# STRUCTURAL APPLICATIONS OF COMPOSITES IN INFRASTRUCTURE

## PART II

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As discussed in Part I, fiber reinforced plastics (FRPs) are partially replacing conventional materials in civil engineering type applications. Several attempts have been made at transferring composite technology developed for aerospace applications into the construction industry (1, 2). The task proved to be more complex than initially expected due to various factors, including large scale and cost constraints of infrastructure applications. This paper reviews critically two of the most promising material systems for infrastructure applications - reinforcing bars for concrete, and reinforcing and rehabilitating conventional materials.

### REINFORCEMENT OF CONCRETE

Mild steel reinforcing bars (rebars) are used extensively to reinforce concrete. Mild steel corrodes quite rapidly under the action of deicing products used in highway structures and other chemicals present in various industrial environments. Steel corrosion leads to expansion of rebars creating tension in concrete and consequent cracking, thus deteriorating the structure rapidly. Steel rebars also produce electromagnetic interference and therefore have to be ruled out for special applications.

FRP rebars were used in Europe and the U.S. in the past on a limited basis but they did not become popular due to their low bond strength and stiffness and poor quality control in production. New and improved FRP rebars and their applications are currently being investigated. While most applications involve straight FRP rebars similar to steel rebars, reinforcement in the form of grid have been proposed and their utilization is being investigated at University of New Hampshire, Durham, using a commercial product called NEFMAC produced by Shimizu Co. of Japan. Actual applications of NEFMAC are shown in Figures 1-5. Fiber Reinforced Plastic (FRP) laminates were successfully employed as reinforcing plates in concrete beams (Figure 6) by H. Saadatmanesh and Mohammad Ehsani of University of Arizona, Tuczon, as a rehabilitation technique for deteriorated structures. FRPs are also 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.

Since the 1930's, glass fiber reinforced plastic (GFRP) has been considered a good substitute for steel as a reinforcement of concrete or to create an initial state of compressive stress in concrete by prestressing GFRP tendons. Reinforcement and prestressing of concrete are common ways to mitigate the low tensile strength of concrete in order to take advantage of its high compressive strength. In fact, reinforced concrete is a fiber reinforced composite material in which the advantageous properties of the constituents are high tensile strength of the rebars (steel or FRP) and the high compressive strength of the concrete matrix. Surface protection of certain types of continuous glass fibers, particularly E-glass fibers, from attacks by the environment or alkaline reaction with concrete has been accomplished by coatings, including resins. For example, a typical continuous E-glass fiber reinforced plastic rebar has a 55% glass volume fraction embedded in a matrix of vinylester or isophthalic resin. These thermoset resin systems have excellent resistance to corrosion and impact, are good electrical and thermal insulators, are easy to manufacture, and are cost effective. Thermoplastic rebars, which are more expensive than thermosets, have a potential for reshaping and welding in the field which motivates current investigation of their potential applications in construction.

Aramid fibers (e.g., DuPont's Kevlar® 29, 49, 149) with higher tensile strength (3.62 GPa) and stiffness (124 GPa for Kevlar® 49) than glass fibers are being used to develop high strength rebars and cables by U.S. and Japanese manufacturers. Aramid fibers have good chemical resistance to solvents, dilute acids, and bases, as well as excellent fatigue strength and low relaxation. Carbon fiber reinforced plastic rebars and seven wire strands (cables) with higher stiffness than glass or aramid fiber rebars are also manufactured as reinforcing or prestressing elements for structural applications. However, carbon fiber rebars and cables are even more expensive than aramid or glass rebars. Chopped fiber reinforced plastic rods are being manufactured by extrusion. These rods are quite expensive and have much lower strength and stiffness than the continuous fiber reinforced plastic rebars.

As with any fiber reinforced material, the strength of reinforced concrete is limited, among other things, by the bond strength between FRP rebars and concrete. Different surface conditions for rebars have been developed to mitigate this critical problem that contributed to the limited application of FRP rebars in the past. Sanding the rebar with emery cloth to

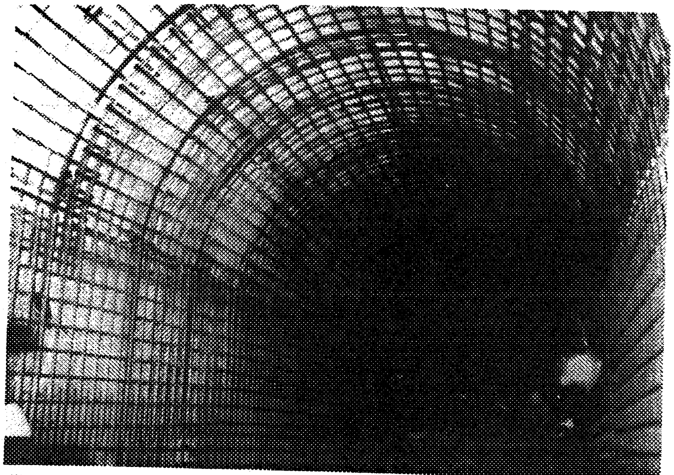


*Figure 1. GRFP reinforcement grid for a tunnel. (Courtesy of NEFCOM Co., Tokyo, Japan)*

