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Structural Applications

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Feature Article

STRUCTURAL APPLICATIONS OF COMPOSITES IN INFRASTRUCTURE

PART I

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Advanced materials, mainly fiber reinforced plastic (FRP) composites, will partially replace conventional materials in civil engineering type applications. This article reviews critically some of the more promising material systems for infrastructure applications, which include buildings, highway bridges, sewage and water treatment facilities, off-shore structures, and transportation systems. Part I presents an overview of the structural systems constructed with FRP and a review of the state of the art on the application of FRP structural shapes. Part II will discuss the reinforcement of concrete with FRP and reinforcement/rehabilitation of conventional materials with FRPs. For an in-depth technical treatment of these topics and an extensive list of references, the reader may consult Reference (1).

The nation's infrastructure is composed of industrial and public works that support our daily activities. Coastal and marine structures, bridge decks, parking garages, building floors, highway embankments, sign posts, chemical and waste treatment plants, and many others are examples of infrastructure components, also called constructed facilities. Steady progress in composite materials technology is helping replace conventional materials like steel and concrete with fiber reinforced composites in conventional as well as in innovative infrastructure applications. A large volume market for fiber reinforced composites lies in the rehabilitation of the American infrastructure, (estimated to be a three trillion dollar effort.) Most of American infrastructure has been built with steel structural shapes or portland cement concrete reinforced with mild steel. Mild steel is frequently exposed to accelerated corrosion leading to catastrophic failures and costly repairs. For example, the cost of replacing a disintegrated bridge deck due to its exposure to deicing chemicals is almost twice the original construction cost. The Federal Highway Administration of the United States Department of Transportation estimated that replacing these decks will cost over $20 billion, increasing at a rate of $500 million per year due to further deterioration. There is a need to develop and use new long-lasting materials with attributes of corrosion resistance and high strength to weight ratio that can be mass produced at low cost to replace and complement conventional materials in the infrastructure sector. Polymer matrix composites (PMCs) are a good candidate to fill many applications of composites in infrastructure. PMCs have already made significant inroads in this sector in applications such as antenna coverage, off-shore construction, water treatment plants, and others to be discussed shortly. The PMC industry is currently searching for new applications because of the maturity of the military use of PMC in recent years. Polymer matrix composites are divided into FRPs and advanced polymer composites. FRPs are inexpensive, as in the case of polyester resins reinforced with continuous glass fibers. Many other low-cost reinforced plastics, such as sheet molded compounds, are not considered by structural engineers to be in this category due to their relatively low strength when compared to continuously reinforced composites. Advanced

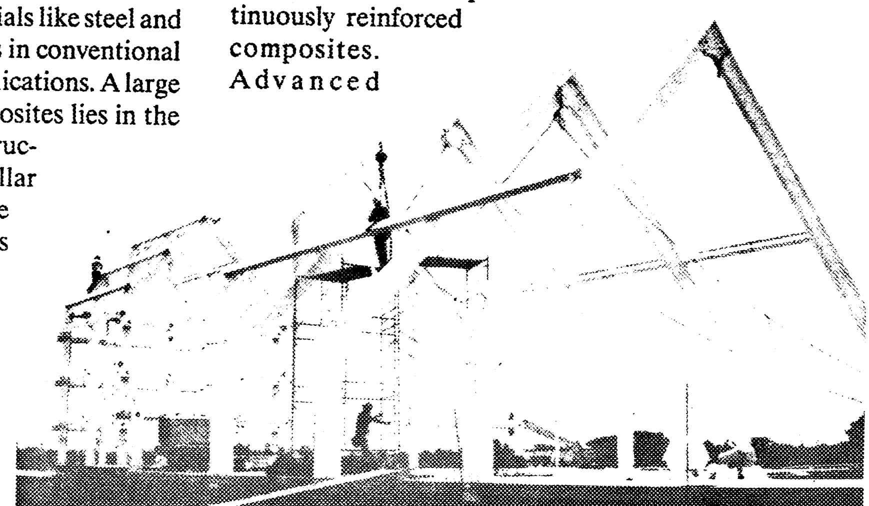

Figure 1. Frame and purlines at AT&T's computer testing facility in Tulsa, OK. (Courtesy of Composite Technology, Forth Worth, TX.)

polymer composites have superior strength and stiffness but are much more expensive than FRPs.

