E. and Davey, S.W., 2000, Fibre Composite Bridges – An Australian Approach. Use of Fibre Reinforced Polymer (FRP) Composites in Civil Infrastructure, University of New South Wales, Sydney, Australia, pp. 1-15.

[3] Huang, D., Van Erp, G.M., Heldt, T.J. and Ayers, S.R., 2002, Development of a New Two-Way Fibre Composite Slab – Modular Approach. In*:* YC Loo *et al.*, *Advances in Mechanics of Structures and Materials, Proceedings of the 17th Australasian Conference on the Mechanics of Structures and Materials.* Lisse: A.A. Balkema.

[4] Davey, S.W., Van Erp, G.M. and Marsh, R., 2001, Fibre Composite Bridge Decks – An Alternative Approach. *Composites Part A*, Vol 3A, No 9, pp. 1339-1343.

[5] Humphreys, M.F. and Van Erp, G.M., 1999, Structural Behaviour of Monocoque Fibre Composite Trusses. *Mechanics of Structures and Materials*, The Netherlands: A.A. Balkema.

[6] Davey, S.W., 2004, A Foundational Investigation of Vinyl Ester / Cenosphere Composite Materials for Civil and Structural Engineering. PhD Dissertation submitted at University of Southern Queensland, Australia.

[7] TA Instruments, 2004, Dynamic Mechanical Analysis (DMA) Training Course Manual.

Polymer Layered Silicate Nanocomposites

By
L C Hollaway, University of Surrey, Guildford Surrey, UK

There are concerns related to the overall durability of advanced polymer composites used in the construction industry, particularly when under load and exposed to harsh and changing environmental conditions. Chemically treated layered silicates (clays) can be mixed with normal polymer matrix materials to form a nanocomposite in which clay layers are evenly distributed throughout the material. There are indications that these high aspect ratio clays increase the strength, fire resistance and reduce the permeability of the material, thus decreasing considerably the *rate* of ingress of corrosive substances into the composite. One area of research at the University of Surrey is being directed towards ascertaining the basic processing, manufacturing and analytical techniques required to produce and characterise polymer-layered silicate nanocomposites suitable for reducing the permeability of composite materials used in the construction industry.

Research has shown that the resin component of the nanocomposite has little effect on the exfoliation of the clay layers, although it is the basic unit of the composite. It has no influence on the way in which the polymer cures, therefore, a low molecular weight DGEBA with *no diluents or additives* is used. This leads to faster pre-intercalation but otherwise it offers no significant long-term advantage. It is particularly difficult to exfoliate the clay nanoparticles into 'an off the shelf' resin used by the construction industry, as these will invariably incorporate additives required by that industry, for example, fast cure on sites. The montmorillonite clay particles are being used in the current investigation and the components that will affect the ease of exfoliation are (i) the curing agent; (ii) the surfactant (chemical modification of the clay particles); (iii) the size of the clay particles (<9μm).

Experimental results at Surrey have shown that after three months exposure of a 55% f.v.f GFRP nanocomposite to a high alkaline environment, a 28% increase in barrier resistance was achieved; this was measured against the residual tensile strengths of identical but pristine composites.

Preliminary Investigation of Basalt Fiber Composite Properties for Applications in Transportation

By
Qiang Liu, Hermione S. Giffard, Montgomery T. Shaw, Richard S. Parnas
Institute of Materials Science, University of Connecticut, Storrs, CT 06269-3136
&
Anne-Marie McDonnell
Connecticut Department of Transportation, Office of Research & Materials, Rocky Hill, CT 06067

Fiber reinforced polymer composites are of interest due to the expensive maintenance associated with steel corrosion. The first applications for civil infrastructure used glass fibers because of their low cost compared to other available fibers. Glass-fiber composites were used in the form of sheets to strengthen existing structures or bars for internal reinforcement of new concrete structures. The use of glass-fiber bars in concrete raised concerns because of their susceptibility to alkaline environments. Current recommendations (ACI 440 2003) limit the design stress of glass-fiber bars to only 20% of their rupture stress to avoid failure by creep rupture. The same criterion is used in the design of rehabilitation techniques when using externally bonded glass-fiber sheets or plates (ACI 440 2002). Compared to glass, basalt fiber is stiffer and stronger [1-3]. It has better resistance to surface damage and acid or alkaline conditions [4-6]. The chemically inert carbon fiber has excellent properties but very high cost [7]. Table 1 compares fabrics used in this report as well as basic properties of basalt and glass fibers, indicating our motivation for considering basalt in transportation applications [3,6,8].

Basalt fiber reinforced polymers offer the promise of innovative applications in transportation. For example, basalt fiber changed the sudden and brittle failure of plain concrete to ductile failure [1,9]. However, use in transportation requires a better knowledge of many properties, especially those associated with environmental durability. In this work, basalt and glass fiber reinforced composites were subjected to several aging environments designed to approximate those seen in transportation applications.

Table 1: Fabric Properties

Fabric Properties	**Basalt Fabric**	**E-Glass (BGF 443)**	**E-Glass (BGF 1527)**
Areal Density, g/m^2	750	425.5	425.5
Filament Diameter, micron	9	6	9
Yarn Linear Density, tex (g/km)	330	134.07	297.63
Weave pattern	Twill 3/1	Twill 1*3 RH	Plain
Yarn Balance (warp/weft)	1.53 = 119/78	1.47 = 173/118	1 = 67/67

Fiber Property	**Basalt Fiber**	**E-Glass Fiber**
Sustained operating temperature, °C	820	480
Tensile strength, (MPa)	4840	3450
Elastic modulus (GPa)	89	77
% weight loss after 3 hrs boiling in: water	0.2	0.7
2N HCl (Hydrochloric acid)	2.2	38.9

The basalt fabric (Albarrie Ltd.) and one glass fabric (BGF 443) were chosen to have the same weave pattern and yarn balance [3,8]. We chose another glass fabric (BGF 1527) to investigate the effect of reinforcement weave pattern on composite mechanical properties. Composite parts were manufactured using 3 layers of basalt fabric or 5 layers of BGF 443. This resulted in approximately the same overall fiber volume fraction of 37.7%, with 15% fiber volume fraction in the weft direction and 22.7% in the warp direction for both basalt and glass composites. In the composites made with the BGF 1527 glass we matched the fiber volume fraction in the weft direction (15%) by using 4 layers of fabric. This provided valid comparisons for tension tests conducted in the weft direction.

These fabrics came with different finishes. Finishes are known to change the compatibility between resin and fiber, and the durability and resistance of the composites to environments [10]. It was necessary to remove them to perform valid comparisons in composite applications. Differences in processing required to remove the finishes required extra analysis of the data [11]. Flat composite plates were prepared using epoxy and vinyl ester resins with the fabrics noted in Table 1.

Tension tests in the weft direction were done according to ASTM D3039-76. Short beam strength was measured in the warp direction according to ASTM D 2344, which is a screening test for shear strength [12]. A variety of environmental aging conditions were used to challenge the materials, including 40°C saturated sodium chloride solution, 40°C distilled water, freeze-thaw cycling in saturated sodium chloride solution, and wet-dry cycling in distilled water at room temperature. Mechanical tests were all conducted at room temperature since the dependence of the standard mechanical properties of polymers and composites on temperature are well known and documented, rendering such tests in this limited program unnecessary [13].

Typical tension curves for unaged epoxy-composite specimens are shown in Figure 1 (a). The Basalt epoxy has an initial slope (Young's modulus) very near the glass composites, while Table 1 indicates the modulus of basalt is larger than glass. The larger waviness of the basalt yarns in the fabric, compared to the glass fabric, as well as other material details evened out the final composite moduli [14-16]. High temperature processing required to remove the finish on the BGF 443 fabric probably caused the premature tensile failure of that material.

The aging of basalt epoxy and glass epoxy in saturated sodium chloride solution is illustrated by Young's modulus data in Figure 1 (b). The error bars represent 95% confidence intervals. The slight reduction in modulus observed after roughly 150 days may be due to interfacial degradation since all interfacial modifiers were removed from the fibers. The tensile strength of the basalt composites did not change during the testing period indicating that the saturated salt solution did not damage the basalt fibers. Similar results were obtained with vinyl ester reinforced with basalt. In contrast, the tensile strength of glass reinforced composites typically decreased significantly after exposure to salt water for 200 days or more at room temperature [16-18]. These results point out that fiber finishes optimized for basalt need to be developed, just as 50 years of work led to the development of excellent sizing packages for glass fibers.

Short beam strength was tested in the warp direction according to ASTM D 2344. The comparison between basalt composites and glass composites (using BGF 443) is shown in Figure 2 (a).

Only the BGF 443 glass fabric is shown because the basalt fabric and the BGF 443 fabric have the same warp direction fiber volume fraction. The displacement indicated in Figure 2 (a) is the nose traveling distance. Although the basalt specimens never fully broke in these short beam shear tests, the first significant and sudden drop in the load versus displacement curve is often defined as the failure point. This point is indicated in the figure, but the basalt composite fails gracefully as it continues to carry load. In contrast, the glass composite failed suddenly at much lower strength.

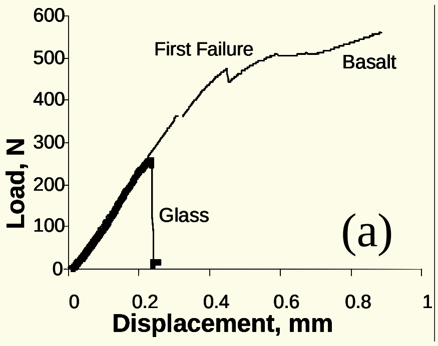


Figure 2(a): Typical load versus displacement curve for basalt and glass epoxy composite specimens

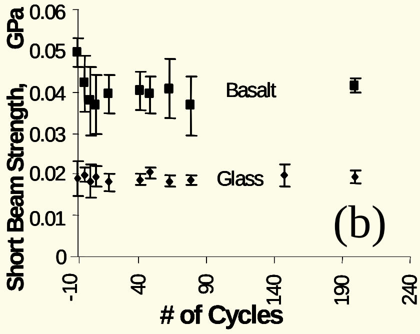


Figure 2(b): Short beam strength versus # of freeze-thaw cycles for basalt epoxy and glass epoxy. The 1st data, at -10, are for unexposed specimens. The 2nd data, at 0, are for specimens soaked in the salt water for 10 days before freeze-thaw cycling began.