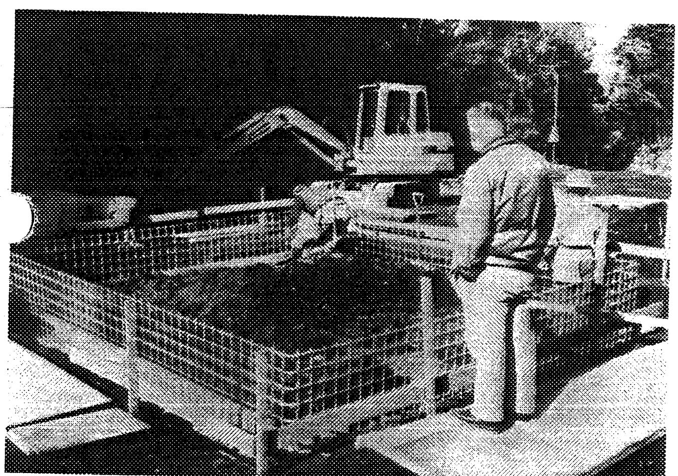
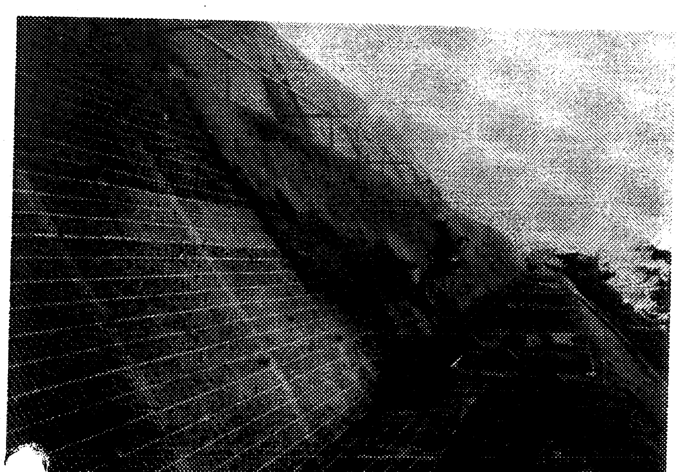


*Figure 2. Concrete silo near seashore reinforced with GFRP grid. (Courtesy of NEFCOM Co., Tokyo, Japan)*



*[Fi]gure 3. Foundation of earth magnetism observatory reinforced with GFRP grid. (Courtesy of NEFCOM Co., Tokyo, Japan)*

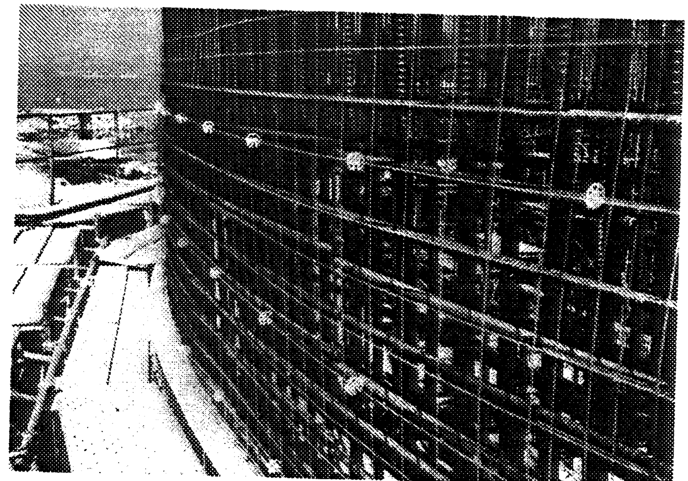


*Figure 4. Lightweight concrete reinforced with GFRP grid in a building with curtain-type walls. (Courtesy of NEFCOM Co., Tokyo, Japan)*