Due to the constraints of continuous reinforcement, low cost, and mass production, one process has been singled out as a major candidate to supply the infrastructure market: pultrusion. Still other processes like filament winding and automatic tape layout are certainly going to find applications in the future, mainly due to the flexibility they offer in producing relatively complex shapes. So far, their limited production rates and higher costs make them less attractive. On the other hand, new pultrusion techniques such as direct injection at the die and pultrusion combined with compression molding and other processes on a continuous production line are being developed in order to add flexibility to the traditional pultrusion process. Another characteristic that favors pultruded products is the modality of the construction industry. Unlike aerospace and mechanical engineering designs that integrate all aspects of manufacturing from the material to the final product, civil engineers often work with standard sections, most of the time prismatic, that can be assembled in a unique way to create the desired structure. This approach has several advantages that should not be underestimated. Standardization brings along significant cost reductions. It also allows for easier compliance with codes of practice that are necessary to regulate the design of structures which may compromise the lives of many people. In this sense, standard prismatic sections have more advantages than disadvantages, and the ability of certain composite production processes to create complex shapes may not be that critical. Furthermore, the transition from conventional materials to FRPs would be easier for the construction industry if composites were produced in sections similar to their counterpart in steel. In fact, user acceptance guided the design of current FRP pultruded structural shapes. However, care must be taken not to compromise the advantages of FRP while trying to mimic existing steel structural shapes. FRPs have significant advantages over conventional materials but show significantly different behavior with regard to stiffness, modes of failure, etc. Therefore, structural design with FRP and the concept of the standard structural shapes to be used must be undertaken with an open mind, in the sense that it must be accepted that the design of a structure with FRPs may lead to a concept that is significantly different from that which we are accustomed to see in conventional materials. Moreover, the main advantage of composites is the possibility of tailoring the material to the specific application. Unlike the aerospace industry where each design is unique, tailoring of the material for each single structure may not be possible in the construction industry because of the need for standardization. However, it must be realized that, due to the large volumes of materials involved in construction, tailoring for classes of structures should be allowed. In fact, this has happened over the years for conventional materials, like steel, where the shapes have evolved into the optimal configurations for classes of applications, i.e., columns, beams, etc.

Beyond the low weight and corrosion resistance, FRPs have certain characteristics unmatched by conventional materials, the most salient one being electromagnetic transparency. Electromagnetic properties of FRPs have motivated the use of FRPs over the years despite the lack of design experience, standards, and material data bases. Imaging equipment used at hospitals has to be mounted on magnetically inert environment to avoid the distortion of the electromagnetic field around the equipment that otherwise would affect the quality of the imaging process. Therefore, ferromagnetic materials, such as mild steel used as reinforcement for concrete, cannot be used to support this kind of equipment. For the same reason, no ferromagnetic materials can be present in the vicinity of communication equipment, which may pose restrictions on the kind of materials used to reinforce concrete over large areas of airport pavement and buildings. These applications encouraged engineers in the use of FRP reinforcing bars for concrete, one of the most successful applications of FRP in the construction industry. Pultruded structural shapes are being increasingly used to build antenna encasements amid tall buildings around the world. Because indoor electronic equipment is much less expensive than outdoor equipment, the additional costs of FRP, if any, compared to aluminum structural shapes are easily justified.

Structural FRPs are increasingly used in mass transportation systems. Although the main applications are on vehicles, composites are being considered for the tracks as well. Low stiffness and high initial cost are the main barriers to the application of FRPs to guideway structures. However, there is enough incentive to consider FRPs for guideway systems. FRPs can be produced in modules that can be easily assembled and quickly replaced in case of deterioration. The flexibility in creating complex shapes with FRPs encourages the concept of developing multipurpose guideways that can carry various services, like communication fiber optic cables and power lines. Corrosion resistance may well lead to a longer life cycle which may justify a higher initial cost if ongoing research can successfully quantify the expected life cycle of composite structures. Various techniques are under development that will allow the composite material to become an intelligent structure; that is, the material will be able to self-monitor its state of deterioration and to produce a warning signal of any imminent failure. These features may help save lives, costs of premature replacement, and ease the maintenance of the system.