An important difference also exists between the failure of the glass composite in tension and in shear. Milder conditions of sizing removal did not alter the brittle failure of the glass composite in shear but greatly improved the tensile behavior of glass, as indicated in figure 1 (a). This difference in glass failure behavior points out that the shear test is dominated by matrix and interface properties [12] while the tension test is, of course, dominated by fiber properties. These results mean that brittle failure of glass in tension was due to fiber damage but the brittle failure of glass in shear is due to a stiff non-compliant interfacial zone. In contrast, it appears the interfacial zone in unaged basalt composites is nearly optimal for stress transfer.

Figure 2(a) is an encouraging result since interfacial engineering efforts with basalt can focus on durability rather than property enhancement. Early durability results for shear are indicated in Figure 2(b) with data for a 10 day soak followed by 199 freeze-thaw cycles, in saturated sodium chloride. The freeze-thaw cycling did not significantly degrade the short beam strength. An initial decrease did occur, however, in the basalt composite during the 10 day soak. Additional data in both salt water and fresh water at 40°C confirm this result, although in all cases the short beam strength of basalt composites remains much larger than that of glass composites. These results indicate that the interfacial zone on unsized basalt fiber may be much better than on unsized glass fiber, but that some degradation occurs upon environmental exposure.

This preliminary work indicates that basalt fiber composites may have much better interlaminar shear strength than glass fiber composites. Both materials appear to have similar modulii. Data interpretation further indicates that the basalt fiber appears more durable than glass, as expected. However, despite these encouraging results, a basalt based composite system will require development, with special attention to the interfacial zone on the basalt fibers to prevent interfacial degradation during long term use.

References

[1] Ramakrishnan, V., Tolmare, N. S., and Brik, V., Performance Evaluation of 3-D Basalt Fiber Reinforced Concrete and Basalt Rod Reinforced Concrete, NCHRP-IDEA Program Project Final Report, Transportation Research Board, Washington, DC, 1998.

[2] Lisakovski, A.N., Tsybulya, Y.L. and Medvedyev, A.A., Yarns of Basalt Continuous Fibers, The Fiber Society, May 2001, Raleigh, NC.

[3] Albarrie Ltd. Product literature. http://www.albarrie.com/Filtration/fil-basalt.html

[4] McCrum, N. G., Buckley, C. P. and Bucknall, C. B., *Principles of Polymer Engineering*, Oxford University Press, New York, 1989.

[5] Callister, W. D. Jr., *Materials Science and Engineering*, 3rd ed., John Wiley, New York, 1994.

[6] Sudaglass web site http://www.sudaglass.com

[7] Kruckenberg, T. M., Paton, R., *Resin Transfer Molding for Aerospace Structures*, Kluwer, The Netherlands, 1998.

[8] BGF, Product literature. http://www.bgf.com/ Brik, V.B., Basalt Fiber Composite Reinforcement for Concrete, NCHR-IDEA Program Project Final Report, Transportation Research Board, Washington, DC, 1997.

[9] Plueddemann, E. P., *Silane Coupling Agents*, 2nd ed., Plenum Press, 1991.

[10] Liu, Q., Shaw, M.T., Parnas, R.S. and McDonnell, A., Proc. Transportation Research Board Annual Meeting, January, 2005, Washington, DC, paper 05-1117, session 487.

[11] Piggott, M. R., *Load Bearing Fiber Composites*, 2nd ed., MERP Enhanced Composites, 2001.

[12] Nielsen, L. E. and Landel, R. F., *Mechanical Properties of Polymers and Composites*, Marcel Dekker, Inc., 1994

[13] Tsai, S. W. and Hahn, T. H., *Introduction to Composite Materials*, Technomic, 1980.

[14] Cox, B. N., Flanagan, G., Handbook of Analytical Methods for Textile Composites, NASA Contractor Report 4750, March 1997.

[15] Chou, T.-W. Ko, F.K., *Textile Structural Composites*, Elsevier, 1989.

[16] Wu, L., Murphy, K., Karbhari, V. M. and Zhang, J. S., Short-Term Effects of Sea Water on E-glass/Vinylester composites, *J. App. Polym. Sci.*, **84**, 2760, 2002.

[17] Schultheisz, C. R., McDonough, W. G., Kondaguntа, S., Schutte, C. L., Macturk, K. S., McAuliffe, M. and Hunston, D. L., Effect of Moisture on E-Glass/Epoxy Interfacial and Fiber Strengths, *Composite Materials: Testing and Design, ASTM STP 1242*, S.J. Hooper (Ed.), **13**, 257, 1997.

PBO Fiber Sheets as Externally Bonded Prestressing Reinforcement for RC/PC Structures in Japan

By
Zhishen Wu
Department of Urban and Civil Engineering, Ibaraki University
Hitachi, 316-8511, Japan

The newly developed PBO fiber consists of rigid-rod chain molecules of Poly (para-phenylene-Benzo-bis-Oxazole). The strength and modulus of the organic fiber are superior to high strength carbon fiber and almost double that of aramid fiber (Figure 1).

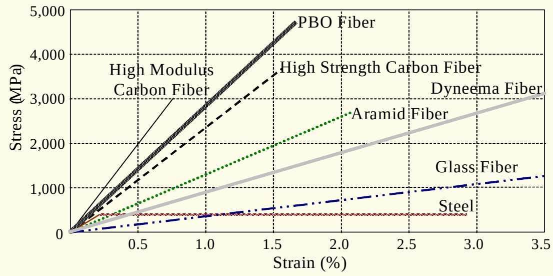


Figure 1: Typical Stress-Strain Relationships of Fibers

In addition, PBO fibers demonstrate high resistance to fire and flame with a LOI (Limited Oxygen Index) value of 68 in comparison to the value of 58 for carbon fibers and 30 for aramid fibers. Because of the high LOI number, the fiber does not burn. When the service temperature exceeds the fiber's decomposition temperature of 650°C, the toxic gases generated are ten times smaller than that by aramid fibers [1]. PBO fibers also exhibit high creep resistance. The retained stress in a relaxation test using sheets of 2 m long and 8 cm wide proves PBO fiber sheets sustain the load in a similar way as carbon fiber sheets do (Figure 2).

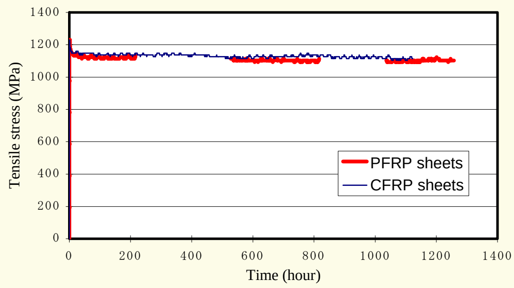


Figure 2: Strength Retention in a Relaxation Test

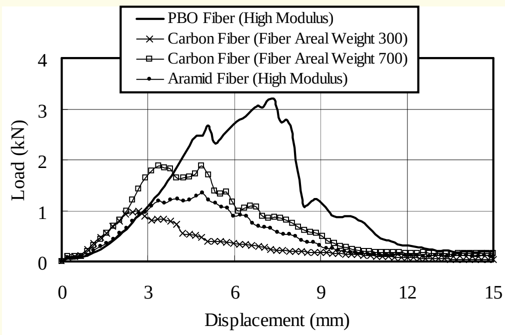


Figure 3: Load-Deflection Curves of Impact Tests

The most attractive feature of PBO fiber seems to be its great impact tolerance and energy absorption capacity. Its high instantaneous impact resistance is unique for structural upgrading applications as a prestressing reinforcement. Figure 3 demonstrates PBO fiber posses much better energy absorption capacity than both carbon and aramid fibers, making the prestressing of PBO sheets without resin impregnation possible.

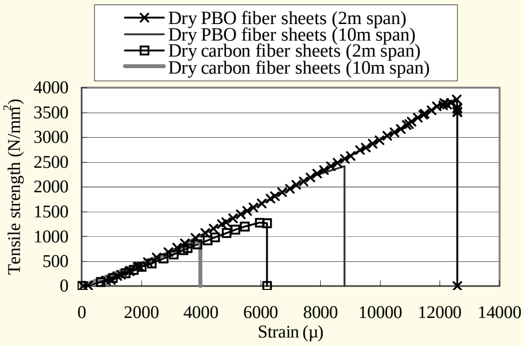


Figure 4: Tensile Tests of Dry Fiber Sheets

Figure 4 compares tensile tests of dry fiber sheets in lengths of 2 m and 10 m to simulate the prestressing process. Because of the relatively low energy absorption behaviour, carbon fiber sheets without resin impregnation break at 40% of its tensile strength when stretched in a length of 2 m and can sustain only 27% when stretched in a length of 10 m. In contrary, the 2-m long dry PBO fiber can be tensioned to 90% of its capacity and the 10-m long fiber holds the load up to 60 %. This is the reason why the current practice of carbon fiber prestressing employs only the prefabricated carbon-resin laminates. The difficulty of using the rigid carbon laminates is the requirement of the flatness of the bonding surface. Debonding can be easily initiated when laminates are attached to an uneven base. Moreover the rigidity of the sheets will introduce additional interface shear stress at bond line. Therefore the flexible fiber sheet together with in-situ bonding can have many advantages over the stiff laminate sheet in prestressing reinforcement.