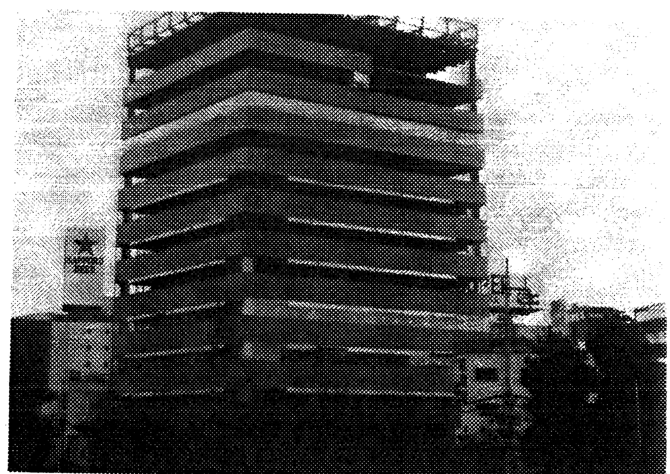


*Figure 5. Slope protection with shotcrete reinforced with GFRP grid. (Courtesy of NEFCOM Co., Tokyo, Japan)*

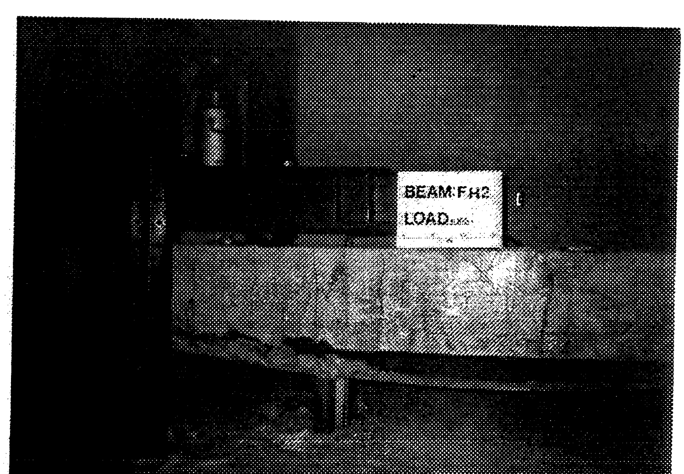



*Figure 6. Failure of a concrete beam strengthened with a GFRP plate. (Courtesy of University of Arizona, Tuscon)*

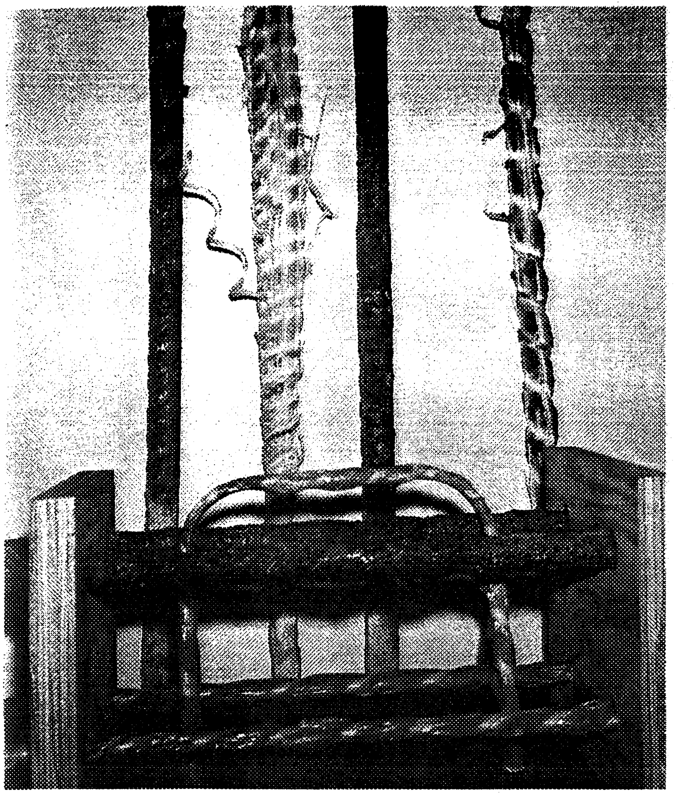


*Figure 7. Sample rebars. From left to right: wrapped, failed wrapped, sand coated, and wrapped sand coated. Also (at bottom) two wrapped, two sand coated rebars, and a portion of a wrapped stirrup.*

create a roughened surface was one of the early attempts to improve bond strength of smooth pultruded rods (3). Angular wrappings or helical ribs, usually at 45° or 45°/135°, produce a deformed surface on the rebar (Figure 7) that improves the bond to concrete. Coating FRP rebars with sand further improves the bond strength. In particular, a combination of ribs and sand coating seems to give the best results.