STRUCTURAL SYSTEMS

Fiber reinforced plastic composite structures have been around for forty years, mostly as showcases with limited applications in civil engineering construction. One of the reasons inhibiting the general use of composites in civil engineering construction is the lack of design criteria of structural connectors, structural components, and structural systems. However, recent advances have led to numerous applications where FRP designs were chosen in

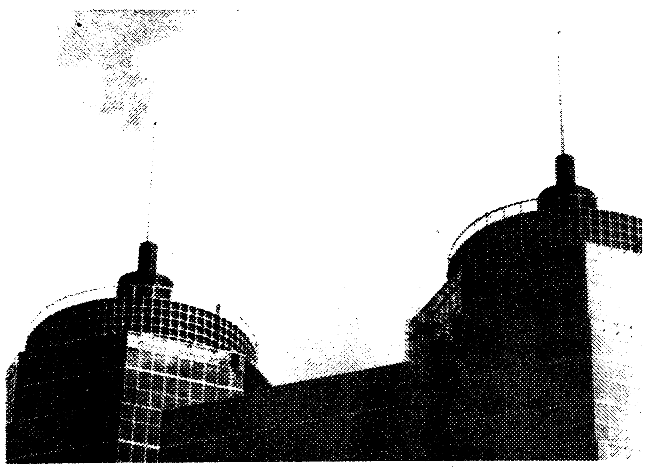

Figure 2. Communication towers at St. Luke's Episcopal Hospital in Houston, TX. (Courtesy of Creative Pultrusions Inc., Alum Bank, PA.)

open competition with projects using conventional materials.

Glass fiber reinforced composite building systems made of FRP components and connectors are being used in civil engineering construction primarily because of their non-magnetic and noncorrosive properties. All-weather, electromagnetically compatible testing facilities have been built for various computer manufacturers and laboratories (Figure 1). In addition, construction of enclosures on the top of St. Luke's Episcopal Hospital in Houston, TX, (Figure 2) to house radio antennas is an excellent example in terms of advancing state-of-the-art construction with FRP shapes.

Continuous fiber mats have been used in Austria as facades in high-rise building construction and as store portal frames. This type of laminate lends itself well to produce economically large structural elements and large-surfaced, thin-walled structural systems such as domes, shells, and stiffened roof components.

In 1989, GE Plastics, Pittsfield, MA, unveiled a "Living Environment" house, using FRPs as innovative housing components and to test many FRP applications, like roofing materials, molded baseboards for electrical and telecommunication purposes, and radiant wall panels with integrated water, electricity and control services. Polymer concrete made of glass-filled Valox PBT in portland cement is among the innovative materials being used. GE Plastics is working on a 110 m^2 (1200 $feet^2$) single-family, affordable starter home with approximately 60 percent plastic materials, which they plan to unveil in 1992.

Innovations in terms of foam-core panel systems are being researched to reduce costs and improve earthquake resistance. The extruded core marketed by Siteco of Italy has hollow sections spaced in such a way as to accommodate reinforced columns. The hollow foam core panels serve as a form to concrete at the time of construction. A sandwich panel with fiber glass reinforced concrete facings and polystyrene extruded foam core is being successfully used for walls, partitions, and floor panels. The polystyrene is extruded into cellular sections with holes designed to hold concrete reinforced with steel rebars as in conventional construction but eliminating the need for molds since the holes in the core act as a permanent mold for concrete. The faces are made of fiberglass reinforced concrete. An acrylic emulsion additive in the concrete is said to inhibit the alkaline reaction between concrete and glass and to improve bond between concrete and the core. The reinforced concrete columns are joined by reinforced concrete beams poured during erection at the same time as the columns. Floor slabs with reinforcing elements are joined in the same fashion. This system was ranked first in all nineteen classifications set up by the French government to compare all types of construction, including materials. The salient advantage of this fiber-reinforced, sandwich composite material is modular construction, with sound and heat insulation being additional advantages.

So far, fiber reinforced plastic components have found very limited use in the construction of bridge systems, which can be attributed to limited availability of technical information on FRPs for bridges. The current literature deals primarily with experimental aspects of some FRP bridges and little information can be found on design issues. McCormick, at University of Virginia, designed and tested a 2.1 x 4.9 m and 45.7 cm deep bridge that was later placed at a recreational park at Charlottesville, VA, to monitor the structural behavior, effect of weathering and user abuse. The decking system was made of concrete and the stringers were composed of trussed webs and a solid flange plate forming a triangular shaped cross section. All components were made of glass-reinforced polyester. Non-metallic fasteners were used in all of the connections. Various pedestrian bridges (Figure 3) were designed by E.T. Technotonics of Philadelphia, PA (under the name PRESTEK) and built by Corrosion Resistant Materials Co. of Everett, PA, using components made by Creative Pultrusions, Inc. All composite personnel bridges (Figure

Figure 3. Golf course bridge at DuPont Country Club in Wilmington, DE. (Courtesy of Creative Pultrusions Inc., Alum Bank, PA.)