The procedure of upgrading the concrete beams, slabs and girders with bonded prestressed composites has been established. The PBO fiber sheets are first stretched to a percentage of prestress, then coated with epoxy resin on-site and applied to the structural surface. After curing, the tensile load is released and the prestress is transferred to the concrete structure. The key to the success is the bond at interface. To achieve a perfect bond, an air bag system with vacuum facility is developed for construction site applications. Moreover the shear stress concentrations at two ends are usually the cause of debonding, and attributed to the large tonnage of prestressing forces. It was found that, within linearly elastic range, the interfacial shear stresses at two ends are proportional to the applied prestressing force and to the square root of the thickness of the FRP sheet [2]. Therefore reduction of shear stress concentration can be accomplished by gradually releasing the prestressing forces at ends and by reducing the number of layers in composite used at ends together with FRP U-anchors or bolt anchorage with bonded steel plates [2]. The schematic of the principle is shown in Figure 5.

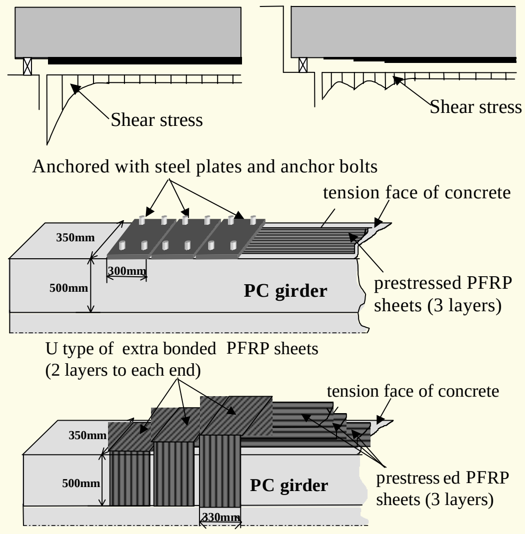


Figure 5: The principle and practice of tapering FRP sheets at prestressing ends

To facilitate the prestressing upgrading technique in structural retrofitting using PBO fibers, a full-scale apparatus has been developed with the capacity of applying the prestressing force and, at the same time, the heat to a temperature of 60 – 80 ^{0}C for a complete on-site curing in 3-6 hours (Figure 6).

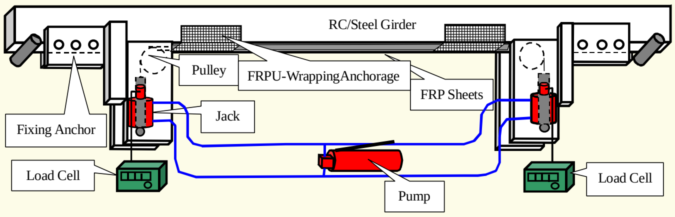


Figure 6: Apparatus for application of prestressing to PBO fiber sheets

The field demonstration of the technology was carried out on two large scale prestressed 1-m tall T-girders in spans of 10 m and 16.7 m respectively. More than 300 people from governments, universities and research institutes of Japan attended the demonstration (Figure 7).

Figure 7: Field demonstration of PBO prestressing technology

The typical load – deflection curves of 10 m long girders with PBO fiber sheets prestressed at different levels are shown in Figure 8.

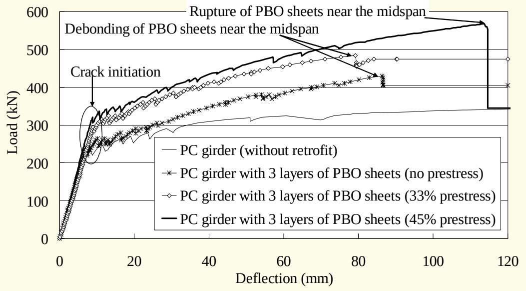


Figure 8: Load-deflection curves of T-girders in 10-m span

The control girder without external reinforcement failed due to yielding of tensile steel followed by concrete crushing. The girder strengthened by three-layer PBO sheets without prestressing exhibited the similar bend-over-point as the control, but gained significant strain hardening after the yielding of steel. With prestressing, the linear proportional limit was increased by 45% and the ultimate load by 65%. High percentage of prestressing could effectively change the failure mode from debonding to PBO tensile rupture, leading to a significant increase in load carrying capacity. The crack opening width was also considerably reduced with prestressing (Figure 9).

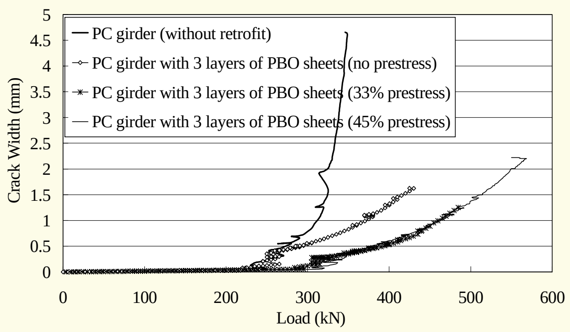


Figure 9: Crack width opening in T-girders

Recently the PBO-Prestressing Upgrading Technique (P-PUT) has been successfully applied to three projects for the retrofitting of RC/PC structures in Japan. The first one was the upgrading of a concrete box girder bridge on National Road 256. Two of the three spans were strengthened by the prestressed PBO sheets in a length of 14 m with eight PBO strips of 0.3-m wide for each girder of 6-m wide. The construction details were reported by Nikkei Construction Magazine [3]. The second one was the strengthening of a highway PC girder viaduct. The third case was the rehabilitation of a PC floor slab bridge on National Road 30. The 33-m long bridge has three spans, which were strengthened by 35 PBO fiber strips in total at various locations along the bridge. The dimension of each POB fiber strip was 6.6 m long and 0.35 m wide, with six layers in each strip. The development of P-PUT is based on the collaborative research involving Ibaraki University, ABE Kogyo Syo Co., Toho Earthtech Inc, Nippon Steel Composite Co. and Toyobo Co., Ltd.

References

[1] Technical Information, "PBO Fiber Zylon", Toyobo Co. Ltd., http://www.toyobo.co.jp/e, Sept. 2001.

[2] Wu, Z.S., Iwashita, K., Hayashi, K., Higuchi, T., Murakami, S. and Koseki, Y, "Strengthening Prestressed-Concrete Girders with Externally Prestressed PBO Fiber Reinforced Polymer Sheets", Journal of reinforced Plastics and Composites, 22(14), 2003, pp1269-1286.

[3] "Prestressed Composite Sheets for Bridge Strengthening", Nikkei Construction, 3-28, 2003, pp. 30-34, (in Japanese).

FRP-Reinforced Glulaminated Columns

By

F. Taheri , M. Nagaraj and N. Cheraghi
Department of Civil Engineering, Dalhousie University
Halifax, Nova Scotia B3J 1Z1, Canada

In the past decade, several investigations have been conducted to study the gain in capacity and performance resulting from combining fiber-reinforced plastics (FRP) with other traditionally used construction materials. A majority of such investigations has been conducted on the use of FRP for reinforcing concrete (see for example, Saadatmanesh *et al.* (1997), Kachlakev and McCurry (2000), and Karbhari, (2004)). In comparison, studies considering the use of FRP for reinforcing wooden structural components have been quite scarce. One of the earlier studies was done by Plevris, N. and Triantafillou (1992), studying the effect of carbon/epoxy for reinforcing fir wooden beams. Other early noteworthy studies are those conducted by Davalos *et al.* (1992), discussing the response of small yellow-poplar Glulam beams reinforced on their tension side with glass/vinylester FRP, and by Abdel-Magid et al (1994) who also studied Glulam reinforced with pultruded glass/vinylester FRP and pultruded glass/resorcinol modified phenolic FRP sheets. Since then other investigators have also considered various combination of FRP for reinforcing wooden beams. There are now commercial FRP/Glulam beam products available in the market (for instance, FiRP® and QuakeWrap™).

When considering research in FRP/wood composites, most of the studies reported to date have examined the static response of FRP reinforced wooden beams. Recently, in a series of papers, the vibration and impact characteristics of FRP reinforced glulaminated beams were systematically investigated (Zou et al (2003), Taheri et al (2005) and Naghipour et al (2005)).

As it can be seen, to the best of our knowledge, all FRP-reinforced Glulam investigations reported to date have mainly considered FRP for reinforcing wooden beams, and to the best of our knowledge no investigation has considered the gain in attributes that could be potentially offered by reinforcing wooden columns and arches with FRP. This was therefore the motivation for the research that started several years ago, to (a) enable us to gain a fundamental understanding of the dynamic response of FRP reinforced Glulam beams that was not considered earlier, and (b) to investigate the potential of creating cost-effective, strong and stable FRP-reinforced wooden columns and arches. The purpose of the investigations was therefore not merely to investigate the attributes of FRP in enhancing conventional Glulam structural components (as most of the earlier studies have done), but to develop economical solutions by using inexpensive and relatively lower grade timber in conjunction with FRP to create structural components that could offer acceptable performance. This was also prompted by the fact that in our opinion wood structures, especially in the form of arches, offer aesthetically pleasing alternative to the commonly used steel and concrete counterparts. Moreover, design of FRP/Glulam structural components, even in the beam form, involves a series of tedious calculations and checks of various factors and parameters; the task becomes even more cumbersome and time consuming when considering Glulam arches. Therefore, another important aim of our work was to develop a robust and user-friendly computer program that would allow engineers and architect to design FRP-reinforced beams, columns and arches, effectively and efficiently.

To establish the potential of FRP-reinforced columns, a research program was designed to (a) examine the stability characteristic of FRP-reinforced Glulam columns with slenderness ratio varying between 16, 24 and 32, tested as pinned-pinned supported and clamped-clamped boundary conditions, with two different types of FRP (glass and carbon reinforced); (b) determine whether FRP reinforcement should be applied to the entire column length, or one could establish an optimum length by which less materials could be used, but similar stability characteristics would be attained; (c) to develop a formulation by which the buckling capacity of such columns could be accurately predicted; and foremost (d) to develop a user-friendly software for design of Glulam wood/FRP products.