## Experimental Determination of Mechanical Properties

Mechanical properties of FRP rebars under tension, compression, torsion, and bending have been obtained at the Constructed Facilities Center at West Virginia University (4). Results generated from these experiments include static stiffness, ultimate strength, and associated modes of failure. Other researchers have conducted tests on glass or aramid fiber rods under tension only. All tension test results show a linear stress-strain relation up to about 95% of the ultimate strength. For smooth FRP rebars, failure is governed by the tensile strength of fibers, whereas matrix cracking is noted for wrapped or ribbed rebars. Since various researchers have experienced difficulties in gripping the ends of the FRP rebars, sand grips were developed at the Constructed Facilities Center of West Virginia University and used to achieve a gradual and uniform load transfer over the whole gripping surface through friction and to make certain that failure does not take place in the grips. The sand layer is used to prevent slippage and to protect the specimen surface from damage that could be caused by direct contact with the steel jaws of the testing machine. Failure modes of various rebars are shown in Figure 7.

Experimental results indicate that the average tensile stiffness depends on the fiber type and volume fraction and is virtually independent of manufacturing company, bar size, bar type (with or without ribs), test procedure, and type of resin. A mean tensile stiffness of 48.263 GPa for 55% fiber volume fraction was reported, whereas the aramid fiber reinforced rebars indicated a mean tensile stiffness of 55.158 GPa. The ultimate tensile strength is sensitive to bar diameter, quality control in manufacturing, matrix system, fiber type, and gripping mechanism. The ultimate tensile strength of continuous glass fiber reinforced rebars with vinylester resins decreases rapidly with increase in bar diameter, a phenomenon that is being investigated at the Constructed Facilities Center of West Virginia University.

Static compressive stiffness and strength properties were measured on rebar specimens prepared according to the ASTM D 695 standard. Unlike the tensile stiffness, the compressive stiffness varies with rebar size, type, quality control in manufacturing, and length to diameter ratio of test specimen. Static properties such as longitudinal shear stiffness and torsional strength of FRP rebars were determined from torsional tests. While the shear stiffness (4.55 GPa) does not significantly vary with the manufacturing quality or rebar type, the torsional strength decreases with increasing diameter and is dependent of manufacturing quality. Static flexural stiffness and strength results were obtained from three point bending tests where strains at the top and bottom surfaces were measured by strain gauges. Ultimate bending strength varies with diameter as in the case of ultimate tensile strength while bending stiffness (41.37 to 46.88 GPa) is virtually independent of rebar type or manufacturing quality.

## Theoretical Modeling of Mechanical Properties

Theoretical modeling of a rebar's mechanical properties, subjected to a variety of static loads, has been attempted through micromechanical modeling, macromechanical modeling, and three-dimensional finite element modeling. The objective of micromechanical modeling is to predict the material properties of the rebar as a function of the properties of the constituent materials. In the macromechanical modeling, FRP rebars are treated as homogeneous but anisotropic straight rods of circular cross section. The finite element method (FEM) has been used to simulate actual tensile test conditions of FRP rebars assuming a linear distribution of shear force transfer between the gripping mechanism and the rebar. First ply failure along with the maximum stress failure criterion was employed. The ultimate tensile strength predicted by the FEM is twenty five percent higher than the experimental value.

To overcome the limitations of both the FEM and the elasticity solutions, Wu and GangaRao of West Virginia University developed a mathematical model using the strength of materials approach, including the shear lag between fibers. The maximum failure strain of the glass fibers (approximately three percent) is considered as the only governing criteria for failure. The major assumption in developing this model, which uses a circular cross section to compute tensile or bending strength, is that the strain distribution across the cross section is parabolic and axisymmetric. The parabolic strain distribution is assumed to result from the radial stresses induced by the gripping mechanism. The model predicts tensile forces in the core fibers lower than those forces at the surface of the bar. Similarly, the strain distribution under bending is assumed to be parabolic across the cross section. This mathematical model resulted in excellent correlations with the experimental results, within seven percent accuracy.

## Behavior of Reinforced Concrete Beams

Bending tests of reinforced concrete beams are commonly used to evaluate the overall performance of the material. Pull-out tests are used specifically to investigate the bond strength between the FRP rebar and concrete. Most of the available design data on FRP rebars as reinforcing elements of concrete members is based on testing of continuous glass FRP, except the bond tests conducted by Pleiman at University of Arkansas with Kevlar® FRP.

In order to take advantage of the high tensile strength of FRP rebars (758-896 MPa), high strength concrete (44.82 - 51.71 MPa) should be used whenever possible. Using high strength concrete (44.82 MPa), ninety percent increase in ultimate bending capacity is obtained when FRP rebars are used in lieu of mild steel rebars. This increase is attributed to full utilization of the rebar's higher ultimate strength, which is higher than that of mild steel. Cracks in concrete beams reinforced with ribbed FRP rebars appear suddenly and crack widths are larger than in similar steel reinforced beams (Figure 8). The first cracking moment (i.e., the bending moment at which the first crack appears) with FRP reinforcement is lower than the cracking moment with steel reinforcement in regular concrete. However, the behavior in all these areas improves substantial- ›y using high strength concrete, with the crack widths being reduced to allowable design limits.