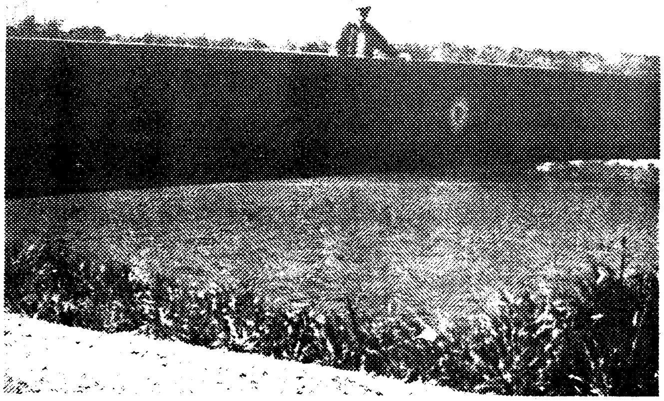

Figure 4. All composite personnel bridge in Ford Bacon and Davis, Alexandria, Louisiana. *(Courtesy of Composite Technology, Forth Worth, TX.)*

4) of up to 28 m span have been designed and built by Andrew Green at Composite Technology of Fort Worth, TX. The first reinforced plastic pedestrian bridge was designed by Yair Tene of North Potomac, MD, and built in 1975 in Israel. The bridge of about 24 m span was cited by the Engineering News Records in 1976 as one of the ten most outstanding achievements in the field. Tene also designed and built a Heavy Assault Bridge with carbon-epoxy bottom chords of about 30 m, which, due to its light-weight and ease of erection, can be deployed in five minutes.

Plecnik of California State University, Long Beach, CA, fabricated new FRP sections intended to be used in bridge superstructures to replace steel or concrete in short span ranges (up to 30 m) or for emergency replacements. The proposed structural shapes are produced by filament winding, maximizing the flexural rigidity of the system by a combination of shape and fiber orientation.

Another novel application of FRPs in bridges is to provide a hollow enclosure system to protect the structure's steelwork from corrosion. The enclosure system, developed in England, has unique interlocking panels which form the structural floor. The enclosure system was found to have minimum weight, an estimated life of at least 30 years, good fire resistance, good long term appearance, and low life-cycle costs. Carbon Fiber Reinforced Plastic (CFRP) laminates were successfully employed as reinforcing plates in concrete beams. Strengthening existing structures with CFRP laminates is being actively researched by Mohammad Ehsani of University of Arizona, Tucson, as a rehabilitation technique for deteriorated structures. CFRPs are being used in combination with concrete slabs to develop and test new model bridges by M. Saiidi and F. Gordaninejad at University of Nevada, Reno.

An interesting application is under development by Plecnik of California State University, Long Beach, CA, in the area of cables for suspension bridges and as post-tensioning devices for prestressed concrete. A link type connection is built directly at each end of the cable with fibers that go around the eye of the link. This link type connector replaces the potted type connectors that rely only on shear stress to transfer the load from the cable to the anchorage and that have been shown to present problems.

Potted type connectors have been successfully used by Strabag Bau-Ag of Germany in conjunction with its glass-fiber reinforced cable. An antenna mast bracing system was built in Munster, Germany, taking advantage of the nonmagnetic properties of the cables, but applications have been mainly in the post-tensioning of concrete. Four different anchorage systems were used on a 7 m span bridge built in Dusseldorf, Germany, in 1980 and monitored for five years. A heavy traffic bridge was then built in Dusseldorf in 1986 with similar technology. A pedestrian bridge was built in 1988 in Berlin, partially prestressed with the same cables. Fiberglass cables were also used in the rehabilitation of the Mairie d'Ivry Metro station in Paris, France, where the nonmagnetic nature of the cable played an important role in the selection of this cable instead of high stress steel cables. The possibility of embedding sensors in FRPs is exploited in two new post-tensioned bridges, the Schiessbergstrasse Bridge in Leverkusen, Germany, and the Notsch bridge in Karnten, Austria. In these applications, the fiberglass cables have comingled fiber optic sensors capable of measuring strains in the cables. Strabag Bau-Ag of Germany also reports successful application of its fiberglass tendons and potted connectors for soil anchorage applications. The non-corrosive properties of the cable have been demonstrated in its application in prefabricated prestressed concrete covers for brine pit covers. These covers must comply with bridge specifications since they are subject to the loads of salt carrying trucks. The covers, which are subjected to highly corrosive effects of chloride vapors, have been in operation since 1987.