Three main series of columns with slenderness ratio of 16, 24 and 32 were considered. Each series had three categories of columns: (i) columns with no FRP-reinforcement (control columns), (ii) columns with FRP adhered to surfaces on their weak-axis, along the entire length of the columns, and (iii) columns with partial length FRP reinforcement. Each category had 2 sub-categories, columns reinforced with glass-vinyl ester FRP, and those reinforced with graphite-epoxy. Each sub-category had 6 columns; 3 tested in pinned-pinned supported boundary condition, and the other 3 tested in clamped-clamped boundary condition. The wood was finger jointed S-P-F FJ Studs SPS3 Grade with 38 x 64 mm^2 cross-sectional area. These sections were glued together with a water based resorcinol adhesive (P-R-F-LT 5210 with FM 6210, produced by Borden Chemical of Columbus, OH.) to form columns with cross sectional area of 57 x 110.5 mm^2 (otherwise, 3 layer of wood were laminated and then planed to produce straight surfaces, hence the dimensions noted).

The test set up used for testing the columns is illustrated in Figure 1.

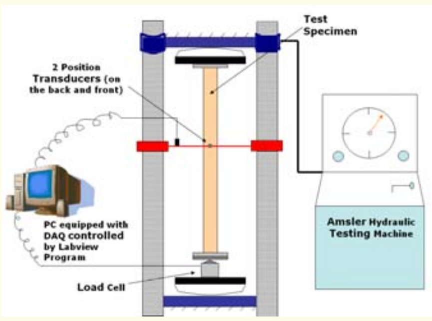


Figure 1: Experimental Set-Up

To date, all columns have been manufactured, but only the columns with slenderness ratio of 16 have been tested so far. Typical average performance of the columns in that category (pinned-pinned supported) is shown in Figure 2. Each curve is the average of 3 tests.

As it can be seen, compared to the columns with FRP applied to their full length, the partially-reinforced columns could offer columns with similar stiffness, but only slightly lower buckling capacity. In comparison to the unreinforced (control) columns, the partially reinforced columns offer considerably stiffer response and 60-70% increased buckling capacity. The experimental results for columns with slenderness ration of 24 and 32, both with pinned-pinned supported and clamped boundary conditions will be completed and presented in the near future.

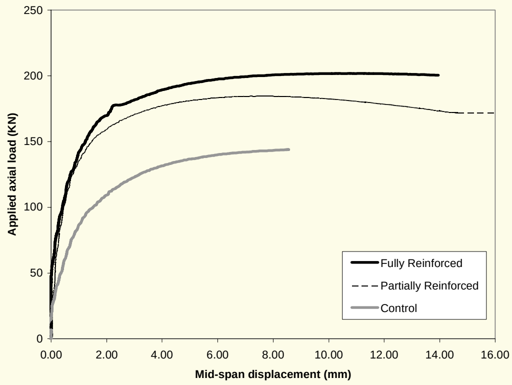


Figure 2: Experimental results for columns with slenderness ratio of 16, with full length FRP reinforcement and pinned-pinned supported.

To further investigate the influence of partial reinforcement, a computational investigation, using the finite element method, was performed. Eigen-value and then nonlinear finite element analyses (FEA) were performed with ANSYS program. Beam and 3D solid elements were used for modelling the response of the columns. ANSYS's 3D element #46 (layered 3D element) was used in our 3D modelling so that behaviour of the FRP and the FRP to wood interface bond-line could be explicitly simulated. Pinned-pinned supported columns with various length were considered. The columns were reinforced with different lengths of FRP having various number layers (1 to 10 layers of reinforcement adhered to either side of the columns). The comparison of the FEA and experimental results for the full-length FRP reinforced 1850 mm long column is illustrated in Figure 3.

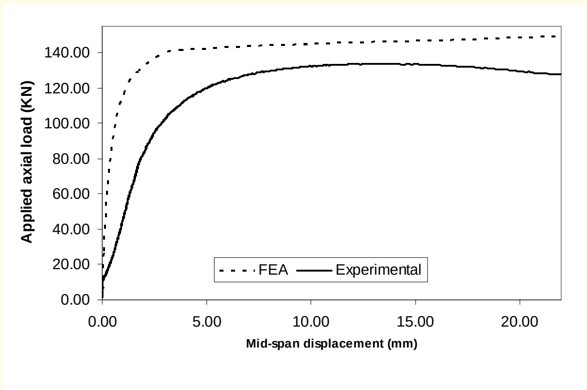


Figure 3: Comparison of the FEA and experimental results

The figure indicates a reasonably good agreement between the FEA and experimental results, especially considering that wood is a relatively inhomogeneous material, and the presence of knots can markedly affect the performance.

Results from further FEA investigation examining the influence of number of FRP layers, as well as the influence of partial length on the buckling capacity of the composite column is illustrated in Figure 4.

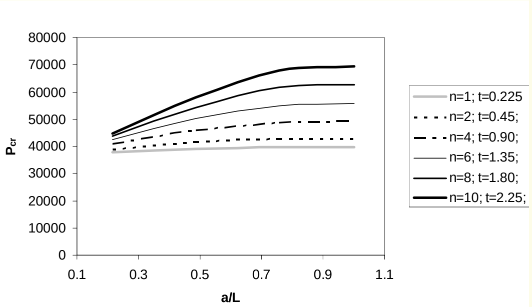


Figure 4: Influence of length and number of layers of FRP reinforcement on the buckling capacity

The results indicate that FRP reinforcement with an approximate length equal to 75% of the full column length could produce an optimum and economical FRP reinforcement. Moreover, as the number of reinforcement layers increases, the buckling capacity increases too, however, this rate of increase is not linear.

As stated, design of Glulam structural components consume considerable effort and time, especially when considering FRP-reinforced Glulam arches, whose design is even more time-consuming.

Figure 5: A sample screen shot of the software developed for designing Glulam beams

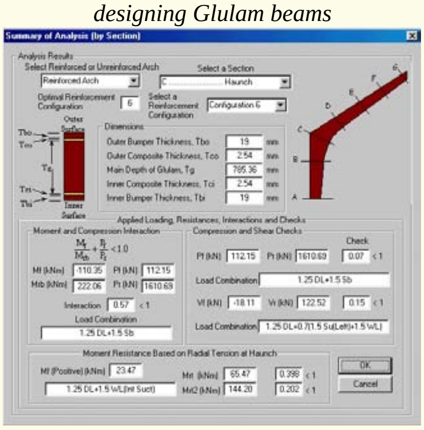


Figure 6: A sample screen shot of the software developed for designing Glulam arches

To effectively promote the utilization of this aesthetically pleasing constriction material, we believe that designer should have access to user-friendly and robust computer design-software. Therefore, a computer program that could allow engineers and architects to design Glulam beams, columns and arches, with ease and in a user-friendly environment has been under development for the past 3years. Some examples of the software and its user-friendly environment are illustrated in Figures 5 and 6.

The results available thus far indicate that it is possible to produce cost-effective columns with superior buckling capacity and performance, using lowest grade glulaminated wood. Similar investigation is being conducted for FRP-reinforced glulaminated arches.

References

[1] Abdel-Magid, B., Dagher, H.J. and Kimball, T.E., (1994), The effect of composite reinforcement on structural wood, Proceedings of the Materials Engineering Conference, n 804, Infrastructute: New Materials and Methods of Repair: 417-424.

[2] DANIEL, I.M. ISHAI, O., (1993), *ENGINEERING MECHANICS OF COMPOSITE MATERIALS*, OXFORD UNIVERSITY PRESS, NY, USA.

[3] Davalos, J.F., Salim, H.A. and Munipalle, U., (1992), Glulam-GRFP composite beams for stress-laminated T-system timber bridges, *Proceedings of 1st International Conference on Advanced Composite Materials in Bridges and Structures CSCE-CGC*, Sherbrooke, Quebec, Canada: 455-463.

[4] Kachlakev, D. and McCurry, D.D, (2000), Behavior of full-scale reinforced concrete beams retrofitted for shear and flexural with FRP laminates, Composites Part B: Engineering, 31(6-7): 445-452.

[5] Karbhari, V.M., (2004), Fiber reinforced composite bridge systems - Transition from the laboratory to the field, Composite Structures, 66(1-4): 5-16.

[6] Plevris, N. and Triantafillou, T., (1992), FRP-reinforcement wood as structural material, *Journal of Materials in Civil Engineering ASCE* 4(3): 300-317.

[7] Saadatmanesh, H., Ehsani, M.R., Jin, L. (1997), Repair of earthquake-damaged RC columns with FRP wraps, ACI Structural Journal, 94(2): 206-215.

[8] Taheri F., G.P. Zou and M. Naghipour, (2005), Experimental and Theoretical Studies on Energy Absorption Response of FRP Strengthened Glulam Beams Under Impact, Forest Products Journal, in press.

[9] Naghipour M., Zou G.P., and F. Taheri, (2005), Evaluation of Vibration Damping of GRP reinforced Glulam Composite Beams. ASCE Journal of Engineering Mechanics, in press.

[10] Zou G.P., M. Naghipour and F. Taheri, (2003), A Nondestructive Method for Evaluating Natural Frequency of Glued-Laminated Beams Reinforced with GRP, Journal of Nondestructive Testing and Evaluation, 19(1-2): 53-65.

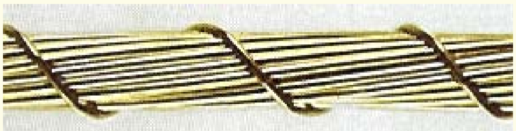
Research Activities

In this issue we highlight specific research activities related to the use of Steel Reinforced Polymer Systems at The University of Missouri-Rolla, and the University of Naples, under the supervision of Professor A. Nanni.