The results reported in Figure 9 correspond to beams reinforced with two rebars of 0.95 cm diameter, commonly called #3 rebar. The ultimate moment capacity of FRP reinforced beams increases with increasing concrete strength (in brackets) as shown in Figure 9. Comparison of the concrete beams reinforced with sand coated FRP rebars versus steel reinforced beams in Figure 9 indicates that FRP reinforced beams have greater ductility than steel reinforced beams. However, larger deflections of FRP reinforced concrete beams are noted after initial cracking because of the lower stiffness of FRP rebars as compared to that of steel rebars.

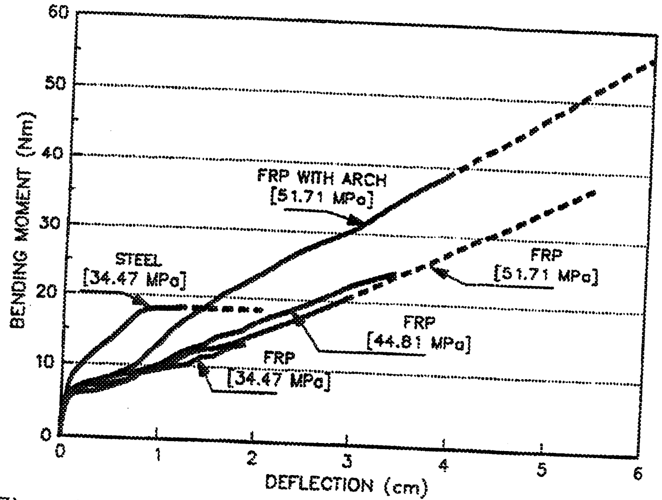



*Figure 9. Bending moment versus deflection of concrete beams reinforced with FRP or steel rebars and various types of concrete.*

The use of smooth FRP rebars does reduce the bending moment capacity by as much as sixty percent because of bond failure between the rebar and concrete. Smooth FRP stirrups (used to hold the reinforcement in place while pouring the concrete) result in shear-bond failure with a moment capacity reduction on the order of thirty-five percent or more. The crack patterns, width, propagation, and distribution have vastly improved using sand coated rebars (Figure 10) due to a better bond between the sand coated rebar and concrete. The observed crack pattern is similar to the pattern expected of a beam reinforced with steel rebars. All other parameters being identical, a concrete beam reinforced with sand coated FRP rebars exhibits a forty percent increase in the initial cracking moment and seventy percent increase in ultimate moment over concrete beam reinforced with ribbed FRP rebars without coating.

*F  e 8. Failure of a concrete beam reinforced with ribbed FRP rebars.*

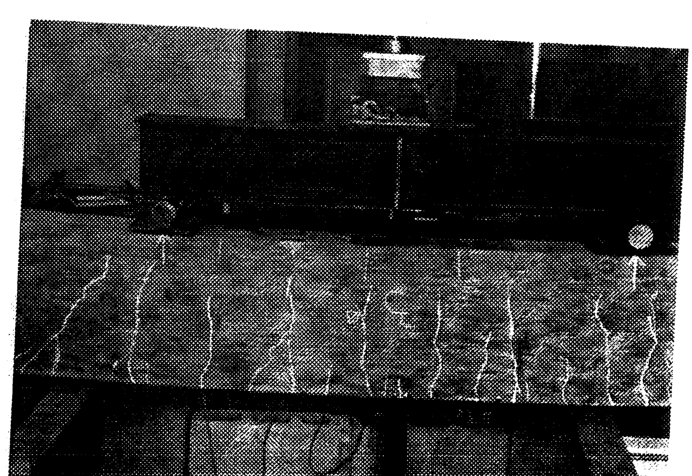


*Figure 10. Crack pattern in a concrete beam reinforced with FRP rebars is similar to that obtained with steel reinforcement.*