A carbon-epoxy cable developed by Tokyo Rope Co. and Toho Rayon Inc., both of Japan, has found applications as

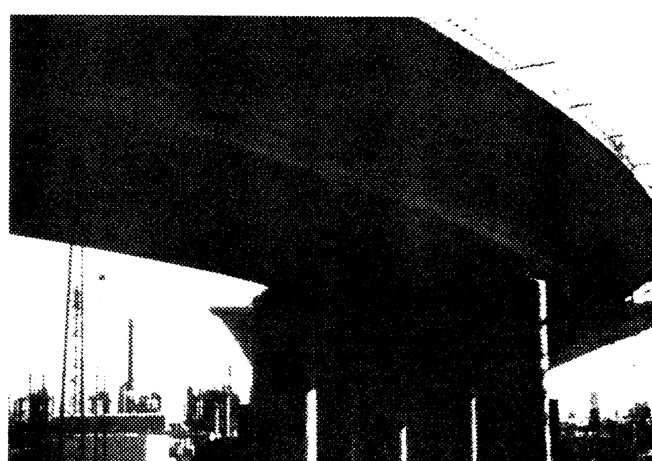

Figure 5. Concrete bridge partially post-tensioned with carbon fiber composite cable in BASF chemical plant at Ludwingshafen, Germany. *(Courtesy of BASF, Charlotte, NC.)*

a post-tensioning device for bridges. BASF, who markets the product in Europe, is using the cable and metallic die-cast/wedge connectors to partially post-tension a bridge in its Ludwigshafen chemical plant in Germany (Figure 5). In Japan, the Shinmiyabashii Bridge was built in 1988 and uses Rope's carbon cables in prefabricated prestressed concrete beams. In this case, a disposable anchorage system is used only temporarily at the factory (until the concrete cures). Then, the bond between concrete and the cable transfers all the load and the anchorage can be removed. In the U.S., Prof. S. Iyer of the South Dakota School of Mines and Technology, Rapid City, SD, is developing various applications for CFRP cables like anchorage systems for coastal structures and post-tensioning of bridges. A detailed account of recent developments in this area can be found in Reference (2).

Glass fiber reinforced plastics have been successfully used in the construction of portal frames and raised floor systems, taking advantage of the nonmagnetic properties of FRPs in the construction of power transmission substations. The major advantage of FRP component applications is that the main load carrying members can be "tailor-made" to resist stresses in high stress concentration zones and to facilitate ease of assembly with other parts. Similarly, glass fiber composites have been used for filament wound pipes of about 3.65 m in diameter. Fiberglass poles come in many shapes and colors and are designed to withstand high wind forces. One of the major advantages of fiber glass poles is that they break within 10 cm from the ground when hit by a vehicle and cause little damage to the vehicle or its occupants.

Understanding of a structural system behavior and system efficiency are very important for optimal design of a structure. Such understanding depends greatly on the performance of structural connectors. Extensive testing has been performed at the Constructed Facilities Center of West Virginia University to establish the single and double lap connectors efficiency of FRP materials. L.C. Bank, of Catholic University of America, performed tests on beam-to-column connections using conventional steel connectors details. Additional research on FRP connectors for moment transfer needs to be performed for optimum design of moment transfer joints.

One of the major limitations of current designs of FRP structures is the lack of understanding of the behavior of composite components, connectors, and structural systems. Netting Analysis has been used for the design of FRP silos, an underground train station, and high pressure pipes, along with empirically determined parameters to establish bending and stretching stiffness. Netting Analysis is an oversimplified approach that may lead to conservative designs that can be regarded, erroneously, as not being competitive with conventional materials. The procedure, which is recommended by the Boiler and Pressure Vessel Code Section XIII, consists in analyzing fiber reinforced composites considering only the fiber mesh. Various commercial finite element codes can be used efficiently for the analysis of FRP structures. In particular, SAP-IV has been used successfully to compute stresses and strains while designing composite tanker trucks. Fatigue effects in such structures as tanker trucks and bridges can be very critical. Due to the lack of experimental data, the structure has to be designed to operate at levels of stress much lower than that for static failure if it is to sustain several million load-cycles during its life. Recent research at the Constructed Facilities Center of West Virginia University has provided some of the tools for a simple design methodology. The classical lamination theory (CLT) was simplified and combined with the concept of effective width for use in the design of FRP structural systems.

While a variety of material combinations can be used, the most promising systems appear to be the reinforcement of concrete, replacement of steel structural shapes by pultruded FRP, and the reinforcement/rehabilitation of conventional materials.