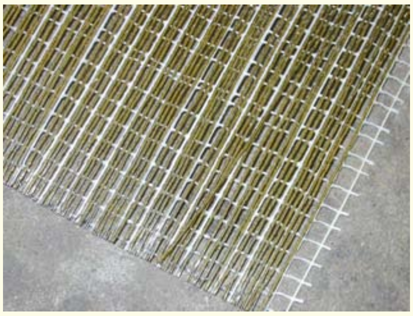
Steel Reinforced Polymer: An Innovative and Promising Material for Strengthening the Infrastructures

The use of advanced composite materials in the construction industry is now days a mainstream technology, supported by design guidelines such as the ACI 440.2R-02 (ACI 440) in the United States, the Fib-Bulletin 14 (2001) in Europe and the recently published TR55 (2004) in the United Kingdom. Fiber reinforced polymer (FRP) composite materials, even though very attractive, may be hindered by lack of ductility and fire resistance. Both issues are currently under study by the research community, in order to provide on one hand, better knowledge in terms of overall structural performance and, on the other, remedies such as coatings that could prolong fire resistance.

A new family of composite materials based on unidirectional high strength twisted steel wires (about 7 times stronger than typical common reinforcing bars) of fine diameter (*0.20 ~ 0.35 mm* (*0.0079 ~ 0.0138 in*) see Figure 1), that can be impregnated with thermo-set (referred to as steel reinforced polymer, SRP) or cementitious (referred to as steel reinforced grout, SRG) resin systems is presented in this work (Hardwire 2002) [1].



Steel Cord with Wires Wrapped by One Wire



Medium Density Tape with Cords Held Together by a Polyester Scrim

Figure 1: Example of a Type of Steel Cord and Tape

SRP/G has the potential to address the two shortcomings mentioned for FRP, infact: a) steel cords have some inherent ductility; and b) impregnation with cementitious paste may overcome the problems of fire endurance and lowering down the application cost considerably.

The steel cords used in SRP are identical to those used for making the reinforcement of automotive tires, and manufactured to obtain the shape of the fabric tape prior to impregnation (Hardwire, 2002). The twisting of the wires allows some mechanical interlock between the cords and the matrix, and may also induce an overall ductile behavior upon stretching. The cords are also coated with either brass or zinc making the material potentially free of any corrosion and suitable for different kind of environmental exposure. Characterization work, including durability studies, is currently in progress as necessary for implementation in future design guidelines. Recent test results [2] showed that the material does not experience a substantial yielding, but rather a similar behavior to the one experienced by high-strength steel used in prestressed concrete (PC) construction, with a slight non-linear range prior to rupture of the cords (Figure 2).

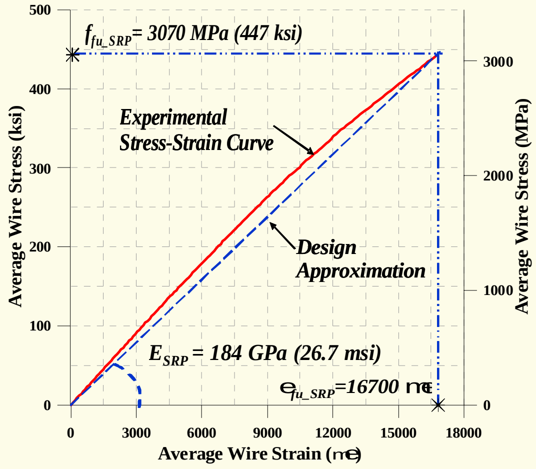


Figure 2: SRP Laminate Stress vs Strain Behavior

Three case studies of research on SRP conducted at the University of Missouri-Rolla (UMR) and at the University of Naples-Italy under the supervision of Dr. A. Nanni are presented.

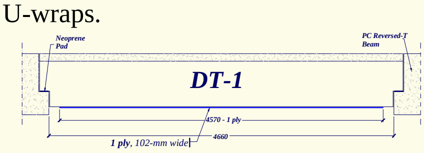
Performance of Double-T Prestressed Concrete Beams Strengthened with Steel Reinforced Polymer

By

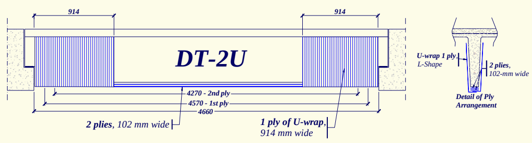
Paolo Casadei[1] and Antonio Nanni[2]

The opportunity for experimenting this new material in the field, became available in the winter of 2003 when the City of Bloomington, Indiana, decommissioned an existing parking garage near the downtown area. The parking garage was a two storey structure consisting of a reinforced concrete (RC) frame, cast in place columns and precast reversed-T PC beams, supporting double-T PC beams, of span length varying from 4.66 m to 13.41 m.

A total of three double-T PC beams were strengthened in flexure with with epoxy-based SRP and tested to failure (Figure 3): beam DT-C is the control beam, beam DT-1 represents the beam strengthened with one ply of SRP and DT-2U the one strengthened with 2 plies of SRP anchored with SRP U-wraps.



a) Beam Strengthened with 1 ply (DT-1)



b) Beam Strengthened with 2 plies + U-wrap (DT-2U)

Figure 3: Test Beams (SI units 1 mm = 0.039 in)

The epoxy resin for both strengthened beams was SikaDur Resin 330 [3]. The choice of the resin was based on

[1] *Lecturer of Structural Engineering, Department of Architecture and Civil Engineering, University of Bath, Bath, BA2 7AY, United Kingdom; Email: P.Casadei@bath.ac.uk*

[2] *V & M Jones Professor, Department of Civil, Architectural and Environmental Engineering, University of Missouri-Rolla, Rolla, MO-65401 USA; Email: nanni@umr.edu*

constructability so that it could be rolled onto the surface for overhead applications, while having enough consistency, even before curing, to be able to hold the weight of the steel tape during cure. The tape was medium density consisting of *6.3 cords per cm* (*12 WPI*) [1].

SRP was installed following the reccomendations of ACI 440 provisions for FRP materials (Figure 4).

Application of Longitudinal Ply

Squeezing Out the Resin Excess

Application of U-Wraps

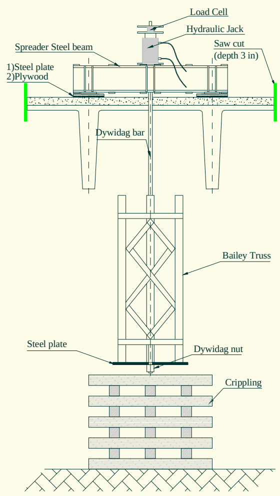
Application of Epoxy on U-Wrap

<u>Figure 4: SRP Installation Procedure</u>

The beams were tested under simply supported conditions and subject to a single concentrated load spread over both stems at mid-span (Figure 5). All three tests were conducted using a close-loop load configuration; the reverse-T PC-Ledger beams, on which the double-T beam rests, supplied the reaction. An electronic data acquisition system recorded data from linear variable differential transducers (LVDTs) and electrical strain-gages applied to the SRP in beams DT-1 and DT-2U.

Bottom View

Top View



Cross Section at Mid-Span

<u>Figure 5: Test Set Up</u>

All beams failed in flexure and had a similar behavior up to the cracking load. Beam DT-C failed due to fracture of the lowest tendon. In beam DT-1, since the SRP ply was not mechanically anchored, failure was dictated by peel off of the ply from each stem almost simultanuously. The SRP laminate started debonding at mid-span initiated by the widening of mid-span cracks and then progressed towards the supports. Complete detachment of the laminate occurred at one end of the beam with part of the concrete substrate attached to the laminate, denoting a good interface bond between the concrete and the SRP. Beam DT-2U, strengthened with two anchored plies per stem, failed due to rupture of the lower tendon, then followed by rupture of the SRP laminate. Delamination propagated from mid-span towards the supports similarly to Beam DT-1, until rupture of the lower tendon occurred and immediately followed by SRP rupture exactly at the location where the SRP U-wrap started. Figure 6 reports the mid-span deflection plots for all three beams.

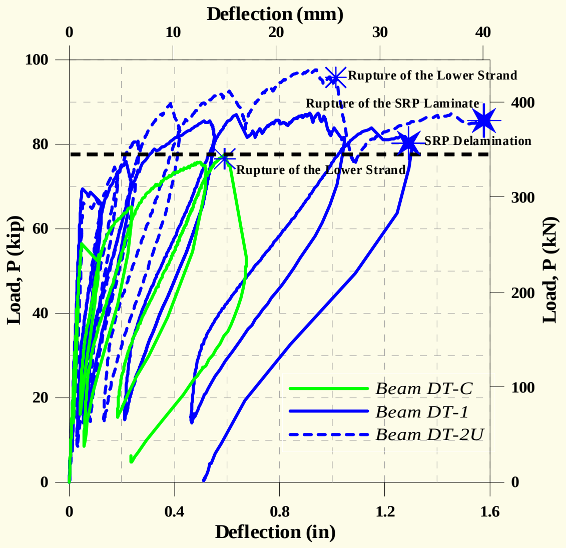


Figure 6: Mid-Span Deflection Plots

Performance of RC Beams Externally Bonded with Steel Reinforced Polymer

By

Andrea Prota[3] and Antonio Nanni

A comprehensive experimental analysis has been carried out at the Department of Structural Analysis and Design of the University of Naples Federico II, Italy, about the behavior of RC members strengthened in flexure using SRP laminates (Figure 7).

Delamination of SRP Bonded with Epoxy Resin

Delamination of SRP Bonded with Cementitious Grout

Figure 7: Beam Flexure Tests at University of Naples Laboratories

A total of ten RC shallow beams (400 mm wide, 200 mm high and 3.7 m long) were tested as simply supported members, over a clear span of 3.4 m. One was used as control beam; seven were strengthened with two different types of steel tape, 3X2 cord (high-density) and 12X cord (low-density) [1]; the high-density tape was impregnated with epoxy resin, the low-density tape was bonded with cementitious grout. The remaining two beams were strengthened with CFRP laminates impregnated with epoxy resin.