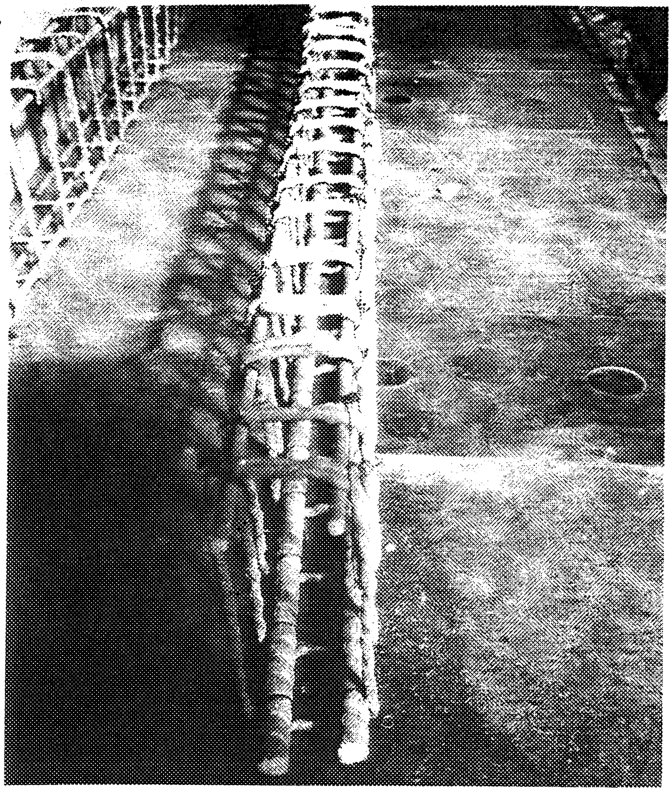


*Figure 11. FRP reinforcement for a beam showing longitudinal reinforcing bars and FRP stirrups.*

Even though the total rebar area may be the same, use of lower diameter FRP rebars (0.95 to 1.58 cm) increases the ultimate moment capacity over larger diameter (2.22 to 2.54 cm) rebars. Therefore, smaller diameter rebars are more efficient than larger diameter rebars, which confirms the behavior discussed in the section on experimental determination of mechanical properties.

The ultimate bending resistance can be computed by the classical bending theory of concrete reinforced with steel rebars, which is broadly accepted by practicing engineers. Bending resistance of concrete beams reinforced with FRP rebars can be computed from the American Concrete Institute (ACO) Building Code, which assumes that the ultimate concrete compressive strain is about 0.003 and specifies a balanced failure criteria (concrete in compression and rebar in tension reach their ultimate strains at the same time). The standard ACI approach gives excellent correlations between the theoretical and experimental results. However, the designer should properly account for ultimate tensile strength variations in FRP rebars with rebar diameter while computing their bending resistance within concrete.

To study the bond strength and failure pattern of FRP reinforced concrete specimens, the WVU modified cantilever test is used because it yields more realistic results than pull-out tests. The bond experiments on FRP rebars show a behavior similar to that of steel rebars. Results of specimens using 0.95 cm sand coated rebars show an ultimate bond strength of about 10.34 - 11.03 MPa for embedment lengths of 15 cm to 30 cm using high strength concrete (69.96 MPa). Ultimate bond strength decreases with an increase in rod diameter. The bond strength of sand coated rebars with higher strength concrete is about fifty to sixty percent higher than that of ribbed steel rebars. The ACI Building Code can conservatively predict the allowable bond strength of concrete beams reinforced with FRP rebars. The procedure has been modified at West Virginia University to yield more accurate computations of the bond strength values by taking into account various FRP rebar diameters and embedment lengths.

FRP rebars have been used in full-size experimental structures, such as beams (Figure 11) and slabs for bridge decks (Figure 12), which have been tested to failure under various conditions by S. Faza and H. GangaRao at West Virginia University. The modes of failure observed in beams reinforced with FRP rebars can be summarized as follows:

- Bond failure when smooth FRP rebars or smooth stirrups are used.
- Shear failure followed by secondary compression failure when large areas of rebars are used.
- Excessive cracking in regular strength concrete beams leading to compression failure followed by secondary tension failure.
- Primary tension failure of sand coated FRP rebars followed by compression failure of concrete when high strength concrete is used.

FRP bars and cables can be used as noncorrosive, magnetically transparent, high strength alternative to steel prestressing tendons to induce initial compressive stress in concrete structures. Glass fibers have been used primarily in FRP prestressing tendons for concrete structures while Aramid fiber and