STRUCTURAL SHAPES

Structural shapes is a generic name for fiber reinforced composite prismatic sections, which are mainly produced by pultrusion. Pultruded sections contain a high percentage of fiber reinforcement (up to 70%), which makes the product structurally sound. Small prismatic sections are also manufactured by extrusion of structural plastics (also called engineering plastics to indicate that they exhibit significant stiffness and strength) reinforced with short fibers. However, these composites fall in a different category with only limited possibilities for structural applications in building and construction due to their low stiffness, low strength, and high creep/relaxation.

Standard pultruded sections (up to 30 x 30 cm wide-flange I-beams and 61 cm deep I-beams) are being used for structural applications. Due to the magnetic transparency of FRP, structural shapes are ideal for antenna coverage like those atop the Sun Bank in Orlando, FL. FRP structural shapes and FRP reinforced concrete are commonly used for buildings housing electromagnetic sensitive

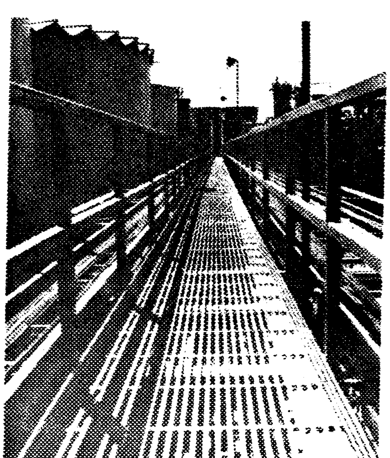

Figure 6. Walkway in caustic environment using FRP structural shapes. (Courtesy of Creative Pultrusions, Inc., Alum Bank, PA.)

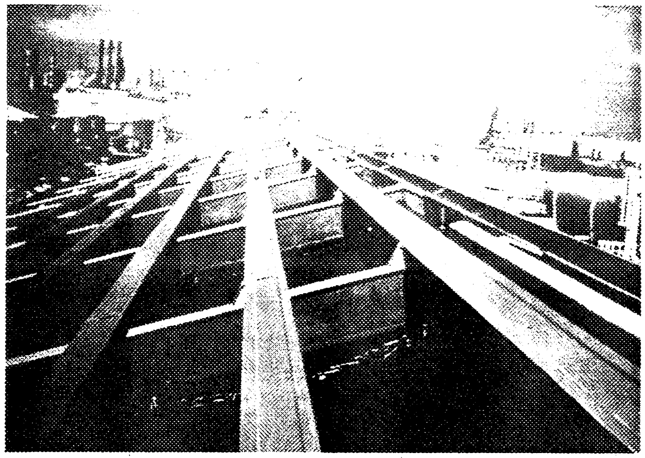

Figure 7. Caustic chlorine facility with spans up to 5.8 m and loads up to 1.9 KPa. Diamond Shemarock, Houston, TX. (Courtesy of Composite Technology, Forth Worth, TX.)

equipment from communications testing equipment to advanced diagnostic equipment in hospitals.

The corrosion resistance of the vinylester resins used in one line of structural shapes makes FRP the material of choice for auxiliary structures in chemical plants. Handrail systems (Figure 6), platforms, ladders, and ladder cage assemblies are some examples of successful applications of FRP in corrosive environments. Replacement of steel components by FRP in major structures, such as the roof of the caustic chlorine facility shown in Figure 7, are common in the chemical plants today. FRPs facilitate the production of modular components like those in the UNILITE Modular System of Cooling Towers (Figure 8) for which corrosion resistance and light weight are additional advantages. Resistance to saline water corrosion and light weight make FRP advantageous for offshore construction and applications in the area of water and effluent

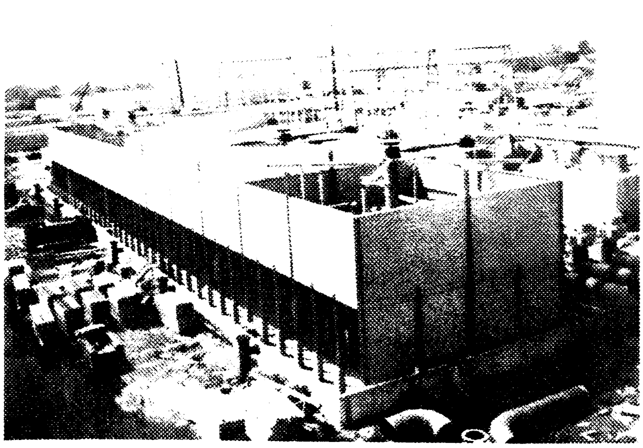

Figure 8. UNILITE modular cooling towers under construction at Westinhouse, Philadelphia, PA. (Courtesy of Composite Technology, Forth Worth, TX.)

treatment. The high dielectric strength of FRP is advantageously used in the construction of laboratories for testing of high-voltage electric power equipment and guideways for electric rapid transit systems (Figure 9).