The experimental results provided important information about the performance of tested members in terms of strength, deflections, failure modes and strains of the externally bonded laminates. The laboratory outcomes were also used to perform a theoretical-experimental analysis in order to asses the possibility of extending the code provisions developed for FRP bonded members to those strengthened using SRP impregnated with cementitious mortar. The analysis confirmed that the ACI 440 provisions approach provides conservative strength estimates for both FRP and SRP systems, if the external reinforcement is bonded with epoxy. The different bond behavior of cementitious mortar could not be predicted by the current ACI 440.2R-02 equations; a modified expression for the bond coefficient km should be calibrated and the experimental data collected within the conducted campaign will represent a useful reference towards that objective.

Strengthening of a Reinforced Concrete Bridge with Externally Bonded Steel Reinforced Polymer

By

Alexis Lopez[4] and Antonio Nanni

Five existing concrete bridges, geographically spread over three Missouri Department of Transportation (MODOT) districts, were strengthened using five different Fiber Reinforced Polymer (FRP) technologies as part of a joint MODOT – University of Missouri-Rolla (UMR) initiative. This project was intended to validate the use of FRP materials to strengthen existing concrete bridges considered structurally deficient. The bridges were selected in consultation with the respective District Offices, in order to allow a wide geographical spread of the project. None of the bridges were chosen on the same route.

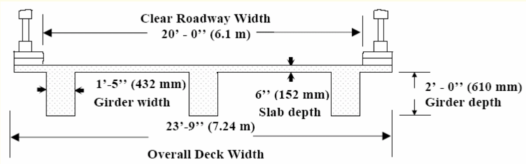
Five different technologies were used for this validation, namely: FRP sheets and Steel Reinforced Polymer (SRP) applied by manual lay-up; pre-cured FRP laminates; near surface mounted (NSM) FRP bars; and, Mechanically Fastened (MF) FRP laminates. More than one strengthening technique was used for each bridge.

Bridge P-0692 located in Dallas County, MO, (Figure 8) was chosen as the candidate bridge for strengthening a span employing steel reinforced polymer SRP as strengthening material. The structure has three spans and each of them consists of three RC girders monolithically cast with the slab. Each span is provided with one transversal beam. All spans are *12.9 m* long. The total bridge length is *38.9 m* and the total width of the deck is *7.2 m*. It was load posted to *16.3 tons* with a speed restriction to *24 km/h*.

[3] Assistant Professor, Department of Structural Analysis and Design, University of Naples Federico II, Naples, Italy; Email: aprota@unina.it

[4] Ph.D. Candidate, Department of Civil, Architectural and Environmental Engineering, University of Missouri-Rolla, Rolla, MO-65401 USA; Email: aalkv5@umr.edu

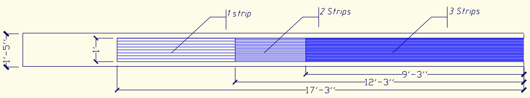
Lateral View of Bridge P0962



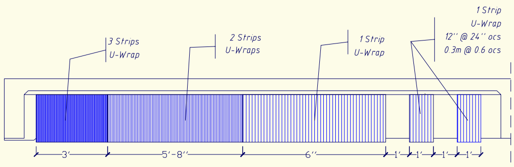
Cross Section of the Bridge

<u>Figure 8: Bridge Geometry (US Customary 1 ft = 0.305 m)</u>

Deck and girders one span were strengthened with two steel tapes different in densities and morphology [1]: a first high-density cord tape, used for flexural reinforcement; and a medium-density cord tape, U-wrapped on the girders for shear reinforcement. *Figures 9a* and *b* report the detailed strengthening layout. The design of the strengthening was conducted considering load configurations and analysis consistent with the AASHTO 2002 specifications (Standard Specifications for Highway Bridges) and computing the strengthening system in compliance with ACI 440 guidelines, accounting for larger safety coefficients to account for the novelty of the application.



Bottom View of Flexural Strengthening (Half Member)

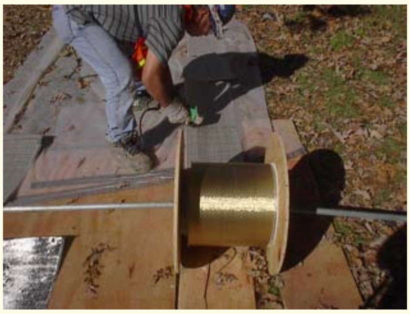


Bottom View of Flexural Strengthening (Half Member)

<u>Figure 9: SRP Reinforcement Layout</u>
<u>(US Customary 1 ft = 0.305 m)</u>

The installation by manual lay-up of SRP laminates is very similar to the one utilized for FRP sheets, requiring the same surface preparation but no rounding of the corners because the steel tape is typically bent mechanically to make 90° sharp bents with no damage to the steel.

Strips of appropriate length according to the design, were cut onsite with commercial handheld electric shears, as shown in Figure 10*a*. A polymeric resin [2] was roller-applied to the concrete surface, to prime and seal the existing pores (Figure 10*b*). Figures 10*c* and 10*d* report the installation of the tapes on girders and deck respectively. A rib-roller was then utilized to press onto the tape to ensure epoxy impregnation and encapsulation of each cord and allow excess resin to squeeze out (Figures 10*e* and *f*). Shear strengthening of the girders was achieved with U-Wraps, obtained by overlapping two L-shaped wraps (see Figure 10*g*). After complete curing of the resin, a topcoat was applied to the affected surfaces to provide cosmetic finish and environmental protection (see Figure 10*h*).



10(a) Cutting the Steel Tape

10(b) Application of Epoxy Resin

10(c) Flexural Strengthening of a Longitudinal Girder

10(d) Flexural Strengthening of the Deck

10(e) Squeezing Out the Resin Excess

10(f) Application of Second Layer of Resin

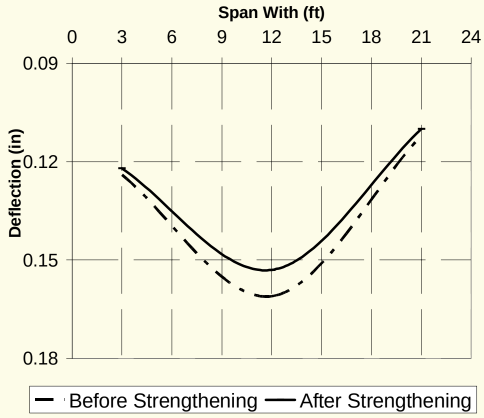
10(g) L-Shapes Wraps Ready for Installation

10(h) Installation Completed with TopCoat

Figure 10: SRP Installation Procedure

To experimentally evaluate the load-carrying capacity of the bridge, in-situ load tests were conducted before and immediately after the strengthening. These tests are repeated every six months and will continue over a period of five years. Deflections were measured at several locations, transversely at mid-span and longitudinally along an exterior and its adjacent interior girder, using a novel non-contact monitoring technique [4]. The static load tests were performed using standard trucks (see Figure 11*a*). Typical results of load tests, before and immediately after strengthening, are shown in Figure 11*b*. It can be seen that after the application of the SRP reinforcement, a marginal decrease in deflection is obtained. Long-term performance of the bridge will be monitored throughout the years, comparing the coming results to these two baselines, till the end of the project in 2008.

11(a) Load Testing



11(b) Transversal Deflection Before and After Strengthening (1 in = 25.4 mm)

Figure 11: Structural Assessment

As a result of the load rating of the bridge, a recommendation to remove the load posting was made. In-situ load test showed an initial good performance of the SRP-strengthened span.

Studies at the University of Missouri-Rolla and at the University of Naples-Italy are underway to characterize the material and to properly calibrate the design factors. The test results of the work in the parking garage [5], the laboratory test campaign [6] and in the bridge strengthening [7] have been submitted for publication. Progress of the bridge project and other studies on the application of steel reinforced polymers to buildings and bridges may be found at the following websites:

http://www.rb2c.umr.edu, and http://www.utc.umr.edu.

References

[1] Hardwire LLC, 2002, "What is Hardwire," www.hardwirellc.com, Pocomoke City, MD.

[2] Huang, X., Birman, V., Nanni, A., and Tunis, G., "Properties and potential for application of steel reinforced polymer and steel reinforced grout composites," Composites, Part B: Engineering, Volume 36, Issue 1, January 2004, Pages 73-82.

[3] Sika, 2004, "Sikadur 330", www.sikausa.com, Lyndhurst, NJ.

[4] Myers, J., and W. Merkle "Use of the Total Station for Serviceability Monitoring of Bridges with Limited Access" 16th World Conference on Nondestructive Testing. Montreal, Canada. August 30- September 3, 2004.

[5] Casadei, P., Nanni, A., Alkhrdaji, T., and Thomas, J., "Performance of Double-T Prestressed Concrete Beams Strengthened with Steel Reinforced Polymer", *Advances in Structural Engineering*, An International Journal *(ASE)*, Accepted January 2005.

[6] Prota, A., Manfredi, G., Nanni, A., Cosenza, E., Pecce, M. "*Flexural Strengthening of RC Beams using Emerging Materials:Ultimate Behavior*", Proceedings of the International Conference FRP Composites in Civil Engineering - CICE 2004 - Seracino (Ed.), 8-10 December 2004, Adelaide, Australia, ISBN 90 5809 638 6, pp. 163-170.

[7] Lopez, A., Galati, N., Alkhrdaji, T., and Nanni, A., "Strengthening of a Reinforced Concrete Bridge with Externally Bonded Steel Reinforced Polymer (SRP)",

Advanced Concrete Technology, Japan Concrete Institute (*JCI*), submitted.