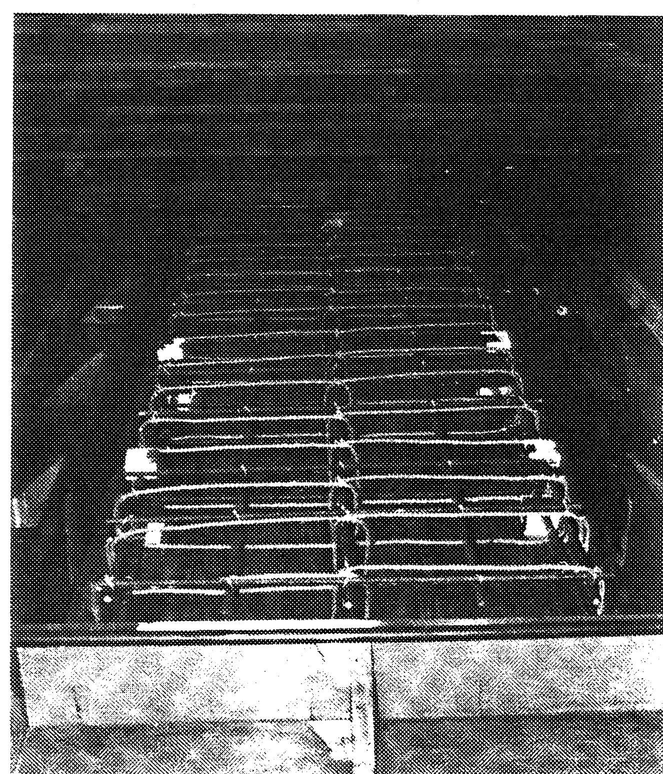


*Figure 12. FRP reinforcement for a concrete bridge deck showing longitudinal/transverse reinforcing bars and FRP stirrups.*

carbon fiber reinforced plastic rods and strands have been used as cables or suspenders. Glass fiber reinforced plastic rods are currently used in the prestressing of bridge girders, prestressed fence posts, hollow core floor slabs and masonry cavity walls. Several concrete beams post-tensioned (the prestressing force is applied to the rods after the concrete has cured) with glass FRP rods were tested and implemented in full-scale bridges in Germany (see Part I, Figure 5). Since the FRP rods have lower stiffness than steel, the prestress losses are much lower than the prestress losses observed using high strength steel rods or cables. The cracking and ultimate moment capacities of beams post-tensioned with FRP rods can be calculated using standard theories of prestressing for high strength steel rods. The overall behavior of beams prestressed with FRP rods is very similar to those prestressed with high strength steels. However, the prestressing force applied to FRP rods in current applications does not usually exceed forty percent of the ultimate strength of the rod. This is done to prevent the stress level to exceed the creep threshold and fatigue endurance limit beyond which progressive damage would occur at a constant stress level. Cumulative damage of FRP rods in tension manifests itself as progressive fiber breaking that can be detected with acoustic emission (AE) hardware. Strong acoustic emission signals can be acquired for different stress levels of concrete beams reinforced with FRP. These signals contain more events and higher amplitudes than the signals from conventional concrete beams reinforced with steel. Even though FRP bars behave linearly almost up to failure, they release strong AE signals or cracking noises at around fifty percent of their ultimate strength. A proper correlation of events with stress levels in concrete or rebars can form a basis for developing intelligent or smart structures that can self-monitor the state of the structure to predict the remaining life. In addition, optical fiber sensors can be embedded in FRP rebars to monitor their strain, stress, and damage state. Monitoring of FRP rebars can be very useful in assessing their condition while pre-tensioning or post-tensioning a structure in the field.

## FRP REINFORCEMENT FOR WOOD

Wood is a conventional construction material. The availability of high-quality, solid-sawn structural wood is decreasing along with the availability of old timber forests. Current forests cannot produce large sections with high stiffness necessary in construction because the demand is being covered by fast-grown farmed timber. Although laminated and reconstituted wood products meet the demand for sections larger than the individual logs used to produce them, the stiffness of the product is limited by the stiffnesses of the constituent materials. For example, single-span deck-and-stringer timber bridges are limited to spans smaller than 24 m, even with new technologies like the stress laminated timber bridge advanced by GangaRao at West Virginia University. The Tacoma Dome (Tacoma, WA, 1982) is the largest single-layer reticulated dome in the world (170.7 m). Although the ength and stability of this dome are quite adequate, it ppears that a larger span using timber alone would not be possible because of the dead load of the structure which requires beams about 1.2 m deep. To increase the strength and stiffness of wood, fiber reinforced plastic composites are being considered as candidates for reinforcing laminate timber products. Although steel plates have been used to reinforce wood, corrosion, weight, and incompatibility between steel and wood present serious problems. Such is not the case with FRP reinforcements, which are noncorrosive and have a range of stiffness (7-50 GPa) that can be tailored for compatibility with wood (7-14 GPa).

Epoxy resins have been used to laminate a unidirectional fiberglass tape to the top and bottom surfaces of solid wood cores in order to increase its stiffness and strength. In reinforcing glued-laminated timber beams (GLULAM) by incorporating FRPs in the form of rovings, woven rovings, cloth mats, and chopped strand mats between the wood layers, compatibility of the adhesive used to bond wood with the FRP presents a major problem as it has been the case with water based adhesives. Increases in strength and stiffness have been reported for wood beams wrapped in fiberglass epoxy composite or when the composite was placed between horizontal lamination, producing best results when nonwoven unidirectional mats are used. Placing glass fibers or glass fiber mats at the glue lines of laminated timber beams also reduces the creep deformations in bending commonly observed in wood subjected to load for long periods of time.