Structural shapes are complemented by other products designed to satisfy structural needs in construction. Industrial floor systems typically use grating systems that allow free circulation of air. FRP grating systems compatible with structural shapes are becoming common for industrial applications where light weight and corrosion resistance are important. Closed environments can be created by wall and roof systems composted of tongue-and-groove FRP panels with polyurethane foam core for added stiffness and vibration insulation.

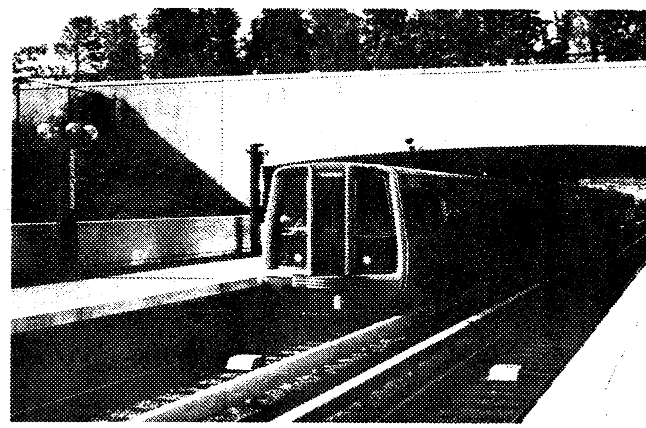

Figure 9. Nonconductive fiberglass covers for high voltage rails on rapid transit systems. (Courtesy of Creative Pultrusions Inc., Alum Bank, PA.)

Material Properties and Standards

The Pultrusion Industry Council of the SPI Composites Institute is currently developing an industry standard for pultruded structural shapes. Current industry standards use a single test (three point bending) to evaluate the bending stiffness, which may be inaccurate due to the influence of shear deformation. Long spans can be used to reduce the error introduced by shear deformation but for the new large sections (e.g., 30 x 30 cm wide-flange or 61 cm deep I-beams) the necessary span is excessively large for testing purposes. An alternate test to measure simultaneously bending and shear stiffness of structural shapes was proposed by Bank of Catholic University of America, DC. This method is based on a series of full-size, three-point-bending tests from which the bending stiffness can be accurately predicted. At least two tests for different spans are needed to eliminate the influence of shear deformations from the computation of bending stiffness. The method also gives the value of the shear stiffness, but it is sensitive to experimental errors and to the particular values of the span selected. Shear stiffness can be efficiently measured from torsion tests as reported by E. Barbero of West Virginia University and A.Green of Composite Technology, Fort Worth, TX.

Stiffness properties have been the main concern of pultrusion manufacturers due to the desire to market a product as similar as possible to the steel or aluminum structural shapes it is to replace. Despite the efforts in this area, the stiffness of the glass reinforcement and the resulting FRP are much lower than their metallic counterparts. This is considered erroneously to be a disadvantage of FRP. Innovative designs of structures can overcome the stiffness problem in various ways. When asked about these concerns, some structural engineers in the civil engineering community were more concerned with the ultimate (failure) strength, consistent properties, and reliability of FRPs, because of liability issues. Furthermore, the failure modes of FRPs are significantly different than those of metals, which will undoubtedly require additional research and education of the engineering community before FRPs are successfully and widely used for infrastructure applications. Pultrusion manufacturers like Creative Pultrusions, Inc. of Alum Bank, PA, are leading the way on extensive testing of their stock structural shapes to support their recommendations to designers who use these products for structural purposes. In a single project, column buckling data and testing procedures are being developed under agreement with West Virginia University's Constructed Facilities Center. The project, sponsored by Creative Pultrusions, Inc. of Alum Bank, PA, involves testing of most types of standard wide-flange I-beams in the short, intermediate, and long column lengths under various boundary conditions. The project also addresses the validation of analytical models to predict properties of future structural shapes. The effort is directed not only to provide data to support structural design but to allow the manufacturer to improve the product by introducing modifications suggested by the analysis and corroborated by experiments. Experimental results on buckling of columns for refrigeration towers were presented by A. Green of Composite Technology, Fort Worth, TX. Analytical results using the finite element method were presented by A. Zureick of Georgia Tech, GA. A simplified method of analysis was developed by Barbero and Raftoyiannis at West Virginia University, who also presented correlations with experimental results. For short columns, it is particularly difficult to translate experimental observations into concise results of buckling loads that, in turn, can be used for design purposes, motivating the development of a new method for data reduction advanced by Tomblin and Barbero of West Virginia University. Similar comprehensive studies should be undertaken to establish data bases of material properties and standardized test procedures if FRP structural shapes are ever to be massively used by the construction industry.