A Consultant's View Point

Mr. Steve Loud is currently Publisher and Editor for "Advanced Materials & Composites News," and "Composites eNews." Previously, he was Vice President and Managing Editor for Composite Market Reports Inc (CMR). Prior to CMR, Mr. Loud was the Vice President-Subcontracts at Teledyne Ryan Aeronautical (TRA) in San Diego where he managed programs for secondary structural components on F-18, F-5, and F-20 aircraft, the B-1B structures proposal team, plus ground-launched (GLCM) and sea-launched (SLCM) Tomahawk cruise missiles. For nearly 20 years, Mr. Loud was with Owens-Corning Fiberglas Corp. (now just called Owens Corning) where he created and directed a subsidiary (Piedmont Products, Inc.) to produce S-Glass TM reinforcing fiber for composites (a zero defect, defense-related product, produced using statistical quality and process control) under government contract.

Composites Innovations Opening Doors to More Growth in Civil Infrastructure

By

Steve Loud

Recent Developments have aided the growth of glass, carbon and aramid fiber composites in buildings and infrastructure applications. And, there is a need for further development, especially in speed of application or installation, to offset the materials cost penalty versus traditional materials.

Composites began to be inserted into the building, construction and especially the civil infrastructure sectors in the 1980s, and rapidly accelerated in interest due to two major influencing factors:

1) the Northridge, California earthquake of January 1994 and the Kobe, Japan quake of January 1995
2) the need for longer-lived bridge decks, in the face of concrete decks with vulnerable steel rebar that corrodes too rapidly in road salt country or coastal areas, which even epoxy coated steel rebar has not satisfied.

In the early 1990s, steel plate repair and strengthening of concrete structures such as buildings and bridges still dominated applications in Europe. Pultruded, thin CFRP (carbon-fiber reinforced polymer or plastic) epoxy bonded strips were tested by EMPA and Dr. Urs Meier in Switzerland, to compete with steel by offering lighter weight and much easier installation. Today, at least in Switzerland, composite plates have taken 95% of the market away from steel plates.

Then, sheet or wallpapering materials, particularly glass fiber and carbon fiber in epoxy became the dominant method for seismic repair and mitigation after the Kobe quake, for stacks, buildings, parking structures, and bridge columns.

This was followed by a high interest in the U.S. in the same sheet materials, with Caltrans sponsoring testing at the University of California, San Diego (UCSD) of both glass and carbon fiber composites versus steel jackets for confining freeway bridge columns against California's constant earthquake threat. This work in turn lead to a large commercial market in retrofitting California parking garages, both columns and beams.

The look at seismic protection of bridges lead to an assessment of GFRP (glass fiber reinforced polymer) composites for bridge deck panels and "fiberglass" rebar for cast-in-place bridge decks, and other variations such as VARTM panels, pultruded stay-in-place forms, and more.

Figure 1 – Lift Bridge in Portland, Oregon with MMC glass fiber composite deck panels.

Today these CFRP and GFRP composites are slowly penetrating their target markets. But, we see growth ahead because of these successes and because of new product innovations like those below.
New players with new ideas, products and systems are continually emerging to push for their share of what is considered to be one of the largest opportunity markets for polymer composite structures.

Following are five (5) new FRP composite structural systems or materials that currently show real promise in the construction, building, and civil infrastructure sectors.

1. New Approaches to Composite/Composite Bridges and Rapid Installation

The use of FRP composites for bridge decks and superstructures remains of high interest. In addition, the use of FRP in composite action with concrete and steel has good appeal and is portrayed in recent demonstration projects.

In October, 2004, Erie County Commissioner of Public Works Maria Lehman, PE opened a new FRP composite-concrete hybrid bridge to traffic after only one month of construction, meeting all program objectives. The accelerated bridge replacement project used four modular FRP-concrete panels for the deck and superstructure.

This is in an area that gets an average of eight feet of snow every year (brought on by the lake effect off Lake Erie) and is forced to apply sand and salt to its bridges to keep them free of ice so they are safe for the traveling public. Because this superstructure does not corrode like steel, drivers should be able to use the bridge for its entire 100 year design life instead of having to replace it after fifty years as is often the case with traditional bridges.

The superstructure panels of FRP and concrete were installed in one afternoon using two backhoes to lift and place them onto the substructure. The four 9.4 meter-long panels are fabricated of pultruded 4" square composite tubes bonded using a VARTM process and skin sheets of composite to form a box shape beam section. A carbon steel free concrete deck was added to the FRP at the factory and functions compositely with the FRP box beam unit.

In another similar project, The Texas Department of Transportation (TxDOT) decided to investigate the feasibility of using fiber-reinforced polymer (FRP) composite materials for new highway bridge structures. Primary FRP structural beams for short-span bridges near the Gulf Coast were identified as a promising application, but they wanted a unique approach to the beams. These bridges span bayous, drainage ditches, and salt-water inlets, with the potential for severe corrosion attack due to factors such as high humidity, salt air, salt and brackish water, and poor drainage. Steel, timber, and concrete have all exhibited corrosion or induced degradation in this environment.

Early in the project, TxDOT identified a key limiting aspect of glass fiber FRP composite materials: their relatively low modulus. To address this issue, the testing program focused on developing a system combining GFRP beams made by Molded Fiber Glass (MFG) and a conventionally (steel rebar) reinforced concrete deck that could effectively sustain traffic loading by means of "composite action" from the two material and structures, to limit overall deflection.

MFG produced 26 beams designed for L/800 deflection and HS-20 loading, all of which were tested in-house. Then, TxDOT personnel tested and passed four of the beams using the Acoustic Emission procedure per sections V and X of ASME Code. Based on this sampling and the ASME RTP-1 procedures. All 26 beams were accepted, with 24 required for the installation, and two spares.

Figure 2 - End-on view of U-shaped beams being positioned. The brace bars are visible spanning the open top of the beams.

Figure 3 - Twelve of the 30-foot beams could be transported on a single trailer.

Teng & Associates of Chicago, Illnois have developed a structural Optimized Composite Beam System for use in rail bridge structures, a project for the High-speed Rail-IDEA program. [United States Patent Number 6,145,270, this beam is a revolutionary new type of structural member]. The "Hybrid-Composite Beams" are comprised of three main sub-components that are a composite shell, compression reinforcement, and tension reinforcement.

The compression reinforcement consists of portland cement concrete which is pumped into a profile or conduit within the beam shell. The tension reinforcement along the bottom of the beam is Hardwire(r) steel wire fabric, anchored at the ends of the compression reinforcement.

Figure 4 - Prototype concept for rail bridge beam of 10-meter length now in fabrication for full-scale field testing.

2. Multi-Axial Fabrics

Many suppliers offer knitted or stitched non-crimp fabrics, with demand for all markets (primarily marine and wind turbines to date) in the 10s of thousands of metric tons annually. These have been of great help to the expansion of composites in the infrastructure as well.

A new player with a totally new approach, Multi-Axial, Inc., announced in December that their new production facility designed for high-volume production of commercial reinforcing fabrics, tapes and composite materials will open soon near San Clemente, California. Their new 25,000 square foot facility will have an annual conversion capacity of more than 25 million pounds of StructurPly(TM) and TowStrand (TM) products.

The Multi-Axial family of StructurPly Engineered Multiaxial Thermoplastic Prepreg products has balanced physical and mechanical properties for both primary and secondary structural applications. The StructurPly Engineered Multiaxial Reinforcement Architectures (performs) were designed and fabricated with up to 24 plies in thickness for RTM and the many related process techniques, wet lay-up fabrication techniques, and for prepregs. This family of products reduces the fabrication cost by as much as 60% of the composite component cost: materials are supplied to the customer that may be placed immediately onto the cure form, eliminating the need for ply cutting or lay-up.

The TowStrand Engineered Selective Reinforcement products were designed to provide the most effective means of selectively reinforcing product types such as: engineered wood products (including GluLam beams) for building construction, snowboards, hockey sticks and the like.

The conversion process includes: Aramid, Basalt, Carbon, E-glass, R-glass(r), S2-Glass(r), Vectran(r), and hybrids of these fibers.

Figure 5 – StructurPly carbon fiber multi-axial fabric in hermoplastic prepreg

This new form of multi-axial fabrics and sheets opens up many new use opportunities for composites.

3. Basalt Fibers

For reinforcement of concrete or plastics, basalt fibers are said to offer inherent benefits of alkali resistance versus glass fibers and lower cost than carbon fibers. Basalt fiber is based on igneous rock melted at 1450 C. Its two largest ingredients are silica at 57.5% and alumina at 16.9%, both close to the levels in E-glass fibers.

High-strength basalt rovings are being introduced at JEC in Paris, France, 2005 (April) by Kamenny Vek. Three new products include high-strength, high-modulus basalt rovings; non-woven fabrics from advanced basalt fibre; and heat and corrosion resistant basalt chopped strands. The products have noticeably higher strength and modulus than existing basalt fibres, high mechanical properties, and a wide operating temperature range at affordable prices.
Basaltex launched its basalt fiber in the U.S. at ACMA Composites 2004 in October in Tampa, Florida - Basaltex offers a unique new product line of continuous fibers and fabrics based on basalt, for reinforcing composites. The company calls it the Thread of Stone. It has superior fire resistance to conventional fiberglass.

The Basalt Fiber Association initiated its formation in June 2004 to provide an educational forum for basalt fiber executives and technologists to share ideas and experiences and to promote the basalt fiber industry. Also, the BFA will bring high-profile basalt fiber speakers to discuss the new opportunities and applications taking place in the industry.

4. Hardwire for Repair and Strengthening and for Blast Mitigation

Hardwire LLC, the world leader in new and emerging steel-fiber-reinforced polymer (and other matrixes) composite technology, introduced a new, faster and free-of-charge resin infusion process for composites based on the use of Hardwire "Micro-Rebar'" unidirectional tapes.