Prestressed strands of fiberglass roving have been incorporated into the cross-section of particle-board using urea-melamine resin to bond particle-board to itself and to the glass roving, achieving a two fold increase in strength and stiffness. A remarkable increase in strength and stiffness in bending, tension, and compression has also been reported when particle-board and plywood was overlaid with fiber glass layers in a wet process.

Medium density and high density hardboards have been reinforced with glass yarn scrim impregnated with phenolic resin placed on the surface of dry formed hardboard. The surface reinforcement increased bending strength and stiffness by up to 35%. Unidirectional, nonwoven roving fiberglass mat, impregnated with phenol resorcinol formaldehyde has been used to reinforce particle-board. The bending stiffness and ultimate moment capacity of particle-board beams reinforced with one layer of resin impregnated glass increased substantially and exhibited considerable residual strength after reaching the ultimate load. A summary of the results by various researchers is presented in Reference [5]. FRP has been used to reinforce wood transmission poles by wrapping them with FRPs. The reinforcement increased both strength and stiffness. The American Plywood Association tested plywood overlaid with FRP in the form of vinylester and polyester resins, with unidirectional glass fiber, chopped strand mat, and woven roving. Strength, stiffness, and impact resistance improvement was reported. Fiberglass impregnated with phenol resorcinol formaldehyde has been used to increase the tension and bending strength of impression finger joints up to 40% over unreinforced joints.

In all these investigations, the composite was made by a hand lay-up process, which added considerable cost to the product due to the amount of labor involved in the fabrication in combination with the cost of the reinforcing material. Davalos and Barbero of West Virginia University proposed to used inexpensive, pultruded glass-vinylester as an additional lamina in a glue-laminated timber beam. Since the FRP reinforcing layer is similar to an additional layer in the wood laminated product, the labor costs are not affected. The cost of the pultruded reinforcement is also quite low, allowing for a competitive product. Recycled plastics can also be used in combination with wood to produce structural components. Wood fibers have also been used extensively as the reinforcement for thermoplastics.

## CONCLUSIONS

Use of FRP as structural components in construction has been limited due to several factors. In general, lack of design guidelines, material properties, designer awareness, and high material cost have hampered efforts to use advanced materials for innovative construction. Attitudes are changing rapidly and substantial growth in the use of FRP in construction is observed.

Reinforcement for concrete with FRP rebars has been proved to be feasible and economical. In the past, applications were limited due to poor quality of rebars, a smooth surface of rebars and associated poor bond strength with concrete, and lack of design guidelines other than those of the ACI for steel reinforcement. However, because of the salient characteristics of FRP rebars, mainly their noncorrosive and nonmagnetic nature, practicing engineers have been motivated to use FRP rebars in advanced reinforced concrete structures. The dramatic deterioration of the U.S. constructed facilities due to corrosion motivated further research in this area. As a consequence, substantial improvements in the product have been achieved. Particularly important are the utilization of ribbed, sand coated rebars with high strength concrete along with designs that depart from a direct replacement of steel by FRP rebars. Today's product and design methods can be used competitively for a number of applications. Current FRP rebars and reinforced or prestressed concrete design methods are far from mature, and striking advancements are yet to be achieved in this field.

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 a specific application in order to be competitive with conventional materials that have lower initial material cost but shorter life cycle and larger maintenance costs.

FRP materials have been shown to be a successful reinforcement for low cost conventional materials such as timber and also for rehabilitation of existing deteriorated structures. Due to their low weight, excellent compatibility with low modulus materials (such as timber and concrete), and corrosion resistance, FRP is being increasingly used for rehabilitation of existing structures, most of which have significantly improved performance after rehabilitation when compared to their original rating, e.g., replacement of heavy concrete bridge decks for lighter FRP decks. FRP reinforced timber will clearly expand the market applications of this inexpensive conventional material.

It is recognized that FRP structures cannot be designed as steel ones. The successful growth of FRP applications hinges upon the development of building and construction systems-design approaches that take into account the peculiarities of composites and use them to advantage. Due to a variety of structures requiring different design conditions, their geographic dispersion, and the nature of their construction, it is imperative that simple and safe design procedures as well as manufacturing and construction techniques be developed and adopted by the construction community, including the regulatory agencies at various levels, professional organizations, contractors, and users. Significant advances in this area have been made in recent years. Additional developments will continue to improve the design tools, materials, and FRP products to cut the initial costs and to improve efficiency of composites in construction.

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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.