The advantage of full size member testing, described so far, is that the results are immediately applicable to structural design. The disadvantage is that these tests provide little information about the performance improvement (stiffness and strength) of the product by making modifications to existing structural shapes. For example, while most pultruded structural shapes are built with unidirectional rovings and randomly oriented mat, bending and column strength can be considerably increased by using angle-ply layers. Structural properties can be inferred from coupon tests, but these are expensive and, again, do not help predict structural properties. The structural properties of pultruded members can be predicted using micromechanical models, which are well established and there is ample evidence suggest that they are accurate to predict stiffness.

Shear deformation, largely ignored while designing structures with conventional materials, must be incorporated in the structural design with FRPs. Shear deformation can be easily incorporated in design by using Timoshenko beam theory instead of classical beam theory. Computation of shear stiffness involves determination of the shear correction factor, which depends on the geometry and material properties of the cross section. Shear prediction by micromechanical models gives a lower bound for the real material property. However, the micromechanical model can be adjusted using limited experimental data. The advantage of this approach is that, by using very limited experimental data, the prediction capability of micromechanical models can be retained where the for constant resin system, fiber type and manufacturing technique remain the same. Reliable experimental determination of shear stiffness can be accomplished also by simple torsion tests.

Since pultruded shapes are currently produced with mostly unidirectional fibers, the transverse strength is much lower than the longitudinal strength. The transverse strength is further reduced by clusters of fibers in fiber bundles with poor impregnation that act as crack initiators. As a consequence, steel-type connections do not perform satisfactorily. Either special connection details or new pultruded sections with increased transverse strength or both need to be developed.

CONCLUSIONS

Substantial growth in the use of FRP in construction has been observed in recent years. Structural shapes are used extensively in highly corrosive environments, water treatment facilities, and electromagnetically transparent antenna covers. Significant improvements are under way with respect to optimal sections and materials for particular applications, improved quality and reduced variability of properties. These improvements will facilitate the application of structural shapes to a broader class of structures of special importance in the development of testing standards and design procedures that will facilitate the structural design with FRP structural shapes. New markets to be conquered by structural shapes are those where low weight, modular construction, and resistance to environment are important considerations. Infrastructure applications involve performance-sensitive structures for which the material has to be optimum for an specific application in order to be competitive with conventional materials that have lower initial material cost but shorter life cycle and large maintenance costs.

Part II of this article reviews two promising material systems for infrastructure applications-reinforcing bars for concrete, and reinforcing/rehabilitation of conventional materials.

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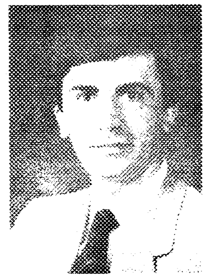
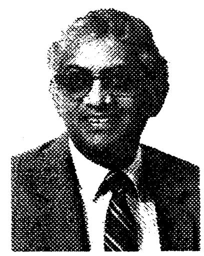
BIOGRAPHIES



Ever J. Barbero, a member of SAMPE® and ASME, graduated from Universidad Nacional de Rio Curato – Argentina with a BS in Electrical Engineering (1983) and a BS in Mechanical Engineering (1983). He was a Research Fellow at INTEC-Argentina from 1984 to 1986, and was awarded the Cunningham Dissertation Fellowship. In October of 1989, he received his Ph.D from Virginia Polytechnic Institute and State University. He is Assistant Professor of Mechanical and Aerospace engineering at West Virginia University and also a member of the Constructed Facilities Center at WVU conducting research on the application and development of fiber reinforced composites for construction of large structures.



Dr. Hota V.S. GangaRao is professor of Civil Engineering, West Virginia University, as well as Director of the Constructed Facilities Center, College of Engineering, Morgantown, WV. His own research includes work in structural systems; development and characterization of mass-produced wood and fiber reinforced composite materials and their applications to constructed facilities; "smart" structural systems; and timber bridge design, the latter resulting in both patents and construction. The co-author of over 150 journals, conference papers, and reports, GangaRao has been selected four times as one of the five Outstanding Researchers of the Year by the College of Engineering. Most recently, he was named one of WVU's 1990-1991 Benedum Distinguished Scholars. Dr. GangaRao earned a bachelor of science degree in civil engineering, with distinction, from the Indian Institute of Technology, Madras; and his master of science and doctoral degrees in structural mechanics and prestressed concrete from North Carolina State University.