The new process, named HIP(tm) (Hardwire Infusion Process), uses Hardwire steel-fiber reinforcing tapes and multi-axial lay-ups that act as an internal resin distribution network to create a simple, highly effective resin infusion processing technique. Due to the superior permeability of the wire material, the HIP process is up to 10 times faster than conventional "over the top or through the core" infusion processes for FRP composites, and there is little to no resin waste.

Figure 6 – Hardwire tape being applied in grout for floor strengthening.

Laminates made from Hardwire using the HIP process exhibit flexural properties in excess of 270 KSI and modulus values as high as 13 MSI.

Based on the steel-belted fiber technology commonly found in tires, Hardwire(r) has already been successfully implemented as a solution for structures and other infrastructure components seeking blast-resistance and blast-mitigation retrofit. A family of reinforcements made from ultra-high strength twisted steel wire cords, Hardwire - 11 times stronger than a typical steel plate - easily reinforces various polymer and cementitious matrix materials and provides high strength (up to 8 kips/inch) and high modulus (up to 30-million psi) in a very thin, ductile material envelope.

5. Grids for Precast Concrete – C-Grid

The AltusGroup is the first-ever national partnership of precast companies. AltusGroup was founded to develop, manufacture and market precast innovations such as the breakthrough CarbonCast line of precast concrete products utilizing C-Grid reinforcement technology.

Acceptance of CarbonCast has been rapid. Affirming the viability and acceptance of carbon fiber reinforcing in precast concrete, AltusGroup has sold nearly 2 million sf of CarbonCast™ precast products in the eight months since the technology's national introduction in February 2004. Another 1 Million square feet of wall panels have been specified since the technology's introduction, with dozens of other projects nationwide now considering the use of CarbonCast.

Engineered by TechFab, LLC of Anderson, S.C., high-strength, ultra-durable C-Grid has superior tensile properties when compared to steel and requires only 1/4" of concrete cover to be effective compared with 3/4" to 3" for steel reinforcing. It also controls shrinkage cracks up to 50 percent better than steel mesh in panels and tees, and it will never corrode.

CarbonCast technology - which replaces secondary steel reinforcing with carbon fiber composite grid to reduce corrosion, decrease wall section weight (which reduces steel substructure costs), and improve insulation properties - has been specified for insulated wall panels, architectural panels or double tees in a variety of end-uses in more than a dozen states across the U.S.

Lower weight, thinner C-GRID reinforced sections will not exhibit the cracking, spalling or stains that can sometimes occur in concrete applications if conventional steel reinforcing is located too close to a surface exposed to weather, abuse or abrasion.

Figure 7 – Simulated CarbonCast precasting of a CFRP grid in concrete panel. Grids come in many materials and areal weights, tailored for the application

CarbonCast(tm) precast products have lightweight, innovative section profiles enabled by replacing conventional primary steel reinforcing with C-GRID(tm), a high-strength composite carbon fiber secondary reinforcing developed by TechFab, LLC, that replaces conventional steel reinforcement. Products, such as CarbonCast architectural panels, are up to 66 percent lighter than conventional precast components, while CarbonCast wall panels have the highest R-values per inch of thickness in the industry.

TechFab, LLC manufactures their adhesive-bonded carbon fiber C-GRID using Zoltek Companies' Panex 35™ commercial-tow carbon fiber.

NEEDS?

Lowest cost reinforcing formats

- ways to place reinforcing fiber even more economically
- multi-axial fabrics made by machine processes faster than looms
- Codes, specs to allow design guidelines for use of these "new" materials by those trained to use the traditional materials.
- Better publicity about successful applications – CGI push with trades

MARKET SIZE

At a SAMPE presentation to a Carbon Fiber Panel in November 2004, Dr. Howard Kliger covered the field of Civil Infrastructure and carbon fibers usage. He said that "the aerospace companies use CF composites to build the weapons, while the civil engineers build the targets."

Most civil engineering uses are stiffness driven which tends to favor carbon fiber usage over glass fiber for repair and strengthening. With prices headed higher for carbon fibers, from the $8-14/lb range, he says that this will hurt the demand growth for carbon fibers in infrastructure. The increase in the price of oil is driving up costs for resins, adhesives, and carbon fibers.

Drawing from the baseline of the Infrastructure Composites Report 2001, jointly researched by Dr. Kliger, plus Steve Loud with Composites Worldwide, Inc, Howard estimates that in 2000, carbon fibers topped consumption of one (1) million lbs in usage for civil infrastructure. Since then there has been a 10-15% per year growth globally. And the share of market is about 50% in Japan, 15% in the U.S., and 35% in Europe and the Rest of the World (ROW). In his market update on the concrete repair sector for the 2003/2004 period he determines that "Industrial" uses for CF, including infrastructure, will consume about 51% of carbon fibers by 2008, with Aerospace at a 23% share and Sporting Goods and Recreation at 26%.

Honors and Member News

Professor Antonio Nanni Honored by UM System President's Award for Research and Creativity

IIFC Fellow Professor Antonio Nanni was recently honored by the University of Missouri System as the recipient of the 2005 President's Award for Research and Creativity. Professor Nanni is a specialist in the field of civil infrastructure renewal including construction materials, their structural performance, and field application. He is a pioneer and leader in use of fiber reinforced polymers (FRP) as a new construction material to repair and strengthen structure. His basic research, technology transfer, and leadership have been the driving force in the phenomenal growth in the use of FRP. The fundamental research he has undertaken will enable our infrastructure to last longer, and even save lives during events such as earthquakes. The following is a summary of his major accomplishments:

- Served as the principal investigator for over $10 million in research sponsored by federal and state agencies, and industry on concrete and advanced composites-based systems.
- Authored over 115 refereed journal papers and 180 refereed conference articles, which have been the basis for the most influential design guidelines for practicing engineers to employ FRP technology on an unprecedented scale.
- Active member in the technical committees of ACI (Fellow), ASCE (Fellow), ASTM and TMS, Founding Fellow of IIFC. Editor-in-Chief of the ASCE Journal of Materials in Civil Engineering.
- Founding Director of the Center for Infrastructure Engineering Studies at UMR.
- Some of his previous awards include:
  - Public Works Magazine 2004 Trendsetters Award and the 1997 Engineering News-Record Award of Excellence.
  - 2004 MSM-UMR Alumni Merit Award for Outstanding Accomplishments

Announcements

International Symposium on Bond Behaviour of FRP in Structures (BBFS 2005) 7 – 9 December 2005, Hong Kong, China

Fibre-reinforced polymer (FRP) composites have found increasingly wide applications in civil structures over the last decade. A key issue in the design and construction of structures incorporating FRP composites is the performance of the bond between FRP and another material or between two FRP elements. **The International Symposium on Bond Behaviour of FRP in Structures (BBFS 2005)** is to provide an international forum for all concerned with the bond behaviour of FRP in all forms of structural applications and a state-of-the-art survey of existing research in this important area.

The conference covers all aspects of bond performance of FRP in structures, including the bond between (external, near surface mounted and internal) FRP and other structural materials such as concrete, masonry, metal and timber as well as between two FRP elements. Topics to be covered include but are not limited to:

- Bond tests: standardization and theoretical modelling
- Debonding failures in structures: mechanisms and theoretical predictions
- Numerical modelling of debonding failure processes
- Durability and fire resistance

In addition to papers reporting new research advances, papers providing a summary of a series of recent investigations are invited.

Over 100 abstracts have been accepted. For more information about this symposium, please visit the symposium website at:

http://www.iifc-hq.org/bbfs2005/

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 for-mats, 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:

Department of Civil and Environmental Engineering
Florida International University
10555 West Flagler Street
Engineering Center 3600 Miami, FL 33174
U.S.A. Phone: (001) 305-348-2314

Fax: (001) 305-348-2802
Email: Mirmiran@fiu.edu

FRP Photo Competition 2005 - Call for Entries

The International Institute for FRP in Construction is now accepting entries for its FRP photography competition. The contest is open to everyone and entry is free. There are 2 categories for the contest:

Category 1 - FRP in an engineering project (under construction or completed)

Category 2 - FRP in a research study.

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)

http://ascelibrary.aip.org/cco/.

Five runners up in each category will have their photographs made into posters and displayed (with due acknowledgment) at international conferences and events where the IIFC exhibits.

To enter the contest, please find more information in the competition website at:

http://www.iifc-hq.org/photocompetition05/

INTERNATIONAL INSTITUTE FOR FRP IN CONSTRUCTION

COUNCIL

AUSTRALIA

Professor D.J. Oehlers	University of Adelaide
Professor G.M. Van Erp	University of Southern Queensland
Professor X.L. Zhao	Monash University

BELGIUM

Professor L. Taerwe	Ghent University

CANADA

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

CHINA

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

GREECE

Professor T.C. Triantafillou	University of Patras

IRAN

Dr. M. Motavalli	University of Tehran

ITALY

Professor E. Cosenza	University of Naples Federico II

JAPAN

Professor T. Ueda	Hokkaido University
Professor Z.S. Wu	Ibaraki University
Dr. H. Fukuyama	Building Research Institute

SINGAPORE

Professor K.H. Tan	National University of Singapore

SWEDEN

Professor B. Taljsten	Lulea University of Technology

SWITZERLAND

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

USA

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

UK

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

ADVISORY COMMITTEE

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

EXECUTIVE COMMITTEE

President

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

Vice-Presidents

Professor K.W. Neale	Univerisity of Sherbrooke, Canada
Professor L.C. Bank	University of Wisconsin–Madison, USA
Professor T. Keller	Swiss Federal Institute of Technology, Switzerland
Professor T. Ueda	Hokkaido University, Japan

Newsletter Editor

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

Treasurer

Professor N. Banthia	University of British Columbia, Canada

Secretary

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

Conference Coordinator

Professor A. Mirmiran	Florida International University, USA

Members-at-Large

Dr. R. Seracino	University of Adelaide, Australia
Professor Z.S. Wu	Ibaraki University, Japan